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16

An Introduction to Temporal-Geographic Information Systems (TGIS) for Assessing, Monitoring and Modelling Regional Water and Soil Processes

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Abstract

In this chapter we introduce the concept of temporal-geographic information systems (TGIS). We first describe some nontemporal concepts of GIS, consider the issues of scale and of continuous and discrete data, and give a brief background to the basis of remote sensing measurements. Using the concept of the 'data construct' as a tool for understanding TGIS data structures, we explain the relationship between characteristics (extent, resolution and density) and domains (attribute, spatial and temporal) of each dataset. Finally, we discuss two emerging issues in TGIS: the assessment of spatial-temporal accuracy and uncertainty, and the use of metadata systems.

我们在本章引入了时态地理信息系统（TGIS）的概念。首先解说 GIS 的非时间概念，考虑了尺度问题、连续数据与离散数据问题，简单介绍了遥感测量的物理背景。从数据构建概念入手，说明 TGIS 数据结构。阐明了每套数据特性（范围、精度和密度）与域性（属性、空间和时间信息）的关系。最后，探讨了 TGIS 中的两个议题：时间空间精度的评估和不确定性，标准格式的数据系统的应用。

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IN THIS CHAPTER we provide background information on some of the techniques that are used to assess the sustainability of regional agricultural systems that are described in subsequent papers in this section. We introduce the concept of temporal-geographic information systems (TGIS) and explain how remote sensing data can be used to generate information for GIS monitoring.

Most readers of this book will have already heard the term ‘GIS’, which usually connotes analysis in the spatial domain. However, to assess the sustainability of agricultural systems, the temporal domain is also needed; we use the term TGIS to describe this concept. The benefit of using this slightly nonstandard term is that the reader immediately contemplates both the spatial and temporal domains. The concept of adding a temporal element is essentially similar to the notion of integrating remote sensing into GIS (IGIS), proposed by Quattrochi (1993). Theoretical and technical aspects of data integration arising from the inclusion of time in GIS are discussed in detail by Langran (1992), Peuquet (1994, 1995) and Mitsova et al. (1995).

Scale, resolution and extent

Many different definitions of the term ‘scale’ are in common use in the TGIS community (Quattrochi 1993; Bian 1997; Cao and Lam 1997), and among other agricultural scientists and policy makers who use output from TGIS. The confusion that this situation creates can sometimes be overcome by using the terms ‘resolution’ or ‘extent’ rather than scale. Below, we describe some of the different ways in which the term ‘scale’ is used, and show why alternative terms may be preferable or qualify what is meant by ‘scale’.

- ‘Cartographic scale’ or ‘map scale’ refers to the ratio first used in the production of paper maps. For example, a cartographic scale of 1:1000 means that 1 mm on the map represents 1 m (1000 mm) on the ground; whereas 1:1,000,000

means that 1 mm on the map represents 1 km (1,000,000 mm) on the ground.

- ‘Geographic scale’ is a term often used by noncartographic scientists to describe area. In this sense, a large study area is said to have a large scale. The term ‘extent’ is preferable to ‘scale’ for describing the size of a study area (which is sometimes referred to by ecologists as the ‘spatial domain’).
- A third meaning of scale is that of resolution — the smallest element (or grain) that can be distinguished. For example, the resolution of an electronic microscope is much finer than that of a traditional optical microscope, and one minute is a finer measure of time than one hour.
- Finally, and most applicable to TGIS analysis and modelling, there is ‘operational scale’ or ‘process scale’. For example, a single wheat plant operates on a smaller spatial extent than a wheat field.

Time can also be the scalar; for example, a tree will usually have a longer temporal extent than an individual wheat plant. Hence, in a spatial-temporal construct, a tree occupies a larger volume than does a wheat plant. Put simply, trees usually live longer and are bigger than wheat plants. Obviously, in this tree-wheat example, the different life forms are operating at different spatial and temporal scales. Thus, a model generated at one scale may not be totally applicable at another scale (i.e. a model generated for trees may not be applicable to wheat plants). Although this may be obvious in the above example, in complex environmental modelling it is not always easy to determine whether scaling up or down from one extent-resolution domain to another is appropriate. For example, is the model developed for a single tree relevant for modelling a stand of trees or a forest? The answer to this question depends on which process is modelled (which in part determines the transferability of the model across scales) and on data availability. Many models

developed for small spatial extents (usually short temporal extents) are ‘data-hungry’ and are not easily applied to larger spatial extents (usually longer temporal extents). Chapter 1 discusses the question of extrapolating from one scale to another with respect to water balance models.

An area of active research in the disciplines of pedology and hydrology is the aptness of ‘upscaling’ (going from small to large, in space and/or time, by crossing geographic scales) and ‘downscaling’ (from large to small). The terms ‘upscaling’ and ‘downscaling’ are not equivalent to the terms ‘aggregating’ or ‘disaggregating’, respectively (Bloschl and Sivapalan 1995). Upscaling and downscaling involve a fundamental change in approach in the TGIS modelling, whereas aggregating implies combining a scale of measurement and disaggregating implies splitting it. For example, crop yield can be aggregated from a district to a county level simply by adding the district level values together; this is routinely performed on the North China Plain (Chapter 18). Weekly rainfall totals can be disaggregated into daily values using some knowledge of rainfall patterns.

In the original definitions of scale relevant to TGIS (Lam and Quattrochi 1992), the concepts of resolution and extent were, by default, both included in ‘geographic scale’. Later modifications (Bian 1997; Cao and Lam 1997) differentiated geographic scale into the related concepts of resolution and extent. To give a spatial example of the concept of extent, the whole of China is a large spatial extent (or ‘patch of dirt’). The entire country could not be modelled using 10 m (fine resolution) grid data because the data volumes would be too large to store on current computing hardware and processing would take too long. It is more likely that China would be modelled with 1000 m (coarse resolution) grid data. In terms of temporal extent, processes of soil genesis, which occur over a long time (a large extent) obviously require coarser measurements and descriptions of temporal resolution than do within-season crop water-use

processes, which occur over a period of a few months (a short extent).

In hierarchy theory — a type of multilevel modelling used in ecology and landscape ecology — temporal and spatial scales tend to covary in relation to one another. That is, processes that operate over large areas usually occur over long periods, and processes that operate over small areas usually do so over short periods (Bloschl and Sivapalan 1995), as in the tree–wheat example given above. However, this principle does not hold for all environmental sciences. For example, extreme climatic events such as hurricanes and typhoons occur over large areas and have a relatively short duration. Therefore, the cartographic notion of a minimum mapping unit, which is spatial, needs to be extended for TGIS to include a temporal component. The minimum element in TGIS, in both space and time, needs to be placed in the context of both the operational (or process) scale and the resolution (and hence extent) of the study. If the two are not matched, a trend may go undetected because any signal measured will be influenced by the overlay of processes occurring at different spatial and temporal resolutions (and hence extents). Thus, if the resolution in space or time is too small, the process studied will appear as noise and any trend in either time or space will not be evident. On the other hand, if the resolution is too large, an established process may only appear as a slowly varying trend.

TGIS has many different environmental applications. Recent reviews include urban systems (Mesev 1997), agrometeorology (Maracchi et al. 2000), rural land use and associated changes in soil condition (Sommer et al. 1998), drought (McVicar and Jupp 1998), aquatic botany (Lehmann and Lachavanne 1997), hydrologic processes (Gurnell and Montgomery 1998; Rango and Shalaby 1998), regional evapotranspiration (Kustas and Norman 1996), atmospheric processes (Bernard et al. 1998), geomorphology (Butler and Walsh 1998) and oceanographic fisheries (Santos 2000). A common

feature of most reviews is the extensive use of remote sensing for what are often considered as two different tasks: monitoring the environment and updating GIS. Here, we consider these two tasks as identical operations.

Geographic Information Systems

Geographic location is a key component of GIS, which themselves are a subset of information systems. There are many information systems that make little or no use of geographic location. For example, in those used by banks and other financial institutions the quantity (i.e. how much money there is) is the main attribute of interest (pardon the pun). However, as such systems become more complex, the temporal components (e.g. calculating interest rates and compound returns on long-term investment strategies) become more important, because quantity depends on factors such as time since a deposit was made or when a loan was established.

Types of data

In GIS, map-type data can be stored digitally, displayed visually and integrated with other data sets. One way to visualise data is as vectors. Vector data are commonly points, lines or polygons, with one, or more, attribute(s) associated with the geographic feature of interest. Examples of point data are meteorological data measurements (e.g. air temperatures, rainfall and solar insolation) and soil pH at a location accurately determined using global positioning system (GPS) technology. Linear data include features such as road, rail and river networks. Attributes associated with a road could be whether it is paved or not and how wide it is. Polygon data are usually thematic maps that include attributes such as administrative boundaries, land use and land cover. Point-based measurements can be interpolated¹ to

generate polygon data. For example, soil pH data recorded at many points can be spatially interpolated to produce a map of soil pH.

GIS data are either continuous or discrete (discontinuous). For example, pH units, (which are continuous from 1 to 14) may be stratified into several discrete pH ranges (e.g. < 5.0 , $5.0\text{--}8.0$ and > 8.0) in order to assess the land capability for potential agricultural uses. Although the extent of any of the three domains (attribute, spatial and temporal) may be equal, the continuous or discontinuous nature of the data needs to be known if it is to be used effectively in spatial-temporal analysis (Heuvelink and Huisman 2000).

Spatial analysis

In GIS, different attributes for the same geographic area are separated to allow for spatial analysis. For example, Figure 1 shows five different attributes of the landscape (or ‘real world’ in GIS terminology) — climate, vegetation, soil, geology and digital elevation. When these five attributes are overlaid, and the landscape stratified into unique combinations, 14 different hydrothermal regions are identified.

An important distinction in GIS is that between land cover and land use. For example, in an area designated ‘State forest’, the land use is forestry; however, the land cover, which in this case would be mainly forest, may vary from 100% (e.g. old-growth forest) to 0% (e.g. roads or areas which have been clear-felled), with a range in between. Many of the variables mapped in GIS are exclusive; that is, the data are thematic, with each area belonging to one class or another. However, there are several examples where spatial data are not exclusive but depend on the user’s perspective. For example, the most valuable asset of a State forest could be its provision of clean water or maintenance of biodiversity (through providing a habitat for flora and fauna). Thematic maps, simulation outputs and all products generated from TGIS need to be

¹ In GIS, the term ‘interpolation’ refers to values of an attribute at unsampled points being estimated from measurements made at surrounding sites.

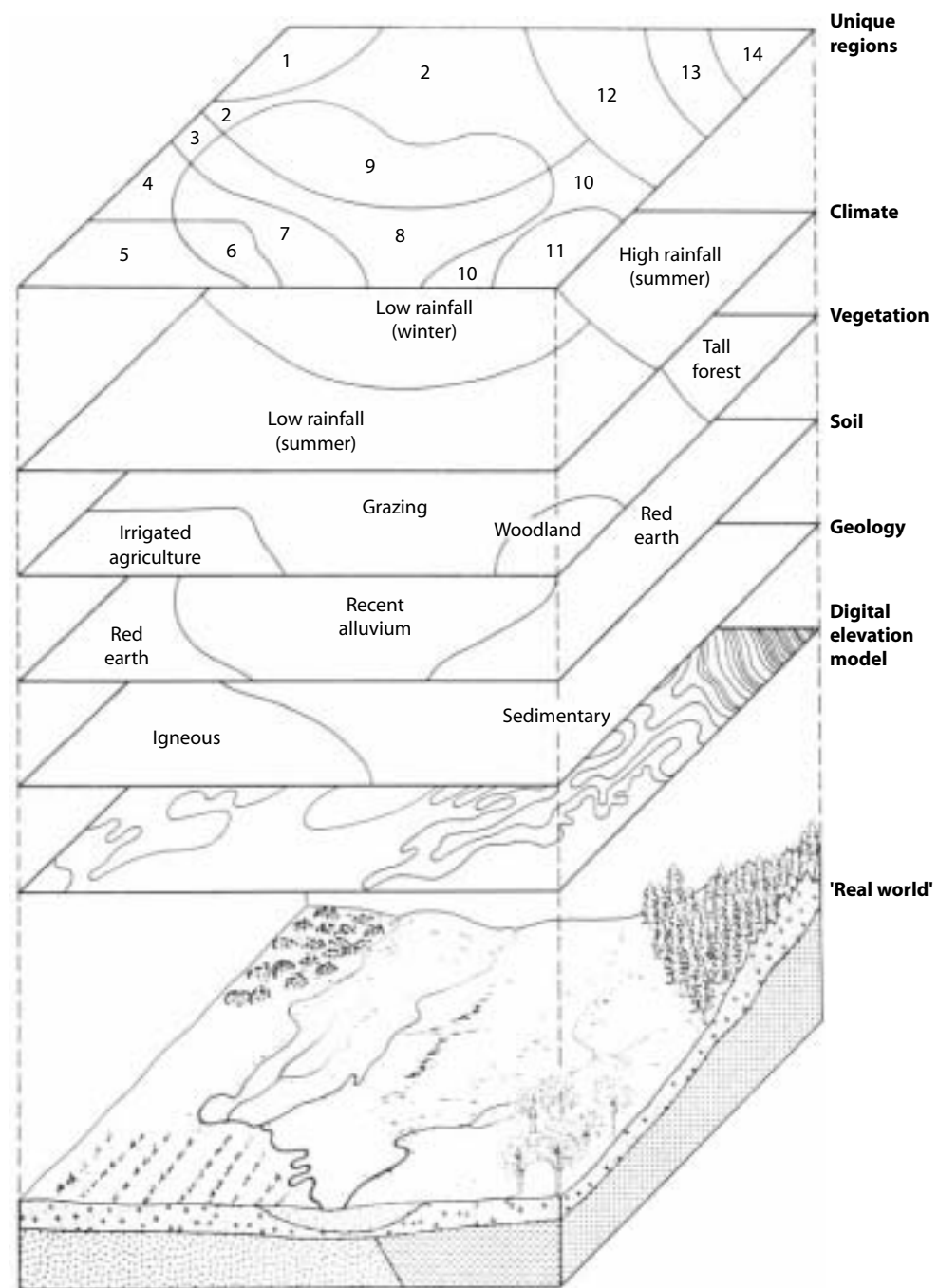


Figure 1. GIS landscape stratification of unique regions, based on five attributes (climate, vegetation, soil, geology and digital elevation model).

critically evaluated because the conclusions can be strongly influenced by the perspective of the user, the accuracy of the data and even the very nature of the data.

Currently, many researchers with point models wish to add a ‘spatial dimension’. Three common ways to add a spatial dimension are described below.

- ‘Area-weighting’ (AW) was first used in the late 1960s and early 1970s; it is simply the multiplication of a response (e.g. crop yield), based on its proportion of a larger area, which is assumed to be homogeneous (Fig. 1).
- The ‘interpolate then calculate’ (IC) approach involves interpolating all driving parameters and variables, and simulating an output for an entire landscape by running the model at many points, with a given spatial resolution over a given spatial extent. This can be a daunting task given the resolution and extent of the study area, the time interval and length of simulation runs, and the number of parameters and variables.
- ‘Calculate then interpolate’ (CI) is a recent approach that is gaining popularity. Stein et al. (1991) introduced CI and found that it was preferable to the IC approach; Bosma et al. (1994) came to the same conclusion in the case of small samples. Bechini et al. (2000), estimating global solar radiation in northern Italy, reported that mean square errors using the CI approach were only about half those calculated using the IC method. Chapter 19 discusses the use of a CI approach to estimate moisture availability within the Murray–Darling Basin (MDB).

The AW approach allows remotely sensed data (discussed in detail below) to be classified to provide a potentially rich source of polygon data. Remotely sensed data are usually classified into discrete land-cover classes; these may be

amalgamated to land-use classes and then integrated with other data layers in GIS. Remote sensing is stored in a raster (grid) data format; this type of format is most suited to spatially continuous data sets (where each grid cell can be thought of as a discrete element), such as those collected by remotely sensed data sources. Other interpolated data sets, such as digital elevation models (DEMs) or climate surfaces (e.g. monthly maximum and minimum air temperatures and rainfall), may also be stored as rasters.

Remote Sensing

‘Remote sensing’ is the term used for the acquisition of digital information describing characteristics of the Earth’s surface. It involves measuring the electromagnetic spectrum (EMS) using satellite, aircraft or ground-based systems. Characteristically, the information is obtained at a distance (or ‘remote’) from the target—hence the name. Sensors on board numerous satellites and aircraft can be used in the assessment of sustainable agriculture. In this section we provide some general background information on remote sensing and describe different techniques involved, drawing heavily on material presented by McVicar and Jupp (1998).

Remote sensing data are obtained as digital recordings of the signal strength from specific portions (channels or bands) of the reflective, thermal or microwave portions of the EMS. Figure 2 shows how a satellite records such data. Some satellites orbit the Earth at approximately 700 km, while others are geostationary, located above the equator at some 36 000 km. Computer analysis of the digital images can highlight features of soils and vegetation. Each pixel (picture element) contributing to the image is a measurement of a particular wavelength of electromagnetic radiation at a particular spatial resolution for a particular location at a particular time (minute, hour, day, month and year).

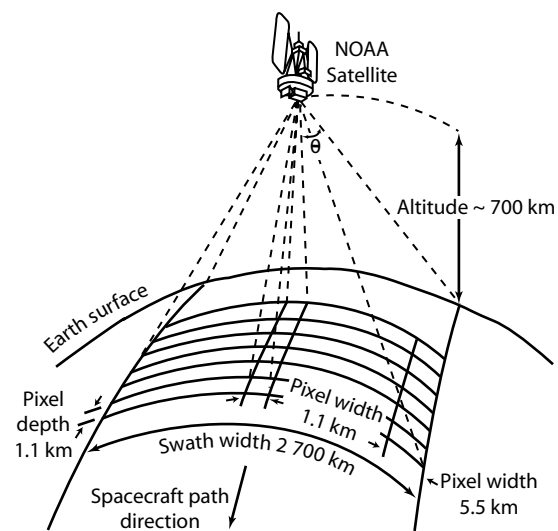


Figure 2. How satellites record data from the Earth's surface (adapted from Harrison and Jupp 1989), specifically NOAA-AVHRR, outlined in Table 1.

Remote sensors can distinguish different types of land cover (e.g. green grass, fine sandy loam and water) by their spectral properties, as shown in Figure 3. This allows the different land covers to be classified (i.e. mapped as separate classes). Remote sensing instruments vary in their ability to resolve the EMS signal. Figure 3 shows the spectral properties of different surfaces as measured by four different sensors. In two of the four cases (Hyperion and MSS) the attribute (spectral) response is continuous; however, because the resolution and extent of the data obtained are very different, the two sensors provide different attribute responses for any particular surface (Table 1). Hyperion, which records 196 calibrated channels, each with a 10 nm spectral resolution, is regarded as a hyperspectral sensor; while MSS is considered a broadband sensor.

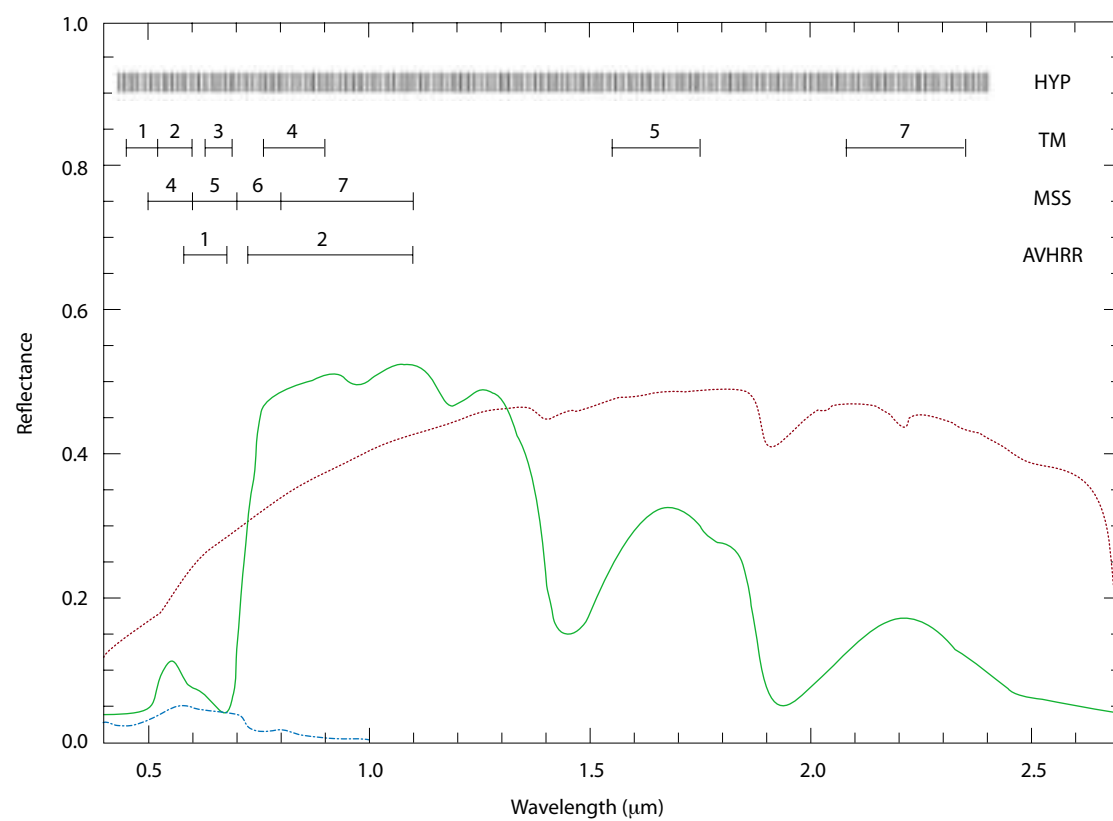


Figure 3. Idealised reflectance plots from 0.4 to 2.7 μm for green grass (solid line), fine sandy loam (dotted line), and water (dash-dot line). The figures show channel resolutions for some typical remote sensing instruments that are further discussed in Table 1. AVHRR = advanced very high resolution radiometer; Hyp = Hyperion; MSS = multispectral scanner; TM = Thematic mapper.

Table 1. General description of some current satellite optical remote sensing based sensors.

Satellite: sensor (quantisation)	Channel number	Spectral resolution	Spatial resolution (in m) at nadir	Sample swath	Repeat cycle	Lifetime
NOAA–AVHRR (10 bit)	1 ^a	580–680 nm	1100	2700 km	Every 12 hours	1978 to present
	2	725–1100 nm				
	3	3.55–3.93 µm				
	4	10.5–11.3 µm				
	5	11.5–12.5 µm				
Landsat:MSS ^b (6 and 7 bit)	4	500–600 nm	80	185 km	Every 16 days ^c	1972 to present
	5	600–700 nm				
	6	700–800 nm				
	7	800–1100 nm				
Landsat:TM ^d (8 bit)	1	450–520 nm	30	185 km	Every 16 days	1983 to present
	2	520–600 nm				
	3	630–690 nm				
	4	769–900 nm				
	5	1.55–1.75 µm				
	7	2.08–2.35 µm				
	6	10.4–12.5 µm	120			
EO-1:Hyperion (12 bit)	242 in total	from 436 nm to 2405 nm	30	7.6 km	Every 16 days	Nov 2000 to Sept 2002

AVHRR = advanced very high resolution radiometer; EO = Earth observing; MSS = multispectral scanner; NOAA = National Oceanographic and Atmospheric Administration; TM = thematic mapper; Note 1000 nm = 1 µm.
^a From 1978 to 1981 only the first four of these five channels were acquired.
^b The Landsat:MSS is a multispectral sensor on board the Landsat satellites. Channels 4–6 are recorded as 7-bit and calibrated to 8-bit; channel 7 is recorded as 6-bit and calibrated to 8-bit.
^c From 1972 to 1983, the repeat cycle for Landsat 1–3 was 18 days.
^d Landsat:TM is the TM sensor on board Landsat 4 and 5. The channel numbers do not ascend in order of increasing wavelength due to the late inclusion of channel 7. The TM sensor was enhanced on Landsat 7, and is hence abbreviated as ETM. There is an additional 15 m panchromatic channel (520 to 900 nm), and the spatial resolution of the thermal channel (10.4–12.5 µm) has reduced from 120 m to 60 m. Landsat 7 was launched on 15 April 1999.

Remote sensing of the Earth’s surface relies on the presence of atmospheric windows—wavelengths of the EMS where a signal generated from properties of the Earth’s surface can pass with little, or no, interaction with the atmosphere. Certain areas of the EMS are not suitable for remote sensing because atmospheric constituents absorb all the electromagnetic radiation in particular wavelengths. For example, in Figure 3, Thematic mapper (TM) Channel 5 is in an atmospheric window that extends from around 1.5 to 1.7 µm. Either side of this window (1.45 and 1.95 µm) there

is a relatively low reflectance for green grass due to a strong absorption of these wavelengths. Figure 4 shows the divisions of the EMS, some of which are discussed in more detail below.

Remote sensing measurements

The following background provides some discussion of the physical basis of remotely sensed measurements and how the flux of photons is converted into a digital image. The terms and concepts may be somewhat daunting to those not actively involved in remote sensing, and it may help

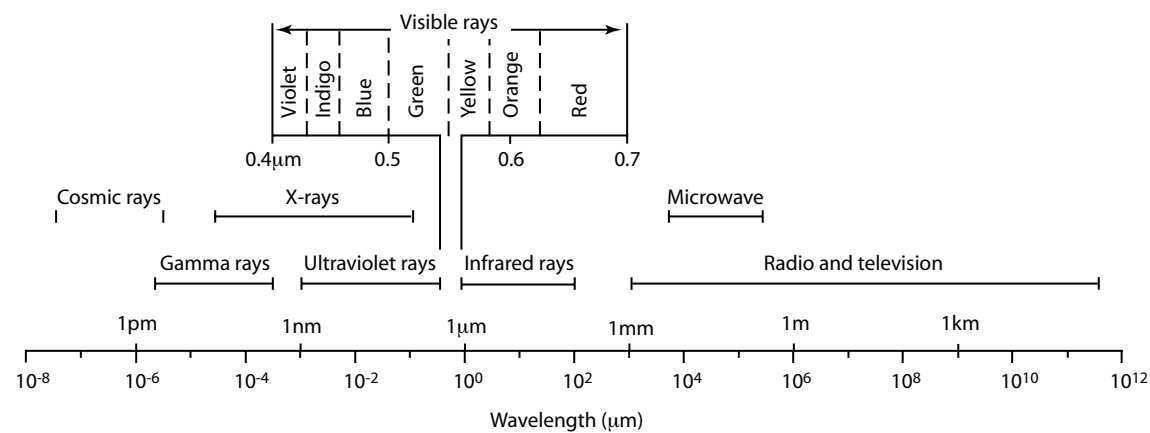


Figure 4. The parts of the electromagnetic spectrum (adapted from Harrison and Jupp 1989).

to think of remote sensing instruments as ‘high-tech’ cameras that record certain characteristics (extent, resolution and density) for each of the three domains (attribute, spatial and temporal).

Satellites and sensors

Table 1 gives characteristics for selected sensors and satellites on board a few of the Earth observing (EO) satellites used for assessing regional agricultural sustainability; these include NOAA (National Oceanographic and Atmospheric Administration), Landsat and EO satellites. The NOAA series of United States satellites carry the advanced very high resolution radiometer (AVHRR) sensor. The NOAA satellites orbit the poles at a height of some 700 km, similar to the height of the Landsat satellites. Data from NOAA are acquired over a large swath width when compared to the Landsat data; this is due to the wide scan angle ($\pm 55^\circ$) of the AVHRR sensor. The local area coverage (LAC) pixel size is 1100 m at the subsatellite point, becoming 5400 m at the edge of the swath. The sensor also records global area coverage (GAC) data, which are a subset of the LAC data and nominally have a 5 km $\times$ 3 km resolution. GAC data are derived from LAC data on board the satellite and are recorded at the National Aeronautics and Space Agency (NASA) Goddard Space Flight Centre. Cracknell (1997) provides an extensive overview of the AVHRR sensor, the NOAA series of satellites and some applications of AVHRR data.

The Landsat series of satellites operate at a height of 700 km; they are polar-orbiting, sun-synchronous and pass a given latitude at the same solar time. Landsat 3 had a thermal channel. The main remote sensing system on Landsat 1–3 was the MSS sensor, while the TM sensor was included on Landsat 4.

EO-1 was launched on 21 November 2000 as part of NASA’s ‘New Millennium’ program. One of the main aims of EO-1 is to demonstrate new technologies. The satellite carries three remote sensing instruments: Hyperion, Advanced Land Imager and Atmospheric Corrector. Hyperion is the first hyperspectral satellite-based sensor available for civilian applications; its spectral extent is from 436 nm to 2406 nm. The exact position of Hyperion’s 7.6 km wide swath is determined by rolling the EO-1 spacecraft and pointing the instrument. Hyperion’s ground resolution is nominally 30 m, similar to TM. To provide the opportunity to cross-validate with the enhanced TM carried by Landsat 7, EO-1 is in orbit one minute after Landsat 7.

Reflective remote sensing

The reflective portion of the EMS ranges nominally from 0.4 to 3.75 μm . Light of shorter wavelength than this is termed ultraviolet (UV). The reflective portion of the EMS can be further subdivided into the visible (0.4–0.7 μm), near-infrared (NIR) (0.7–1.1 μm), and shortwave-infrared (SWIR) (1.1–3.75 μm). Our remote sensing devices (eyes) allow

us to see in the visible portion of the EMS, and to distinguish colours through different properties of reflective surfaces. However, there are differences in the way people see shades of certain colours. For example, some people cannot sense subtle changes in colours — things are black or white, there are no shades of grey — whereas more perceptive people sense different shades of grey. In remote sensing, this is akin to the idea of ‘quantisation’, the term used to refer to the number of possible levels of response. Remote sensing converts an analogue photon flux to digital images, where the number of quantisation levels is a function of the number of bits used to represent the photon flux. The number of quantisation levels equals two to the power of the number of bits. Thus, 7-bit data provide 128 (2^7) levels of quantisation, 8-bit data 256 (2^8), 10-bit data 1024 (2^{10}) and 12-bit data 4096 (2^{12}). The ability of remote sensing measurements to distinguish different properties of the Earth’s surface in the EMS is partly determined by the level of quantisation.

Many remote sensing instruments have channels situated in the red and NIR parts of the spectrum (see Table 1). These two reflective bands are often combined to produce vegetation indexes. The most common linear combinations are the simple ratio (NIR/red) and normalised difference vegetation index (NDVI), which is derived from $(\text{NIR} - \text{red}) / (\text{NIR} + \text{red})$. Several publications (Tian 1989; Kaufman and Tanre 1992; Thenkabail et al. 1994; Leprieur et al. 1996) provide comprehensive listings of vegetation indexes.

Figure 5 shows how a typical green leaf reflects light. Chlorophyll pigments in the leaf absorb red light. Radiation in the NIR portion of the spectrum is scattered by the internal spongy mesophyll leaf structure, leading to higher values in the NIR channels. This interaction between leaves and the light that strikes them is one determinant of the different responses in the red and NIR portions of reflective light shown in Figure 5.

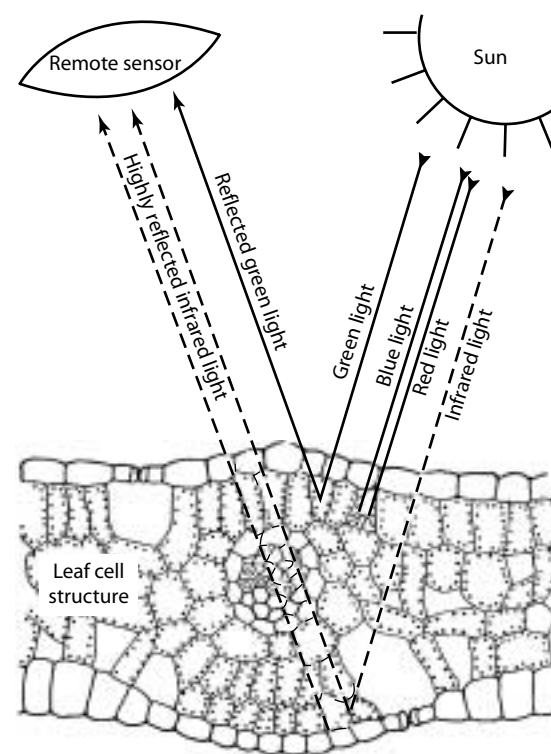


Figure 5. Reflectance of a typical green leaf in cross-section; chloroplasts reflect the green light and absorb red and blue light for photosynthesis. Near infrared light is highly scattered by water in the spongy mesophyll cells (adapted from Harrison and Jupp (1989).

There are positive correlations between NDVI and factors such as plant condition (Sellers 1985); foliage presence (including leaf area index (LAI)) (Curran et al. 1992; Tucker 1979; Nemani and Running 1989; McVicar et al. 1996a; McVicar et al. 1996b; McVicar et al. 1996c); and per cent foliage cover (Lu et al. 2001). Based on the relationship between LAI and NDVI, many previous studies have modelled crop yield by integrating the area under the NDVI curve (denoted $\int \text{NDVI}$) for all or part of the growing season (Rasmussen 1998a; Rasmussen 1998b; McVicar et al. 2000; Honghui et al. 1999). Some researchers have used regression-based models developed from NDVI data acquired at specific times during the growing season (Maselli et al. 1992; Smith et al. 1995).

The amount of green leaf is one determinant of the signal strength in the reflective portion of the EMS. Several other important factors that affect the acquired value include soil colour and sun-target-sensor geometry.

The following discussion draws heavily on Roderick et al. (2000), whose work elegantly illustrated the effect of soil colour and quantisation on overall reflectance, and showed how change can be distinguished using remotely sensed measurements. The authors assumed a Lambertian surface (one that has no angular dependency), with no shade present and two soils, one dark (5% albedo²) and the other bright (30% albedo), with green grass (10% albedo) in the red portion of the EMS. Table 2 shows the simulated landscape’s reflectance as the amount of simulated grass cover increases by 20% intervals from 0 to 100%.

On a dark soil, a 20% increase in green grass results in an overall 1% increase in albedo; on a bright soil it results in a 4% decrease. Hence, the albedo of the elements that make up the scene and their relative proportions are important to the overall albedo. We can invert this reasoning and ask ‘How much change in green grass is needed to detect a change for different instrument quantisation?’ Table 3 shows the results.

For dark soils sensed with a 7-bit instrument, a 15% change in cover is needed to change the recorded digital number by 1. This reduces to 0.5% for a 12-bit system. At the same level of quantisation, a larger relative difference between end-members requires a smaller change in per cent grass cover to detect change. This is because there is a greater difference in the albedo of the end-members when looking at bright soils (20% difference) than when considering the dark soil (5% difference) example.

² Albedo is the fraction of light that is reflected by a body or surface.

Table 2. Overall reflectance (%) when the amount of green grass (10% albedo) increases by intervals of 20% cover over a dark (5% albedo) and bright (30% albedo) soil.

Green grass cover (%)	Overall reflectance (%) when on a dark soil	Overall reflectance (%) when on a bright soil
0	5	30
20	6	26
40	7	22
60	8	18
80	9	14
100	10	10

In reality, the land surface is not a perfect Lambertian reflector (Liang and Strahler 2000) — most surfaces in the optical (reflective and thermal) portions of the EMS are strongly anisotropic³. The geometry of sun, target and sensor, and the size, shape and spacing of elements (e.g. trees over bare ground) controls the amount of shadow contributing to the signal (Hall et al. 1995). This effect, termed the bidirectional reflectance distribution function (BRDF) (Burgess and Pairman 1997; Deering 1989), is characteristic of vegetation structure in reflective remotely sensed images. This means that in addition to the albedo of the scene elements and their relative proportions, the spatial distribution and the pixel size of observation affect the signal measured by remote sensing instruments (Jupp 1989ab; Woodcock and Strahler 1987; Walker et al. 1986; Jupp and Walker 1996). In addition, the match between the operational scale and the resolution partly controls the strength of relationships between surface properties and remote sensing (Friedl 1997). Image information content is minimal when the resolution is approximately equal to the operational scale (Woodcock et al. 1988ab). Other factors affecting

³ Anisotropic means having different physical properties in different directions.

Table 3. The change needed in amount of green grass to detect a change for different instrument quantisation levels.

Quantisation	Levels	Precision (1/level)	Change of green grass cover on dark soil (%)	Change of green grass cover on bright soil (%)
7-bit	128	0.007813	15.626	3.907
8-bit	256	0.003906	7.812	1.953
10-bit	1024	0.000977	1.954	0.489
12-bit	4096	0.000244	0.488	0.122

the reflective portion of the EMS include changes in the observed signal due to changes in the atmospheric component of the signal, including atmospheric precipitable water (Choudhury and DiGirolamo 1995; Hobbs 1997), and changes in the response of the sensor over time (Mitchell 1999).

Thermal remote sensing

The thermal portion of the EMS ranges nominally from 3.75 to 12.5 μm . The observed surface temperature is a function of the radiant energy emitted by the surface which is remotely sensed, be it land, ocean or cloud top. Models have been developed to allow surface temperature to be extracted from thermal remote sensing data. Prata et al. (1995) review the algorithms and issues, including land emissivity estimation, involved in the calculation of land-surface temperature, denoted T_s .

Thermal remote sensing is an observation of the status of the surface energy balance (SEB) at a specific time of day. The SEB is driven by the net radiation at the surface. During the daytime, the net radiation is usually dominated by incoming shortwave radiation from the sun, the amount reflected depending on the albedo of the surface. There are also longwave components that well up and down. At the ground surface, the net all-wave radiation is balanced between the sensible, latent and ground heat fluxes. The ground heat flux averages out over long periods of time; thus, the SEB represents the balance between the sensible and latent heat fluxes. During the day, T_s is partially dependent on the relative magnitude of the sensible and latent heat fluxes (Quattrochi and Luvall 1999;

McVicar and Bierwirth 2001). This is exploited in the mapping of regional moisture availability for the MDB, as reported in Chapter 19.

Remotely sensed thermal data are also recorded at night. At this time, the SEB is dominated by the release from the ground of heat that was absorbed during daylight hours, which is governed by how much heat was absorbed during the day and the rate at which it is released after sunset. The environment's capacity to store heat depends on the amount of water it is storing.

Microwave remote sensing

The microwave portion of the EMS ranges nominally from 0.75 to 100 cm. Radio signals have wavelengths that are included in these bands. These systems can either be active (the sensor sends its own signal) or passive (the background signal from the Earth's surface is observed). This range of the EMS is further divided into five smaller sections that are used for remote sensing (Table 4).

Both passive and active microwave observations have been used to determine the near-surface soil moisture for a number of experimental field sites. Radar (radio detection and ranging), is an active system based upon sending a pulse of microwave energy and then recording the strength, and sometimes polarisation, of the return pulses. The way the signal is returned provides information to determine characteristics of the landscape. Radar has been used in the determination of near-surface soil moisture. Table 5 gives technical specifications of the current satellite radar systems — the Japanese

Earth Resources Satellite (JERS), the Earth Resource Satellite (ERS) and the RADARSAT. JERS observes the Earth’s surface using eight spectral bands in the reflective portion of the EMS. ERS was launched and is operated by the European Space Agency. RADARSAT is a synthetic aperture RADAR (SAR) on board a Canadian satellite.

A ‘Data Construct’ Perspective

Within TGIS remotely sensed data, GIS data, point-based measurements and model outputs (either point and spatial) can all be integrated, as they all have spatial and temporal characteristics associated with the data attribute. Economic and social data can also be integrated as they too have temporal and (usually) spatial components. Some data used to assess regional agricultural sustainability are ‘aspatial’ in that they do not have a precise spatial reference (e.g. wool prices or interest rates), but the temporal nature of these variables can be incorporated into larger information systems.

The integration of several data types, usually with varying spatial–temporal characteristics, allows for more objective determination of agricultural sustainability. In the chapters in this section, the data used depend in part on the specific issue that is

being modelled under the broad topic of ‘regional agricultural sustainability’.

Temporal aspects of TGIS

Time plays a minimal part in some aspects of TGIS modelling. For example, in most environments there is little or no acknowledgment of the temporal attribute of DEMs—because it is generally temporally invariant, the time when the data was captured is of little relevance. However, in other aspects of TGIS modelling, time is an important component (e.g. in the case of active erosion, soil characteristics changing in response to changes in vegetation, soils becoming acidified, or crop water use and irrigation scheduling through the growing season).

Temporal component of DEM

Elevation varies with time in some circumstances; for example, in small, deep actively eroding gullies on the Loess Plateau (as described in Chapter 10). The DEM for these small parts of the plateau may need to be updated perhaps every two years, or possibly after heavy episodic rainfall events that instigate erosion. In contrast, the DEM for the entire plateau may be updated only when there are major technological and methodical advancements

Table 4. The parts of the microwave section of the electromagnetic spectrum used for remote sensing.

	Band				
	P	L	S	C	X
Wavelength (cm)	100–30	30–15	15–7.5	7.5–3.75	3.75–2.4

Table 5. Technical specifications of current satellite- based radar data.

Sensor	Wavelength	Pixel size (m ²)	Incidence angle	Polarisation	Swath width (km)	Recorded since	Current repeat cycle
JERS	L-band	18	35°	HH	75	June 1993	44 days
ERS	C-band	12.5	23°	VV	102.5	Sept 1991	35 days
RADARSAT	C-band	100	20–49°	HH	500 ^a	Nov 1995	3 days

ERS = Earth Resource Satellite; JERS = Japanese Earth Resources Satellite; RADAR = radio detection and ranging
^a The ScanSAR wide mode is reported here, as it has the largest swath width and therefore has the most potential for regional agricultural assessment through electrical conductivity. The large incidence angle means that the repeat cycle is only a few days. However, the entire 30° range may not be suitable for the accurate estimation of soil moisture.

in producing such measurements, perhaps every 20 years. The date when data are captured can be used to model rates of erosion (in units of cubic metres of soil lost per year) and to monitor the movement of gully fronts. On the Loess Plateau, authorities can use such data to ensure the long-term viability, based on geomorphic stability, of roads and rail networks. Massive expenditure is required to construct new highways and railways to support the increased transport of goods and services in China's rapidly developing economy. Therefore, it is important to ensure that transport pathways are not placed in positions where they will need constant maintenance (or even rebuilding) because of slump erosion in gullies after heavy rains.

Temporal components of soils

Temporal data can also be important for soils. Certain physical properties, such as water-holding capacity, may be considered temporally inert, and therefore may need to be mapped only once. However, TGIS scientists need to understand the processes that control the water-holding capacity of soils in order to take these processes into account. For example, there are plans to control erosion on the Loess Plateau and rising watertables in southeastern Australia by replanting vast tracks of land with deep-rooted perennial vegetation. This change in land use will have a range of effects (spatial and temporal) on the soil:

- The initial vegetation type replanted will depend on environmental considerations such as rainfall amount and seasonality, and may be a mix of trees, shrubs or grasses. The mix is likely to change with time, as soil conditions improve.
- Changing the land use from agricultural systems based on cropping or grazing to deeper-rooted perennial vegetation will usually, over time, result in increased levels of organic matter and nutrients (N, P and K) in the top layers of the soil.
- The changes to the top layers of soil are likely to change infiltration rates and soil water-holding

capacity, especially for soils relatively close to the surface.

- If areas are replanted with shrubs, changes to the soil properties are unlikely to be constant because the plants will induce spatial variation: soil that is close to the shrub will be influenced more quickly and intensely than soil further away as a result of organic matter produced by the plant. This potential influence at the microscale will reduce with time, as the shrubs grow bigger and plant material is laterally distributed by water and wind flowing over the soil surface.

The concept of soils being in motion due to combinations of wind and water systems, operating at different space and time scales, with varying residence times between motions, can make it difficult to understand the origins of present-day soil properties (Gatehouse et al. 2001). TGIS can help to provide conceptual models of landscape evolution that can be used to assess the impact of possible management actions on a range of landscape functions.

A further example of the importance of time to soil spatial data is the identification and monitoring of soil degradation due to waterlogging, which in southeastern Australia leads to the development of acid sulfate soils. Knowing when data was captured allows scientists to assess the rate of change of acid sulfate scalds. More importantly, such monitoring will allow conceptual models of the processes governing the development of acid sulfate soils to be further refined.

Temporal components of water balance

Assessment of spatial-temporal patterns and trends in regional ecohydrology often involves the use of time-series data, such as in situ regional yield estimates, water use figures and remotely sensed data. Because it provides repeated measurements at a particular spatial resolution and electromagnetic

wavelength, remote sensing makes it possible to monitor dynamic environmental conditions. This is illustrated in Chapter 19 for assessing moisture availability in the MDB and in Chapters 18 and 20 for vegetation cover.

Data are usually integrated from several different sources, all with varying TGIS data constructs. In order to spatially monitor (or temporally map) an issue concerning regional agricultural sustainability, it is helpful to think of the data construct as a cube, in which two of the three dimensions are spatial (latitude and longitude) and one is temporal. To provide a culinary analogy, the data construct for monitoring moisture availability in a region (as in Chapter 19) could be thought of as pancakes of remotely sensed data intersected at right angles by skewers of point-based meteorological data. In some situations, more complex spatial-temporal data models are needed (e.g. event-driven and four-dimensional data models) (Peuquet 2001; Chen and Jiang 2000; Zhang and Hunter 2000). For example, in modelling the movement of pollutants in groundwater and the atmosphere, the extra dimension of elevation (or depth) must be included in the TGIS data construct. The most appropriate spatial-temporal data model to use will depend on the application, and there are subtle interactions between database design and utility that should be taken into account (Roddick et al. 2001; Abraham and Roddick 1999).

Linking remotely sensed data with meteorological data (as in Chapter 19) illustrates the concept of the 'data construct', as the two types of data have very different spatial, temporal and attribute characteristics. For example, cloud-free AVHRR data for the land surface may be available only weekly; whereas some meteorological variables are recorded as daily extremes (maximum and minimum air temperatures), daily averages (vapour pressure) or daily integrals (precipitation and solar radiation).

Spatial aspects of TGIS

Remotely sensed data are spatially dense because the image is a census at a particular spatial resolution and electromagnetic wavelength rather than a point sample. There is a contrast between spatial density of remote sensing and isolated meteorological stations or field sites. For example, meteorological stations may be 200 km apart but remotely sensed data might be measured at a spatial resolution of 1 km for each of those 200 km.

While GIS data may cover entire regions, they are often produced from the spatial interpolation (or extrapolation) of point samples; this is frequently the case for meteorological and soil data. In these instances, the spatial extent of the GIS data may appear to be complete, but in fact the spatial density of the input data is low. For example, a thematic map of soil classes may be developed from a series of observation points located every 5 km² for a 1000 km² area. The data from these 200 point samples are interpolated to characterise the soils for the larger area. Whether or not this is valid will depend on the spatial autocorrelation of the soil property being mapped. If the soil is uniform, only one observation may be needed to characterise the entire area, whereas if the soils vary considerably, the 200 observations may provide a poor representation. Soil maps are currently generated using stratified soil sampling based on continuous data sets. Where such data are radiometric or DEMs, they are usually obtained from interpolation of point or linear data, so it is important to track the density of the input data. Also, some error analysis of the interpolation process used to create the surface should be included in the associated metadata system.

To fully understand the data construct of all data sets being integrated in a TGIS for a specific application, it is useful to consider the characteristics of each data set in terms of a three-by-three matrix. The attribute (spectral), spatial and temporal characteristics can be defined in terms of the extent, resolution and density of the different

data sets (Table 6). In order to use TGIS effectively to assess and monitor the agricultural sustainability of a region, all the elements that make up this matrix need to be taken into account.

Emerging Issues

Accuracy and uncertainty assessments

For geospatial simulation modelling, including AW, IC and CI approaches, sensitivity analysis is needed to determine the uncertainty of the final output (Mowrer and Congalton 2000). Sources of uncertainty include both input data and the model itself (Heuvelink and Pebesma 1999). Recently, Gahegan and Ehlers (2000) provided a framework to model uncertainty when linking remotely sensed and GIS data, but they assumed that remotely sensed data would be used only in a thematic (or discontinuous) way. In analysing uncertainty and error propagation in GIS, positional accuracy is often forgotten; this may become an issue for institutionally available GIS data in Australia (Van Niel and McVicar 2001; Van Niel and McVicar 2002). There are many methods for assessing the accuracy of thematic maps derived from the classification of remote sensing data (Fenstermaker

1994); these should be used to estimate overall accuracy, user and producer accuracy for the map, and how each class can best be used in TGIS analysis.

Metadata

Awareness of the importance of metadata (data about data) in TGIS is increasing. As monitoring frameworks extend, any changes in the measurement system or processing must be recorded, to allow those undertaking retrospective analysis of such data sets to understand the genesis of the data. This is also true for data collected over large areas, possibly by many individuals. Operational agencies that collect and disseminate data routinely (e.g. national meteorological and national mapping agencies) allocate many resources to ensuring that metadata are collected, updated and readily available. A metadata system to comprehensively study long-term, large-area environmental issues is becoming a central part of any TGIS. In short, the metadata are at least as important as the data. In TGIS, if there are no metadata, there may as well be no data. A crucial part of a comprehensive metadata system is keeping track of where data are stored and of their current backup status. Assessing the quality of data is also

Table 6. Matrix showing characteristics of remotely sensed data sets in terms of their domain.

Domain	Characteristic		
	Extent	Resolution	Density
Attribute (spectral)	Portion of the EMS being sampled	Bandwidth	Number of bands in a particular portion of the EMS (e.g. hyperspectral sensors have higher spectral density than broadband instruments)
Spatial	Area covered by the image	Smallest pixel or picture element acquired	Complete ^a
Temporal	Recording period over which the data are available ^b	Period of data acquisition ^c	Repeat characteristics of the satellite (and, for some applications, the availability of cloud-free data)

^a This contrasts with the potentially lower spatial density of point observations
^b For some remotely sensed systems (e.g. Landsat MSS) data have been recorded for 25 years
^c For remotely sensed systems this is a matter of seconds, which contrasts with point data such as the daily rainfall totals recorded at meteorological stations

important in developing TGIS. This is easier in the case of data collected directly by the TGIS developer than it is for data that are collected by others or obtained remotely and then integrated into the system. The issues of metadata and the data life cycle (Goodchild 2000) need to be comprehensively addressed, especially for institutionally maintained and distributed data.

TGIS researchers working alone or in small groups may have no or little understanding of issues relating to metadata. However, if they wish to become part of interconnected TGIS studies, they must give due consideration and resources to this issue. During the course of this ACIAR project (July 1997 to June 2001), there was a rapid increase in the number of databases available from the internet for China, Australia and other countries. Evidently, global 'interconnectedness' is only beginning.

Conclusions

The spatial-temporal data construct of regional databases can be used to monitor and assess the sustainability of agricultural production within the broader environmental context. Data are integrated from a variety of sources, and information extracted by empirical relationships, 'data-mining' and spatial-temporal process models.

For all geographic regions, spatial and temporal trend analysis of regional agricultural sustainability (and other variables) must be based on data. Currently, there is a mismatch between the data that are available and what is required to infer causal relationships between measures of regional agricultural sustainability and agricultural practices for large areas over long periods. The collection of data and the quality and availability of databases are major issues facing organisations involved in research and policy of regional agriculture. These issues need to be addressed by those managing agricultural, water and land resources.

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References

- Abraham, T. and Roddick, J.F. 1999. Survey of spatio-temporal databases. *Geoinformatica*, 3, 61–99.
- Bechini, L., Ducco, G., Donatelli, M. and Stein, A. 2000. Modeling, interpolation and stochastic simulation in space and time of global solar radiation. *Agriculture, Ecosystems and Environment*, 81, 29–42.
- Bernard, L., Schmidt, B., Streit, U. and Uhlenkücken, C. 1998. Managing, modeling, and visualizing high-dimensional spatio-temporal data in an integrated system. *Geoinformatica*, 2, 59–77.
- Bian, L. 1997. Multiscale nature of spatial data in scaling of environmental models. In: Quattrochi, D.A. and Goodchild, M.F., eds, *Scale in Remote Sensing and GIS*. Boca Raton, CRC Press Inc., 13–26.
- Bloschl, G. and Sivapalan, M. 1995. Scale issues in hydrological modelling: a review. In: Kalma, J.D. and Sivapalan, M., eds, *Scale Issues in Hydrological Modelling*. Chistester, John Wiley & Sons, 9–48.
- Bosma, W.J.P., Marinussen, M.P.J.C. and van der Zee, S.E.A.T.M. 1994. Simulation and areal interpolation of reactive solute transport. *Geoderma*, 62, 217–231.
- Burgess, W. and Pairman, D. 1997. Bidirectional reflectance effects in NOAA AVHRR data. *International Journal of Remote Sensing*, 18, 2815–2825.
- Butler, D.R. and Walsh, S.J. 1998. The application of remote sensing and geographic information systems in the study of geomorphology: An introduction. *Geomorphology*, 21, 179–181.
- Cao, C. and Lam, N. 1997. Understanding the scale and resolution effects in remote sensing and GIS. In: Quattrochi, D.A. and Goodchild, M.F., eds, *Scale in Remote Sensing and GIS*. Boca Raton, CRC Press Inc., 57–72.
- Chen, J. and Jiang, J. 2000. An event-based approach to spatio-temporal data modeling in land subdivision systems. *Geoinformatica*, 4, 387–402.
- Choudhury, B.J. and DiGirolamo, N.E. 1995. Quantifying the effect of emissivity on the relation between AVHRR split window temperature difference and atmospheric precipitable water over land surface. *Remote Sensing of Environment*, 54, 313–323.
- Cracknell, A.P. 1997. *The Advanced Very High Resolution Radiometer (AVHRR)*. London, Taylor & Francis.
- Curran, P.J., Dungan, J.L. and Gholz, H.L. 1992. Seasonal LAI in slash pine estimated with Landsat TM. *Remote Sensing of Environment*, 39, 3–13.
- Deering, D.W. 1989. Field measurements of bidirectional reflectance. In: Asrar, G., ed., *Theory and Application of Optical Remote Sensing*. New York, John Wiley and Sons, 14–65.

- Fenstermaker, L.K. ed. 1994. Remote Sensing Thematic Accuracy: a compendium. American Society for Photogrammetry and Remote Sensing.
- Friedl, M.A. 1997. Examining the effects of sensor resolution and sub-pixel heterogeneity in spectral vegetation indices: implications for biophysical modelling. In: Quattrochi, D.A. and Goodchild, M.F., eds, Scale in Remote Sensing and GIS. Boca Raton, CRC Press Inc., 113–139.
- Gahegan, M. and Ehlers, M. 2000. A framework for the modelling of uncertainty between remote sensing and geographic information systems. *Journal of Photogrammetry and Remote Sensing*, 55, 176–188.
- Gatehouse, R.D., Williams, I.S. and Pillans, B.J. 2001. Finger-printing windblown dust in south-eastern Australian soils by uranium-lead dating of detrital zircon. *Australian Journal of Soil Research*, 39, 7–12.
- Goodchild, M.F. 2000. Communicating the results of accuracy assessment: metadata, digital libraries and assessing fitness of use. In: Mowrer, H.T. and Congalton, R.G., eds, Quantifying Spatial Uncertainty in Natural Resources: theory and applications for GIS and remote sensing. Chelsea, Michigan, Sleeping Bear Press, 3–15.
- Gurnell, A. and Montgomery, D. 1998. Preface: hydrological applications of GIS. *Hydrological Processes*, 12, 821–822.
- Hall, F.G., Shimabukuro, Y.E. and Huemmrich, K.F. 1995. Remote sensing of forest biophysical structure using reflectance decomposition and geometric reflectance models. *Ecological Applications*, 5, 993–1013.
- Harrison, B.A. and Jupp, D.L.B. 1989. Introduction to Remotely Sensed Data, CSIRO Publications.
- Heuvelink, G.B.M. and Huisman, J.A. 2000. Choosing Between Abrupt and Gradual Spatial Variation ? In: Mowrer, H.T. and Congalton, R.G., eds, Quantifying Spatial Uncertainty in Natural Resources: Theory and Applications for GIS and Remote Sensing. Chelsea, Michigan, Sleeping Bear Press, 111–117.
- Heuvelink, G.B.M. and Pebesma, E.J. 1999. Spatial aggregation and soil process modelling. *Geoderma*, 89, 47–65.
- Hobbs, T.J. 1997. Atmospheric correction of NOAA-11 NDVI data in the arid rangelands of Central Australia. *International Journal of Remote Sensing*, 18, 1051–1058.
- Honghui, L., Xiaohuan, Y. and Naibin, W. 1999. Remote sensing based estimation system for winter wheat yield in North China Plain. *Chinese Geographical Journal*, 9, 40–48.
- Jupp, D.L.B., Strahler, A.H. and Woodcock, C.E. 1989a. Autocorrelation and regularization in digital images I. Basic theory. *IEEE Transactions on Geoscience and Remote Sensing*, 26, 463–473.
- Jupp, D.L.B., Strahler, A.H. and Woodcock, C.E. 1989b. Autocorrelation and regularization in digital images II. Simple image models. *IEEE Transactions on Geoscience and Remote Sensing*, 27, 247–258.
- Jupp, D.L.B. and Walker, J. 1996. Detecting structural and growth changes in woodlands and forests: The challenge for remote sensing and the role of geo-optical modelling. In: Gholz, H.L., Nakane, K. and Shimoda, H., eds, The Use of Remote Sensing in the Modeling of Forest Productivity. Dordrecht, The Netherlands, Kluwer Academic Publications, 75–108.
- Kaufman, Y.J. and Tanre, D. 1992. Atmospherically Resistant Vegetation Index (ARVI) for EOS-MODIS. *IEEE Transactions on Geoscience and Remote Sensing*, 30, 261–270.
- Kustas, W.P. and Norman, J.M. 1996. Use of remote sensing for evapotranspiration monitoring over land. *Hydrological Sciences Journal des Sciences Hydrologiques*, 41, 495–516.
- Lam, N. and Quattrochi, D.A. 1992. On the issues of scale, resolution, and fractal analysis in the mapping sciences. *Professional Geographer*, 44, 88–98.
- Langran, G. 1992. Time in Geographic Information Systems. London, Taylor and Francis.
- Lehmann, A. and Lachavanne, J.B. 1997. Geographic information systems and remote sensing in aquatic botany. *Aquatic Botany*, 58, 195–207.
- Leprieux, C., Kerr, Y.H. and Pichon, J.M. 1996. Critical assessment of vegetation indices from AVHRR in a semi-arid environment. *International Journal of Remote Sensing*, 17, 2549–2563.
- Liang, S. and Strahler, A.H. eds. 2000. Land Surface Bidirectional Reflectance Distribution Function (BRDF); Recent Advances and Future Prospects, Harwood Academic Publishers.
- Lu, H., Raupach, M.R. and McVicar, T.R. 2001. Decomposition of Vegetation Cover into Woody and Herbaceous Components Using AVHRR NDVI Time Series. Canberra, Australia, CSIRO Land and Water, pp. 44.
- Maracchi, G., Péronaud, V. and Kleschenko, A.D. 2000. Applications of geographical information systems and remote sensing in agrometeorology. *Agricultural and Forest Meteorology*, 103, 119–136.
- Maselli, F., Conese, C., Petkov, L. and Gilabert, M. 1992. Use of NOAA-AVHRR NDVI data for environmental monitoring and crop forecasting in the Sahel. Preliminary Results. *International Journal of Remote Sensing*, 13, 2743–2749.
- McVicar, T.R. and Bierwirth, P.N. 2001. Rapidly Assessing the 1997 Drought in Papua New Guinea using Composite AVHRR Imagery. *International Journal of Remote Sensing*, 22, 2109–2128.
- McVicar, T.R. and Jupp, D.L.B. 1998. The current and potential operational uses of remote sensing to aid decisions on drought exceptional circumstances in Australia: a review. *Agricultural Systems*, 57, 399–468.
- McVicar, T.R., Jupp, D.L.B., Reece, P.H. and Williams, N.A. 1996a. Relating LANDSAT TM vegetation indices to in situ leaf area index measurements. Canberra, ACT, CSIRO, Division of Water Resources, 80.
- McVicar, T.R., Jupp, D.L.B. and Williams, N.A. 1996b. Relating AVHRR vegetation indices to LANDSAT TM leaf area index estimates. Canberra, ACT, CSIRO, Division of Water Resources, 33.
- McVicar, T.R., Walker, J., Jupp, D.L.B., Pierce, L.L., Byrne, G.T. and Dallwitz, R. 1996c. Relating AVHRR vegetation indices to in situ leaf area index. Canberra, ACT, CSIRO, Division of Water Resources, 54.
- McVicar, T.R., Zhang, G., Bradford, A.S., Wang, H., Dawes, W.R., Zhang, L. and Lingtao, L. 2000. Developing a spatial information system to monitor regional agricultural water use efficiency for Hebei Province on the North China Plain. Canberra, Australia, CSIRO Land and Water, 55.

- Mesev, V. 1997. Remote sensing of urban systems: hierarchical integration with GIS. *Computers, Environment and Urban Systems*, 21, 175–187.
- Mitasova, H., Mitas, L., Brown, W.M., Gerdes, D.P., Kosinovsky, I. and Baker, T. 1995. Modelling spatially and temporally distributed phenomena: new methods and tools for GRASS GIS. *International Journal of Geographic Information Science*, 9, 433–446.
- Mitchell, R.M. 1999. Calibration status of the NOAA AVHRR solar reflectance channels: CalWatch Revision 1. CSIRO Atmospheric Research Technical Paper No. 42, Melbourne, 20.
- Mowrer, H.T. and Congalton, R.G. 2000. Introduction: the past, present, and future of spatial uncertainty analysis. In: Mowrer, H.T. and Congalton, R.G., eds, *Quantifying Spatial Uncertainty in Natural Resources: Theory and Applications for GIS and Remote Sensing*. Chelsea, Michigan, Sleeping Bear Press, xv–xxiv.
- Nemani, R.R. and Running, S.W. 1989. Testing a theoretical climate-soil-leaf area hydrologic equilibrium of forests using satellite data and ecosystem simulation. *Agricultural and Forest Meteorology*, 44, 245–260.
- Peuquet, D.J. 1994. It's about time: a conceptual framework for the representation of spatial-temporal dynamics in geographic information systems. *Annals of the Association of American Geographers*, 84, 441–461.
- Peuquet, D.J. 1995. An event-based spatial-temporal data model (ESTDM) for temporal analysis of geographical data. *International Journal of Geographic Information Science*, 9, 7–24.
- Peuquet, D.J. 2001. Making space for time: issues in space-time data representation. *Geoinformatica*, 5, 11–32.
- Prata, A.J., Caselles, V., Coll, C., Ottle, C. and Sobrino, J. 1995. Thermal remote sensing of land surface temperature from satellites: Current status and future prospects. *Remote Sensing Reviews*, 12, 175–224.
- Quattrochi, D.A. 1993. The need for a lexicon of scale terms in integrating remote sensing data with geographic information systems. *Journal of Geography*, 92, 206–212.
- Quattrochi, D.A. and Luval, J.C. 1999. Thermal infrared remote sensing for analysis of landscape ecological processes: methods and applications. *Landscape Ecology*, 14, 577–598.
- Rango, A. and Shalaby, A.I. 1998. Operational applications of remote sensing in hydrology: success, prospects and problems. *Hydrological Sciences Journal des Sciences Hydrologiques*, 43, 947–968.
- Rasmussen, M.S. 1998a. Developing simple, operational, consistent NDVI-vegetation models by applying environmental and climatic information: Part I: Assessment of net primary productivity. *International Journal of Remote Sensing*, 19, 97–117.
- Rasmussen, M.S. 1998b. Developing simple, operational, consistent NDVI-vegetation models by applying environmental and climatic information: Part II: Crop yield assessment. *International Journal of Remote Sensing*, 19, 119–139.
- Roddick, J.F., Grandi, F., Mandreoli, F. and Rita Scalas, M. 2001. Beyond schema versioning: a flexible model for spatio-temporal schema selection. *Geoinformatica*, 5, 33–50.
- Roderick, M.L., Chewing, V. and Smith, R.C.G. 2000. Remote sensing in vegetation and animal studies. In: 't Mennetje, L. and Jones, R.M., eds, *Field and Laboratory Methods for Grassland and Animal Production Research*. Wallingford UK, CABI, 205–225.
- Santos, A.M.P. 2000. Fisheries oceanography using satellite and airborne remote sensing methods: a review. *Fisheries Research*, 49, 1–20.
- Sellers, P.J. 1985. Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing*, 6, 1335–1372.
- Smith, R.C.G., Adams, J., Stephens, D.J. and Hick, P.T. 1995. Forecasting wheat yield in a Mediterranean-type environment from the NOAA Satellite. *Australian Journal of Agricultural Research*, 46, 113–125.
- Sommer, S., Hill, J. and Mégier, J. 1998. The potential of remote sensing for monitoring rural land use changes and their effects on soil conditions. *Agriculture, Ecosystems and Environment*, 67, 197–209.
- Stein, A., Staritsky, I.G., Bouma, J., Van Eijsbergen, A.C. and Bgegt, A.K. 1991. Simulation of moisture deficits and areal interpolation by universal cokriging. *Water Resources Research*, 27, 1963–1973.
- Thenkabail, P.S., Ward, A.B., Lyon, J.G. and Merry, C.J. 1994. Thematic mapper vegetation indices for determining soybean and corn growth parameters. *Photogrammetric Engineering and Remote Sensing*, 60, 437–442.
- Tian, G. 1989. *Spectral Signatures and Vegetation Indices of Crops*. Canberra, ACT, CSIRO Division of Water Resources.
- Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, 8, 127–150.
- Van Niel, T.G. and McVicar, T.R. 2001. Assessing positional accuracy and its effects on rice crop area measurement: an application at Coleambally Irrigation Area. *Australian Journal of Experimental Agriculture*, 41, 557–566.
- Van Niel, T.G. and McVicar, T.R. 2002. Experimental evaluation of positional accuracy estimates of a linear network using point- and line-based testing methods. *International Journal of Geographic Information Sciences*, (Accepted).
- Walker, J., Jupp, D.L.B., Penridge, L.K. and Tian, G. 1986. Interpretation of vegetation structure in Landsat MSS imagery: a case study in disturbed semi-arid eucalypt woodlands. Part 1. field data analysis. *Journal of Environmental Management*, 23, 19–33.
- Woodcock, C.E. and Strahler, A.H. 1987. The factor of scale in remote sensing. *Remote Sensing of Environment*, 21, 311–332.
- Woodcock, C.E., Strahler, A.H. and Jupp, D.L.B. 1988a. The use of variograms in remote sensing: I scene models and simulated images. *Remote Sensing of Environment*, 25, 323–348.
- Woodcock, C.E., Strahler, A.H. and Jupp, D.L.B. 1988b. The use of variograms in remote sensing: II real digital images. *Remote Sensing of Environment*, 25, 349–379.
- Zhang, W. and Hunter, G.J. 2000. Temporal interpolation of spatially dynamic objects. *Geoinformatica*, 4, 403–418.

17

The Duration of Soil Saturation: Point Measurements Versus a Catchment-Scale Method

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Abstract

Almost two-thirds of the farms in southern Australia have a texture-contrast soil profile with sandy or loamy A and E horizons overlying clay B horizons. A common problem with some of these soils is the development of a perched watertable in winter, which causes severe reduction in crop yield and exacerbates land degradation. The aim of this study was to measure the extent of the variability in the duration of soil saturation in texture-contrast soils on slopes in a catchment in the Mount Lofty Ranges, South Australia. Furthermore, a method based on a topographic index was used to predict soil saturation at catchment scale, which was then compared to the conventional point-scale measurements.

In the relatively dry years of the study, water duration on the upper slopes was surprisingly higher than on the lower slopes but was rarely expressed at the soil surface. Furthermore, the cause of soil saturation on the mid- and upper slopes was different from that on the lower slopes. However, it was predicted that in wet years water would last longer on the lower slopes due to saturation by groundwaters. As the catchment-scale method was based on a topographic index, it should be useful for predicting the duration of saturation in wet years but not in dry years.

The information obtained on the variability and causes of waterlogging will be of benefit to farmers. It showed that the failure of some current management options to adequately control perched watertables on slopes is partly due to the lack of understanding of their causes and to inadequate prediction of their variability in catchments.

南澳几乎三分之二的农地土壤剖面质地不均，粘土层 B 之上有砂土或壤土层 A 和 E 覆盖。这类土壤的残留水位冬天通常较高，导致作物大幅减产，加剧土地退化。本研究的目的是测量劳伏特山区一个坡地上土壤水分饱和状态持续时间的变动范围，采用地形指数法，预测整个流域范围内的饱和状况，然后将其与传统的点测结果相对比。

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在相对干旱的年份，坡地上部土壤饱和期竟然较下部的长，但在土壤表面很少表现出来。而且，坡地中上部和下部水分饱和的原因不同。不过在多雨年份，正如预期的那样，因地下水原因，坡地下部水分饱和最久。因流域尺度的方法基于地形指数，所以可对多雨年份的水分饱和期进行预测，但不适合干旱年份。

研究收集到的涝渍变动及成因材料对农户有用。这些材料也表明，现行的某些治理措施无法有效控制残留地下水位，部分原因就在于对其成因缺乏了解，对其变化未能预报。

A COMMON morphological feature of texture-contrast (Chittleborough 1992) or duplex (Northcote 1979) soils of the agricultural lands of southern Australia (Fig. 1) is the strong contrast between the coarse textured A and E horizons and the fine textured B horizon. However, chemical, mineralogical and physical properties of the texture-contrast soils can vary (Tennant et al. 1992; McFarlane and Cox 1992). Texture-contrast soils are also common in other parts of the world (Chittleborough 1992). The B horizons of texture-contrast soils in catchments in Western Australia have been shown by Cox (1988) to have saturated hydraulic conductivities (K_s) as low as 0.002 m/day, whereas the A horizon is at least 10 times this value.

A common problem reported with some of these soils, due to a lack of vertical flow capacity in the B horizon, is the development of a perched watertable in winter (Cox and McFarlane 1995). On sloping land this results in significant throughflow to lower slopes, causing waterlogging (saturation of the root zone: see Fig. 2), reduction in crop yields and increased land degradation.

By comparison, the texture-contrast soils whose subsoils have a high K_s (up to 1.2 m/day in catchments in Western Australia; Cox 1988) have been termed 'leaky' (Cox and Fleming 1997); in these situations, throughflow in the A horizon is a

minor component of the catchment water budget (Fleming and Cox 1998), with B horizon throughflow dominating (Stevens et al. 1999).

The aim of this study was to measure the causes and extent of waterlogging in texture-contrast soils on slopes in a catchment in the Mount Lofty Ranges, South Australia. A method based on a topographic index was used to predict waterlogging at the catchment scale, which was then compared to the conventional point-scale measurements. This information was necessary for advising farmers on better strategies to control waterlogging.



Figure 1. Location of texture-contrast soils in Australia (Chittleborough 1992).



Figure 2. Waterlogging of texture-contrast soils (Keynes catchment, Mount Lofty Ranges, 1993).

Materials and Methods

Site description

The study was carried out in the Keynes catchment near Keyneton in the Mount Lofty Ranges in South Australia. The Overview provides background information on the Mount Lofty Ranges. The climate is Mediterranean, with cool, wet winters and hot, dry summers. The long-term (91-year) average rainfall in Keyneton is 544 mm; evaporation is 839 mm.¹ Annual rainfall in the town is not significantly different from the catchment (Pritchard 1998). The long-term average data show that rainfall exceeds evaporation from April to October. During our study, monthly rainfall was measured by a tipping bucket pluviometer attached to a weather station (Monitor Sensors Pty Ltd). Potential evaporation was calculated using the Priestly–Taylor equation (Priestly and Taylor 1972).

Two toposequences with predominantly annual pastures (Cox and Pitman 2001) were chosen for this study: a 150 m convex toposequence (sites KH0 to KH9) and a 240 m concave toposequence (sites KV1–KV10). The sites were from flat (KH0, KV1) to crest (KH9, KV10) and thought to incorporate

most soil types in the catchment and both diverging and converging water flow.

Pedology and soil physics

Soil horizons along each toposequence were hand-textured and described according to McDonald et al. (1990); they were classified according to US taxonomy (Soil Survey Staff 1996). Soil toposequences were drawn according to the method of Rinder et al. (1994).

A constant head well permeameter (Talsma and Hallam 1980) and the equation of Reynolds and Elrick (1991) were used to measure K_s of the A, E and B horizons in triplicate. Bulk density (ρ_b) was measured with depth by taking duplicate soil cores (4.7 cm wide and 5 cm thick) from soil pits dug at the end of the project. All soils were analysed by the method of Rayment and Higginson (1992).

Measurement and quantification of perched watertables

To measure point-scale water duration, dipwells were installed at eight sites (KH1–KH8) along the convex toposequence and 10 sites (KV1–KV10) along the concave toposequence. At each site, a hole was dug with an auger to 0.5–0.6 m; the hole was lined with 50-mm diameter PVC pipe and capped on the top and bottom. All dipwells were fully slotted below ground level and sand packed. Dipwell water levels were manually measured every week in winter and less frequently at other times for five years (1 January 1994 to 31 December 1998). In addition, at three sites along each toposequence—lower slope (KH1 and KV1); mid-slope (KH5 and KV5); and upper slope (KH8 and KV10)—a data-logger and capacitance probe were installed to electronically measure water levels.

Water duration was quantified by accumulating, over the monitored period, the depth of water between the soil surface and 0.5 m (average depth to

¹ Point patched meteorological data:
see <http://www.dnr.qld.gov.au/silo>

the B horizon); this was termed the water duration index (WDI):

$$WDI_{50} = \sum_{i=1}^n S_i \quad (1)$$

where n is the number of days in the analysis period and S_i is a statistic that is defined as:

$$S_i = 50 - D_i \quad \text{for } D_i < 50 \text{ cm}$$

$$S_i = 0 \quad \text{for } D_i \geq 50 \text{ cm}$$

where D_i is the average depth (in centimetres) of the watertable below the soil surface on day i and $D_i > 50$ (the average depth of the B horizon in centimetres) means that the soil is not waterlogged. Cox et al. (1996) give a full explanation of the index.

Measurement and quantification of depth of saturation

Point scale

An aluminium access tube was installed to 2 m at five landscape positions on the convex slope—crest (KH9); upper slope (KH8); mid-slope (KH5); lower slope (KH1); and flat (KH0)—and three on the concave slope—upper slope (KV10); mid-slope (KV5); and lower slope (KV1)—using the method of Greacen (1981). Volumetric water content was measured every 15 cm (to 2 m) each 2 to 4 weeks for five years by a neutron moisture meter (NMM). Soil cores were taken on four occasions at each depth interval at each site and an NMM calibration was developed for each to determine volumetric water content and percentage saturation.

Catchment scale

To map the extent of soil saturation, a topographic index (Equation 2) was calculated for the study area to represent the geomorphic processes associated with soil water and its spatial distribution in the landscape. The variables of the index were

evaluated on a cell-by-cell basis from a digital elevation model (DEM).

$$\ln (A_s / \tan \theta) \quad (2)$$

where A_s = specific catchment area, and $\tan \theta$ = local slope angle.

Results and Discussion

Rainfall

Annual rainfall was below average (544 mm), except in 1996 (Table 1).

Topographic index

Figure 3 shows a three-dimensional representation of the topographic index. The index indicated that:

- permanent or long periods of soil saturation occur on the flats and lower slopes;
- infrequent to very infrequent saturation occurs on the mid-slopes; and
- short to long periods of saturation occur on the upper slopes and crests (for example, the mid-slopes have the darkest shading in Figure 3, and are the driest).

Point measured waterlogging

Table 1 shows three contrasting examples of the severity of water duration as measured in the dipwells. Figure 4 shows variations in perched watertables along the convex toposequence. A perched watertable rarely formed on some of the texture-contrast soils, but other such soils were very susceptible, even in dry years. The shortest water duration was measured on the mid-slopes, which agreed with the prediction from the topographic index. However, longer water duration was measured on the upper slopes than on the lower slopes. The lower slopes and flats probably have a long water duration when groundwaters are highest (when rainfall is above average).

Table 1. Rainfall (mm) and water duration.

	1994	1995	1996	1997	1998
Annual rainfall (mm) ^a	304	468	548	404	426
Water duration (WDI ₅₀ cm/day) ^b					
Lower slope	0	71	330	0	0
Mid-slope	0	0	2	0	0
Upper slope	485	345	850	289	134

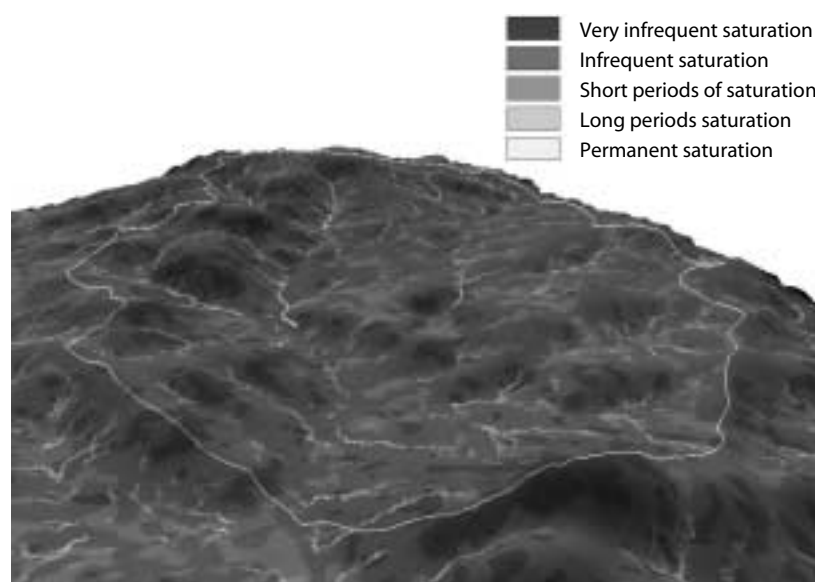
^a Long-term average annual rainfall is 544 mm^b Water duration at 50 cm depth (cm/day)**Figure 3.** 3D representation of topographic index showing duration of saturation.

Figure 5 shows the relationship between the waterlogging and the annual rainfall less evaporation. Equation 3 expresses waterlogging as the average water duration severity over the hillslope:

$$\text{WDI}_{50} = 0.0072 (R - E)^{2.0374}, r^2 = 0.914 \quad (3)$$

where WDI₅₀ is the water duration index (cm/day), *R* is rainfall (mm), and *E* is evaporation (mm).

Neutron moisture meter data

Figure 6 shows the water status of three soils as determined from the NMM data. Soil saturation was sometimes due to the development and

persistence of perched watertables and at other times due to groundwaters each winter, depending on the position in the landscape. Soils on the lower slopes were wettest each winter below about 1.5 m. Saturation was due to saline groundwater; the duration and severity were due to the height the groundwater rose each winter. Although the degree of saturation increased in the A horizon each winter, a perched watertable never developed on the boundary between the A and B horizons on the flats and lower slopes. Saturation of the soils on the mid-slopes was due to a perched watertable developing either on or within the clay B horizon. In addition, groundwaters contributed to

saturation to within 1.0 m of the soil surface in 1995 and 1996. On the upper slopes, the lower A and B horizon soils became saturated each winter due to a perched watertable. In some soils the perching occurred at the boundary between the A and B horizons; in others it was deeper in the soil profile, nearer the boundary of the B and C horizons. In 1996, the wettest season, saturation extended into the upper C horizon.

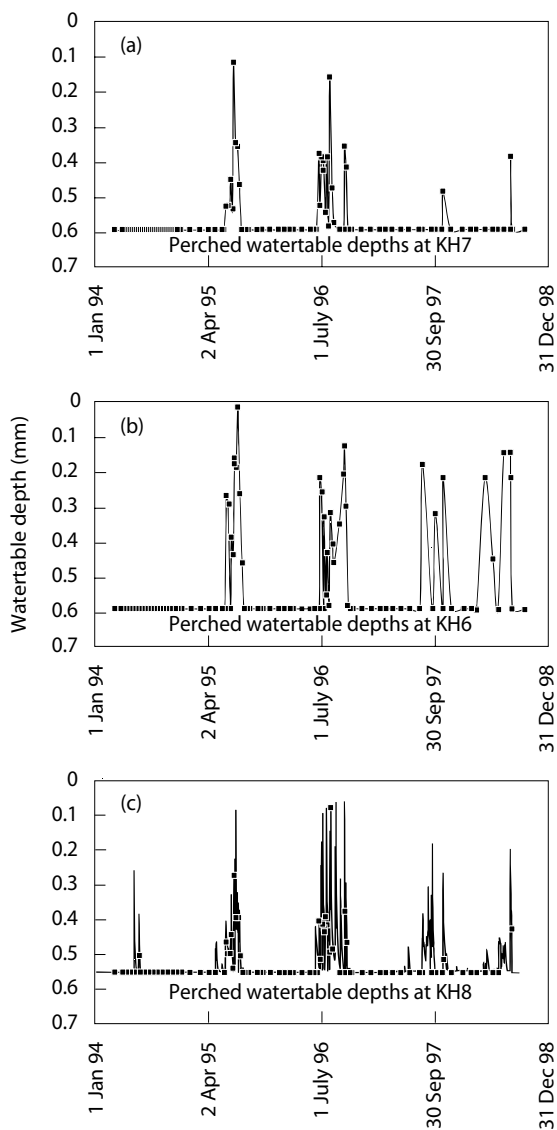


Figure 4. Examples of the development of a perched watertable along the convex toposequence.

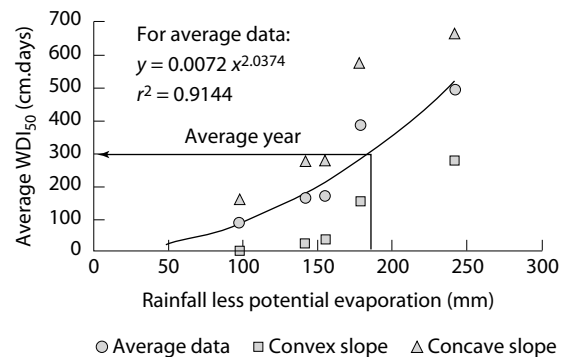


Figure 5. The relationship between rainfall less evaporation and waterlogging.

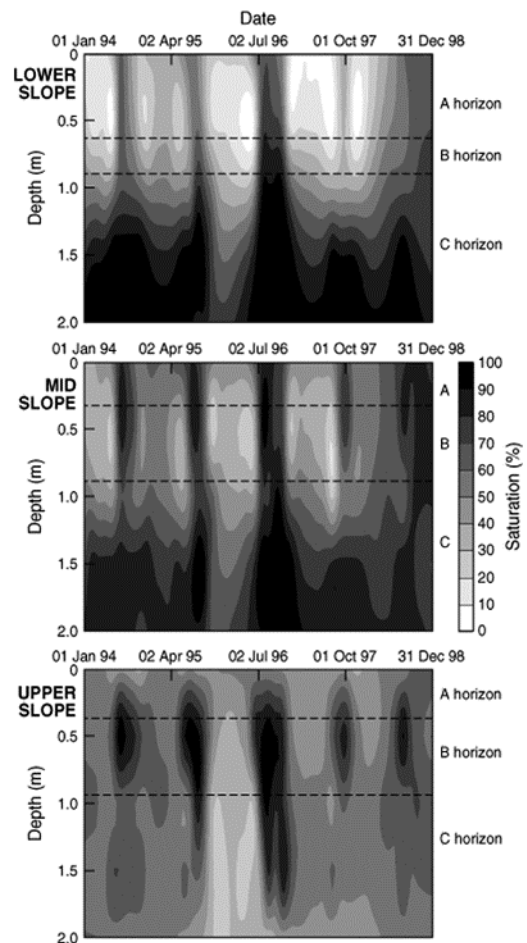


Figure 6. Examples of the degree of soil saturation at three positions in the landscape over five years.

Conclusions

In relatively dry years, water duration on the upper slopes of catchments in the Mount Lofty Ranges is higher than on the lower slopes. This is because the cause of soil saturation on the lower slopes is different from that on the mid- and upper slopes. It is predicted that the highest water duration on the lower slopes will occur in wet years (due to saturation by groundwaters); this is consistent with indications from a topographic index.

The failure of current management options to adequately control perched watertables on slopes is partly due to the lack of understanding of their causes and to inadequate prediction of their variability.

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References

- Chittleborough, D.J. 1992. Formation and pedology of duplex soils. *Australian Journal of Experimental Agriculture*, 32, 815–825.
- Cox, J.W. 1988. Seepage interceptor drainage of duplex soils in south-western Australia. University of Western Australia, PhD Thesis.
- Cox, J.W. and Ashley, R. 2000. Water quality of gully drainage from texture-contrast soils in the Mount Lofty Ranges in low rainfall years. *Australian Journal of Soil Research*, 38, 959–972.
- Cox, J.W. and Fleming, N.K. 1997. Understanding landscape processes. Proceedings of an Australian Institute of Agricultural Science and Technology Symposium: Property and Catchment Planning, Issues Challenges and Professional Responsibilities, Waite Institute, Adelaide, 16 September 1997.
- Cox, J.W., Fritsch, E. and Fitzpatrick, R.W. 1996. Interpretation of soil features produced by modern and ancient processes in degraded landscapes: VII. Water duration. *Australian Journal of Soil Research*, 34, 803–824.
- Cox, J.W. and McFarlane, D.J. 1995. The causes of waterlogging in shallow soils and their drainage in southwestern Australia. *Journal of Hydrology*, 167, 175–194.
- Cox, J.W. and Pitman, A. 2001. Chemical concentrations in drainage from perennials grown on sloping duplex soils. *Australian Journal of Agriculture Research* 52, 211–220.
- Fleming, N.K. and Cox, J.W. 1998. Nutrient losses off dairy catchments located on texture contrast soils: carbon, phosphorus, sulphur and other chemicals. *Australian Journal of Soil Research*, 36, 979–995.
- Greacen, E.L. 1981. Soil Water Assessment by the Neutron Method. Australia, CSIRO.
- McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. 1990. *Australian Soil and Land Survey, Field Handbook*. Second edition. Melbourne, Inkata Press.
- McFarlane, D.J. and Cox, J.W. 1992. Management of excess water in duplex soils. *Australian Journal of Experimental Agriculture*, 32, 857–864.
- Northcote, K.H. 1979. *A Factual Key for the Recognition of Australian Soils*. Fourth edition. Glenside, Rellim Technical.
- Priestly, C.H.B. and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, 100, 81–92.
- Pritchard, J. 1998. Modelling the water balance of duplex soils at Keyneton, Mt Lofty Ranges, SA. University of Adelaide, BSc Honours Thesis.
- Rayment, G.E. and Higginson, F.R. 1992. *Australian Laboratory Handbook of Soil and Water Chemical Methods*. Sydney, Inkata Press.
- Reynolds, W.D. and Elrick, D.E. 1991. Determination of hydraulic conductivity using a tension infiltrometer. *Soil Science Society of America Journal*, 55, 633–639.
- Rinder, G.E., Fritsch, E. and Fitzpatrick, R.W. 1994. Computing procedures for mapping soil features at sub-catchment scale. *Australian Journal of Soil Research*, 32, 909–913.
- Soil Survey Staff. 1996. *Keys to Soil Taxonomy*, 7th edition. Washington DC, United States Department of Agriculture, United States Government Printing Office.
- Stevens, D.P., Cox, J.W. and Chittleborough, D.J. 1999. Pathways for phosphorus, nitrogen and carbon over and through texturally differentiated soils, South Australia. *Australian Journal of Soil Research*, 37, 679–693.
- Talsma, T. and Hallam, P.M. 1980. Hydraulic conductivity measurement of forest catchments. *Australian Journal of Soil Research*, 18, 139–148.
- Tennant, D., Scholz, G., Dixon, J. and Purdie, B. 1992. Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. *Australian Journal of Experimental Agriculture*, 32, 827–843.

18

Monitoring Regional Water Use Efficiency Indicators on the North China Plain

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Abstract

Increasing competition for water in China, due to industrialisation of its economy and urbanisation of its population, has led to the introduction of water-saving agricultural practices to increase agricultural water use efficiency (Ag WUE). This study assessed whether changes in management practices increased regional Ag WUE for a focus area covering 20% of the 300,000 km² North China Plain (NCP). An 'input–output' definition of regional Ag WUE was used, where 'input' is the water available over the crop growing season and 'output' is grain yield. Regional databases of precipitation, irrigation and yield from 1984 to 1996 were established in a geographic information system (GIS) to calculate winter wheat and summer corn Ag WUE on a county basis. For wheat, the average Ag WUE was 7.0 kg/ha/mm in 1984, whereas in 1996 it was 14.3 kg/ha/mm. For corn, Ag WUE increased from 9.0 kg/ha/mm in 1984 to 10.1 kg/ha/mm in 1996, although values of more than 11.5 kg/ha/mm were obtained for both 1991 and 1992. Time series plots of the resulting Ag WUE and its components were generated to reveal spatial and temporal variability. Counties with a relatively high mean Ag WUE and a low year-to-year consistency were found to have the highest potential for improving Ag WUE management. Total county water resources (WR) were also calculated for the time series, and normalisation of Ag WUE and WR on a county basis also showed that there have been recent improvements in Ag WUE. For some counties in wet years, it may be possible to plant larger areas of crop to increase county-level Ag WUE. For the focus study site (and for the time series data available), it is most likely that recently introduced water-saving agricultural practices in the NCP region are associated with improvements to Ag WUE.

工业化和城市化的发展导致中国用水矛盾日益加剧，促使采取节水农业，以求提高水分利用效率（WUE）。本研究的目的是评估研究区农业经营方式的改变是否提高了 WUE。文中用到的区域农业 WUE “投入–产出”定义是：投入 = 作物生长季节可利用的水分，产出 = 作物产量。将该区从 1984 到 1996 年的降水、灌溉和产量数据储存在地理信息系统中，以县为单位计算

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各年度玉米和小麦的 WUE。结果表明，小麦的平均 WUE 值在 1984 年是 7.0 千克每公顷毫米，1996 年提高到 14.3，同期玉米的由 9.0 千克每公顷毫米提高到 10.1，尽管在 1991 和 1992 年曾超过了 11.5。WUE 按年份顺序生成，以表现其时间、空间变化过程。平均 WUE 相对较高而且年际变化大的县份，最有治理潜力。我们也计算了同期各县水资源总量（WR）。各县的农业 WUE 和 WR 正态分布也表明 WUE 在近年有所改善。在多雨年份，有些县份扩大作物种植面积有可能提高县级水平的农业 WUE。就研究区现有资料的年份而言，WUE 的提高很可能同近年实行的节水农业有关。

THERE is increasing competition for water in China due to industrialisation of its economy and urbanisation of its population (Brown and Halweil 1998; Rosegrant and Ringler 2000; Anderson and Peng 1998). This competition, coupled with the need for environmental river flows to ensure that aquatic and riparian ecosystems are sustainable, has placed increasing demands on the Chinese agricultural sector to maintain and increase production using less water. China depends on irrigation water to produce 70% of its grain supply (Brown and Halweil 1998; Zhang 1999). This water is obtained from surface and groundwater systems, at rates that are not sustainable (Jin et al. 1999; Zhang et al. 1998). Since 1978, the beginning of the post-Mao 'pragmatic period' (Muldavin 1997), water-saving agricultural practices and rural land tenure reforms (Wei 1997; Lin 1997; Xing 1997) were widely and proactively implemented by the Chinese central government to increase agricultural production. In North China, grain yield increased from 72 million tonnes in 1979 to 114 million tonnes in 1995 (Yang 1998), while the area of cultivated land decreased by 1.5 million ha (Yang and Li 2000). Currently, the area of arable land per capita in China is one-third the world average (Cao et al. 1995).

Achieving increased grain production with less land area has meant that agricultural systems have become intensively managed. Many agricultural

practices designed to save water have been implemented (Wang et al. in press), and fertilisers have been widely used to overcome nutrient limitations, although overapplication has raised concerns about environmental degradation and pollution (Yong and Jiabao 1999; Rozelle et al. 1997).

Stanhill (1986) suggested three main components of water-saving agriculture: reducing delivery losses in irrigation systems; improving water transfer (from either irrigation or rainfall) to a depth where roots can access the water; and maximising water use efficiency (WUE) by crops. Minimising delivery losses is essentially an engineering problem. Water balance modelling can be used to ensure that water is applied at suitable times and in suitable amounts to optimise plant transpiration (Wang et al. 2001). Soil structure and fertility can be altered (for example, by increasing soil organic matter). Variations in regional WUE need to be monitored to assess the effectiveness of water-saving agricultural practices in the context of spatial and temporal variation of water resources. Different measurements and modelling approaches are required to determine agricultural WUE (abbreviated as Ag WUE hereafter) at different scales.

Stanhill (1986) defined WUE both hydrologically and physiologically. Hydrological WUE is the ratio of evapotranspiration to the water potentially

available for plant growth. It is expressed as a percentage or fraction (0–1). Physiological WUE measures the amount of plant growth for a given volume of water. Physiological WUE can be defined for different measures of ‘plant growth’ and ‘volume of water’. Turner (1986) noted that care is needed when defining WUE. For example, in some studies ‘plant growth’ is measured in units of net biomass (including roots) (Ritchie 1983; Tanner and Sinclair 1983; Turner 1997) or crop grain yield (Tanner and Sinclair 1983; Turner 1997). In various previous studies, the units for ‘volume of water’ were total transpiration (Tanner and Sinclair 1983; Turner 1997; French and Schultz 1984a,b), total evapotranspiration (Ritchie 1983; Tanner and Sinclair 1983; Turner 1997), total water input (Sinclair et al. 1984), or total growing season precipitation plus initial soil water at the time of sowing (French and Schultz 1984a,b).

Sinclair et al. (1984) introduced different time scales for several definitions of WUE. Scales ranged from an instant to a day or a growing season that can be linked to a range of spatial scales, which in turn extend from a single leaf, through a canopy, field, farm or region (Table 1). The scales are linked: leaf WUE (in the order of tens of square centimetres) will usually be measured over a short time (e.g. from 1 second to 1 day); regional WUE (in the order of thousands of square kilometres) will usually be measured over a longer time (e.g. from a day to a growing season). To date, there has been very little research focusing on farm-level (Tuong and Bhuiyan 1999) or regional assessments of WUE.

Single-leaf WUE is commonly defined as the net carbon dioxide (CO₂) uptake per unit of transpiration. On a continuous basis—that is, at any instant within a day—it is expressed as the ratio of leaf net photosynthetic rate to leaf transpiration rate. On a daily basis it is expressed as the ratio of daytime CO₂ uptake to daytime transpiration. Canopy (or community) WUE is commonly defined as the ratio of the crop canopy’s net CO₂ assimilation to its transpiration—that is, the ratio of the canopy’s CO₂ flux to the water flux for transpiration. Canopy WUE can be expressed continuously and at a daily time scale, as above, and can also be calculated at specific plant growth stages. WUE can be defined as grain yield per unit of water transpired, measured in kilograms per hectare per millimetre (kg/ha/mm). It can be measured at field level or regional level but there are difficulties in measuring regional WUE because the region may support multiple land uses and multiple crops during the same season. We have therefore developed an ‘input–output’ definition of regional WUE (Zoebl 2000). ‘Input’ is the water available over the crop growing season (i.e. rainfall plus irrigation) and ‘output’ is grain yield. This ‘input–output’ approach takes into account spatial and temporal constructs of regionally available databases.

In this chapter we define agricultural WUE as grain yield per unit water available for crop growth. This definition ignores precipitation that falls on ‘bare’ soil (areas that are not sown to actively growing crops). We present the data as kilograms of crop

Table 1. Linkages between different spatial and temporal scales for physiological water use efficiency, and some common units by which they are measured.

Spatial scale	Temporal scale	Units
Single leaf	Second—day—growth stage	mg CO ₂ /g H ₂ O or μmol CO ₂ /mmol H ₂ O
Canopy	Second—day—growth stage	mg CO ₂ /g H ₂ O or μmol CO ₂ /mmol H ₂ O
Field	Day—growth stage—season	mg CO ₂ /gH ₂ O or kg/ha/mm
Farm	Growth stage—season—year	kg/ha/mm or t/km ² /GL
Region	Season—year	kg/ha/mm or t/km ² /GL

yield per hectare of crop area per millimetre of water available for crop growth (kg/ha/mm). To assess the link between Ag WUE and total county water resources, we have also mapped the volume of water available to a county over the growing season. This includes precipitation that falls on ‘bare’ soil, and is expressed as gigalitres (GL or 10^9 L). ‘Water resources’ is abbreviated to ‘WR’ hereafter. As total county WRs are a function of county area, they should be compared only for counties of a similar size or, more strictly, for the same county at different times.

The base unit of the region is the administrative county, which is the smallest geographic resolution that the available databases covered (Cao et al. 1995). Many variables influence Ag WUE, but data are not available for many of them. They include:

- species or crop varieties, comprising plant breeding (Li et al. 1995) and genetic modifications;
- soil conditions (Gong and Lin 2000), comprising soil erosion, sodicity, and salinisation (Rozelle et al. 1997);
- agricultural practices, involving the use of fertilisers (Garabet et al. 1998), efficient irrigation management (Zhang and Oweis 1999; Zhang et al. 1998; Liu et al. 1998), time of planting and crop rotation (Li et al. 2000), planting density (Karrou 1998), and the use of mulch (Tolk et al. 1999) or plastic film (Jin et al. 1999) to reduce soil evaporation; and
- climate change (Smit and Yunlong 1996; Loaiciga et al. 1996), including precipitation patterns (Thomas 2000) and CO_2 concentration (Hunsaker et al. 2000).

At the regional scale, the interactions are complex and unknown, making absolute measures of Ag WUE difficult. The spatial information system developed here to monitor regional Ag WUE is most suited to interpreting relative trends, both spatially

and temporally. The aim of our research is to monitor regional Ag WUE on the North China Plain (NCP) using readily available data. The method developed for this purpose can be used in other agricultural regions. This work is a starting point for more detailed analyses to infer causal relationships between Ag WUE and agricultural practice.

Materials and Methods

Description of the study site

The study was carried out in Hebei Province on the NCP (Fig. 1). The Overview describes the general characteristics of the NCP region. We selected the Hebei Province portion of the NCP because it allowed us to establish regional precipitation, yield and irrigation databases. The Hebei Plain is defined by longitudes $113.5\text{--}118.0^\circ\text{E}$ and latitudes $36.0\text{--}40.0^\circ\text{N}$; it comprises 90 counties covering $61,636\text{ km}^2$, or 20% of the NCP (see Fig. 1). Of these, 84 counties produce agricultural output; the average size is 710 km^2 , with a standard deviation of 310 km^2 . The largest county covers 1980 km^2 and the smallest 204 km^2 . Most of the study area is essentially flat, with some of the western counties straddling the plains and foothills of the Taihang Mountains (McVicar et al. 2000).

In the study area, the main crops are winter wheat and summer corn. Most rain falls in the summer, so more irrigation is applied during the growth period of winter wheat, which is planted in early October. During winter, the growth of wheat is limited by low air temperatures, so grain development occurs during the following spring and summer. Farmers commonly apply fertiliser in late March to early April, and irrigate at the same time (‘fertigate’) to ensure that the fertiliser is dissolved. Wheat is harvested in early June the following year. A variety of crops are grown in summer, including corn, millet, soybeans and sorghum. In this chapter this season is denoted ‘corn’ as the crop dominates autumn harvests. Usually the monsoon period provides enough rainfall for summer crop growth; however, farmers commonly fertigate once during

the summer season. Peanuts, cotton and several other nongrain producing crops are also grown during this season. Most of these crops are planted in mid-June and harvested in late September.

Exact dates for planting and harvesting over the entire NCP vary slightly depending on latitude. The dates reported below were optimised for the study area; the numbers in parentheses refer to the day of the year (for nonleap years), a notation used throughout this chapter. We assume the wheat growing season is from 1 October (day 274) until 10 June (day 161) the following year, and that corn is planted on 15 June (day 166) and harvested on 20 September (day 263). Throughout the year, small plots of intensively managed market garden vegetables are also grown. Dual cropping is carried out over the entire NCP; however, some rice is

grown in the southern portion of the NCP in Anhui and Jiangsu Provinces.

Available water for the growing seasons

For the wheat growing season, the ‘volume of water’ available for crop growth comprises precipitation (P_{wheat}), irrigation (I_{wheat}), and initial effective soil water storage (W_{o_wheat}). We used daily precipitation data (see below) from the day after harvest of the summer crops, in early autumn on day 264, until the harvest of wheat on day 161 the following year. All precipitation and irrigation in this period was assigned to the wheat growing season. W_{o_wheat} , defined as available soil water (to a depth of 1.5 m) minus wilting point moisture content, has been related to the cumulative precipitation from 1 July to 30 September (Yuan et al. 1992). Researchers at Luancheng Eco-Agro-

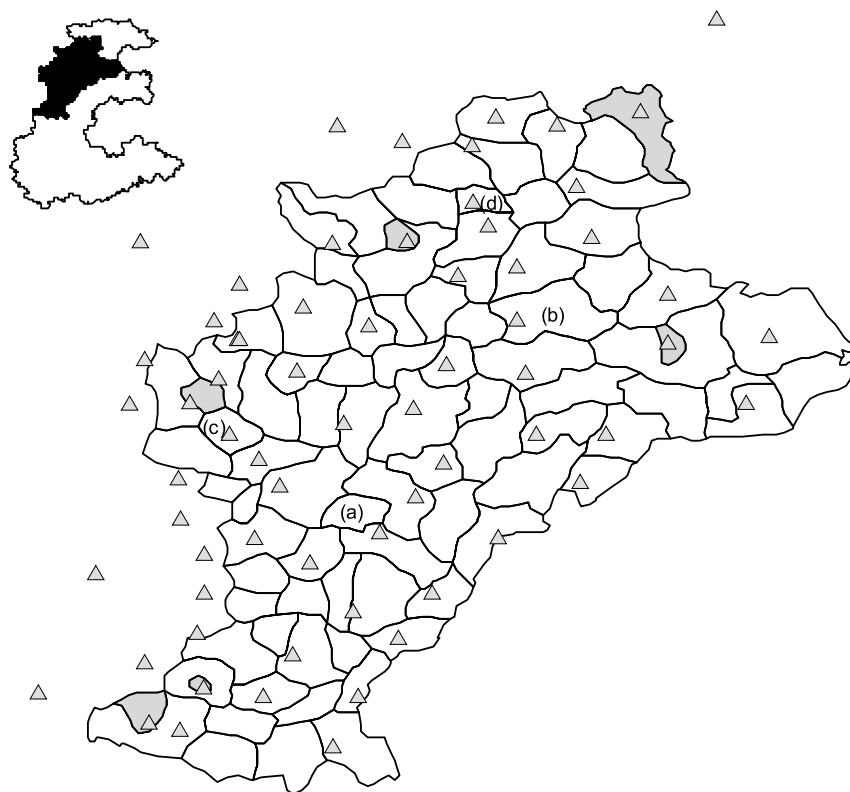


Figure 1. Location of counties and meteorological stations (Δ) in the Hebei Plain study area. The Hebei Plain area is shaded black in the inset map of the North China Plain. Four focus counties are identified: (a) Xinhe (132232); (b) Heijian (132922); (c) Luancheng (130124) and (d) Rongchen (132435). Nonagricultural counties, cities and industrial zones are shaded grey.

System Experimental Station used data over 16 years (1971–86) to develop the following relationship between the variables:

$$W_{o_wheat} = -33.688 + 0.595 \sum P_{1July..30Sept},$$

$$\text{with } r^2 = 0.837.$$

Due to the summer-dominated rainfall, residual soil water (W_{o_wheat}) remaining after the summer corn growing season affects yields of the following wheat crop (Y_{wheat}).

The volume of water for the corn growing season also includes precipitation (P_{corn}) and irrigation (I_{corn}). The change in effective soil water storage from the start to the end of the corn growing season (ΔW_{corn}) is of little importance to the final corn yield (Y_{corn}). This is because $P_{corn} + I_{corn} > \Delta W_{corn}$. The corn season is defined from the day after harvest of wheat on day 162 until the harvest of the autumn crops on day 263. Assuming that ΔW_{corn} is negligible results in a slight increase in wheat Ag WUE estimates and a slight decrease of corn Ag WUE.

Within a growing season, the amount and timing of rainfall and irrigation are obviously important for crop growth and final yields; however, due to the ‘seasonal’ resolution of the irrigation data (see below), we have integrated the precipitation data seasonally. This is the basis for our ‘input–output’ definition of Ag WUE, which used readily available regional data. To monitor Ag WUE regionally, we also assumed that capillary rise to the root zone, deep drainage from the root zone, and runoff were negligible. At the regional level, we defined Ag WUE as follows:

$$\text{Ag WUE}_{wheat} = \frac{Y_{wheat}}{P_{wheat} + I_{wheat} + W_{o_wheat}} \text{ and}$$

$$\text{Ag WUE}_{corn} = \frac{Y_{corn}}{P_{corn} + I_{corn}}$$

with units of kg/ha/mm. The ‘input–output’ Ag WUE approach takes into account the spatial and temporal constructs of the regional databases that

are available. The required databases, introduced below, were developed in a geographic information system (GIS) to calculate and map variations in Ag WUE regionally.

Precipitation data

Daily precipitation data were recorded from 1981 to 1996 at 65 stations in Hebei Province covering the study area. More than 50 stations are well distributed over the Hebei Plain; another 13 stations are located outside the NCP in the Taihang Mountains to the west. At each of the 65 stations P_{wheat} , W_{o_wheat} and P_{corn} were calculated. Using ANUSPLIN (Hutchinson 1999), these three variables were then spatially interpolated over the entire study area at a resolution of 1/120th of a degree. Selection of spline model parameters is fully documented in McVicar et al. (2000). For the three variables, the average for each county for each growing season was used in the calculations.

Irrigation data

The spatial irrigation database was established by contacting the relevant officials in each county, from the Agricultural Bureau, the Hydrological Bureau or the Agricultural Planning Bureau, depending on which organisation kept records. In the study area, all irrigation water is obtained from the regional groundwater aquifers by using electric pumps. The farmers pay the electricity costs twice a year (at the end of the wheat and corn growing seasons). Taking into account depth to watertable, the electricity costs are converted to electricity use, which translates into a volume of water extracted at each pump. This is aggregated to provide the amount of water used for irrigation at a county level. Seasonal irrigation amounts used for wheat and corn in 49 of the 84 agricultural counties were recorded from 1981 to 1996. Timing and location of individual irrigation events were not available. County-level irrigation amounts for the wheat season represent approximately nine months; for corn they represent approximately three months.

Yield data

The Hebei Province Agricultural Bureau recorded yield data for 84 counties (Fig. 1) from 1984 to 1996. The Chinese national standard, which has been used routinely over the last 20 years, was used to estimate county-level yield data. Briefly, the method relies on aggregating estimated yields from the village, to the township, to the county. Within the study area, 15–30 villages contribute to a township, and there are 10–20 townships within a county. For each village, the farmland is divided into three classes of productivity: good, medium and poor. At least 10% of the farmland of the entire village is sampled, with at least 3% being in each class. In the three classes, random sampling of grain yield is undertaken, calculated by seeds per spike multiplied by the number of spikes multiplied by the average seed weight. The three variables are determined for a 4 m² (2 m × 2 m) quadrat, repeated within a paddock two to five times depending on local variability. The average weight of a seed is determined from a 1000-seed sample in each quadrat. If the difference between all the variables is less than 2%, the average of the two samples is used to represent the paddock. If the difference is more than 2%, another sample is acquired and the difference between the new sample and the average of the previous samples is determined. This routine is continued until the difference is less than 2%. The average grain yield of the quadrat is then determined for each class. This value is then weighted by area, using the relative areas of the three classes of farmland productivity, to produce an estimate of yield for each village. These values are aggregated through the township level to the county level.

Data for both 1986 and 1988 were missing, and values for two counties were not recorded for one year¹ so there are 922 observations of yield and crop area for the main crop types, including wheat, corn, millet, sorghum and soybeans. We estimated the

county yield for 1986 and 1988 using regional remotely sensed data; full technical details of this process are documented in McVicar et al. (2000). While the area of each crop in each county was known, the location was not. This restricted our analysis to an entire county level. Table 2 shows the yields and areas planted for summer and autumn harvested crops. For crops harvested in early June, wheat contributed more than 90% of the yield for all 922 observations. Sixty-four per cent of the counties had wheat planted to more than 30% of the county area. Corn was the most important autumn harvested crop, although millet, sorghum and soybeans were also important. For 63% of the 922 observations, the combined area planted with corn, millet, sorghum and soybeans within each county was more than 30% of the county area. For many counties, less than 50% of the county area was usually planted with crops.

County total water resources

We calculated (in GL) the total WR for both the wheat and corn growing periods for each county. The volume was obtained by summing [1] the product of crop area by the amount of irrigation water applied; and [2] the product of county area by average county precipitation. In the case of wheat, we added estimates of initial soil water content. For wheat, WR was calculated as:

$$\begin{aligned} & \left(\text{crop area (ha)} \times I_{\text{wheat}} \text{ (mm)} \right) [1] \\ & + \left(\text{country area (ha)} \times \left(\frac{P_{\text{wheat}} \text{ (mm)} + W_{o_wheat} \text{ (mm)}}{2} \right) \right) [2] \end{aligned}$$

As discussed previously, there is no corresponding W_o term for corn.

¹ Xincheng (132436) was missing in 1993 and Hengshui (133001) was missing in 1996 (figures in brackets represent the Chinese Central Government County Code Identification).

Table 2. Decile frequency distributions for both summer and autumn harvested crops (normalised by county yield and county area) for the 84 agricultural producing counties over 11 years (1984–96) for grains.

Summer-harvested crops			Autumn-harvested crops ^a									
Wheat			Corn		Millet		Sorghum		Soybean		Combined grains	
Per cent range	% by yield	% by area	% by yield	% by area	% by yield	% by area	% by yield	% by area	% by yield	% by area	% by yield	% by area
> 90	100 (922)	0 (0)	8(76)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	56(524)	0 (0)
80–90	0 (0)	0 (0)	20(184)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	31(287)	0 (0)
70–80	0 (0)	0 (0)	25(232)	0 (0)	0(1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	9(83)	0 (0)
60–70	0 (0)	2 (16)	21(196)	0 (0)	1(5)	0 (0)	0 (0)	0 (0)	0(2)	0 (0)	2(15)	0(3)
50–60	0 (0)	8 (72)	13(118)	0(1)	2(17)	0 (0)	0 (0)	0 (0)	0(2)	0 (0)	1(7)	4(39)
40–50	0 (0)	18 (171)	6(53)	5(47)	2(14)	0 (0)	0 (0)	0 (0)	0(2)	0 (0)	1(6)	21(194)
30–40	0 (0)	36 (333)	3(24)	18(162)	3(25)	0 (0)	0(3)	0 (0)	1(5)	0 (0)	0 (0)	38(344)
20–30	0 (0)	32 (293)	1(12)	34(312)	9(83)	0(1)	1(8)	0 (0)	4(36)	0(2)	0 (0)	34(316)
10–20	0 (0)	4 (35)	2(21)	35(326)	25(234)	10(88)	4(32)	0 (0)	21(194)	12(107)	0 (0)	3(25)
< 10	0 (0)	0 (2)	1(6)	8(74)	58(543)	90(833)	95(879)	100(922)	74(681)	88(813)	0 (0)	0(1)

^a Harvested mid-September
Note: Wheat yield was calculated as the percentage of the total summer grain harvest. Wheat area was the percentage of each county planted to wheat. The percentage of the total autumn grain harvest was calculated for corn, millet, sorghum, and soybean. Autumn crop areas are the percentage of county planted with each crop. Combined grains are corn, millet, sorghum, and soybean. Numbers in brackets are the number of observations

Results and Discussion

Agricultural water use efficiency

Figures 2 and 3 show the Ag WUE from 1984 until 1996 for the wheat and corn growing seasons, respectively; they also show the components used for the calculation of Ag WUE. The data are presented for the year of harvest. The use of the county average from the interpolated surfaces for P_{wheat} , W_{o_wheat} and P_{corn} introduces uncertainty into the final Ag WUE calculation. To understand the potential uncertainty introduced, we divided the average county range by the average mean for P_{wheat} , W_{o_wheat} and P_{corn} . For P_{wheat} , for the 1092 observations (84 counties over 13 years), the average range (12.43 mm) divided by the average mean (147.70 mm) was 8.42%. For W_{o_wheat} , the average range (24.18 mm) divided by the average mean (165.35 mm) was 14.63%. For P_{corn} , the average range (48.11 mm) divided by the average mean (386.01 mm) was 12.46%. These statistics illustrate that taking the county average interpolated output introduced less than 15% uncertainty into the seasonal county-based Ag WUE calculation.

For both wheat and corn in 1986 and 1988, county yields estimated from regional remote sensing appeared to be erroneous (Figs 2 and 3). Comparing these two years with all other yield data revealed that the relative spatial variability across the study site for these two years was dampened. That is, the yield estimated for counties in the east (with low measured yields) appears to be overestimated; for counties in the west (with high measured yields), it appears to be underestimated. The poor performance of the remotely sensed estimates of yield is probably caused by resampling on the satellite to produce global area coverage data (McVicar et al. 2000). The data for 1986 and 1988 for both wheat and corn have been ignored in all subsequent analysis of Ag WUE.

For the 538 valid measurements (49 counties over 11 years), Ag WUE for wheat had a mean value of 9.6 kg/ha/mm, with a standard deviation of 3.8 kg/ha/mm and a range of 21.5–1.2 kg/ha/mm. During the corn growing season, the mean Ag WUE was 9.5 kg/ha/mm, with a standard deviation of 5.1 kg/ha/mm and a range of 39.0–1.7 kg/ha/mm. Table 3 shows the average annual Ag WUE for both the wheat and corn growing seasons for the 49 counties. For wheat, the average Ag WUE was 7.0 kg/ha/mm in 1984; in 1996 it was 14.3 kg/ha/mm. For corn, Ag WUE increased from 9.0 kg/ha/mm in 1984 to 10.1 kg/ha/mm in 1996, although values of more than 11.5 kg/ha/mm were obtained in both 1991 and 1992. Figures 2 and 3 show the temporal and spatial variation for the wheat and corn growing seasons. If data were not available, the map is shaded grey and internal county boundaries are dissolved; this convention is used throughout the chapter.

Table 4 shows the frequency distributions for Ag WUE for both the wheat and corn growing seasons. For wheat, Ag WUE for 482 of the 538 observations (89%) was in the range 0–15 kg/ha/mm. Two previous studies conducted on the NCP, both using a seasonal evapotranspiration (ET) WUE definition, reported wheat Ag WUE values similar to those presented here. In the first, Zhang et al. (1999) assessed four different experimental sites, and reported values of 9.8–12.2 kg/ha/mm for rainfed conditions, and 11.8–14.0 kg/ha/mm for irrigated wheat. In the second, Jin et al. (1999) studied the impact of mulch, fertiliser and irrigation scheduling and reported values of 14.9–23.0 kg/ha/mm. The range of values presented in Table 4 is consistent with WUE values for wheat presented for other areas in China (9.3–15.5 kg/ha/mm, Zhang et al. 1998; 6.5–12.1 kg/ha/mm, Li et al. 2000), and for other locations, including Australia (2.5–10.4 kg/ha/mm, O’Leary et al. 1985; 5.5–16.5 kg/ha/mm, Regan et al. 1997), West Asia and North Africa (4.1–8.9 kg/ha/mm, Karrou 1998; 2.5–16.0 kg/ha/mm, Zhang and Oweis 1999; 8.1 to 11.0 kg/ha/mm, Oweis et al. 2000).

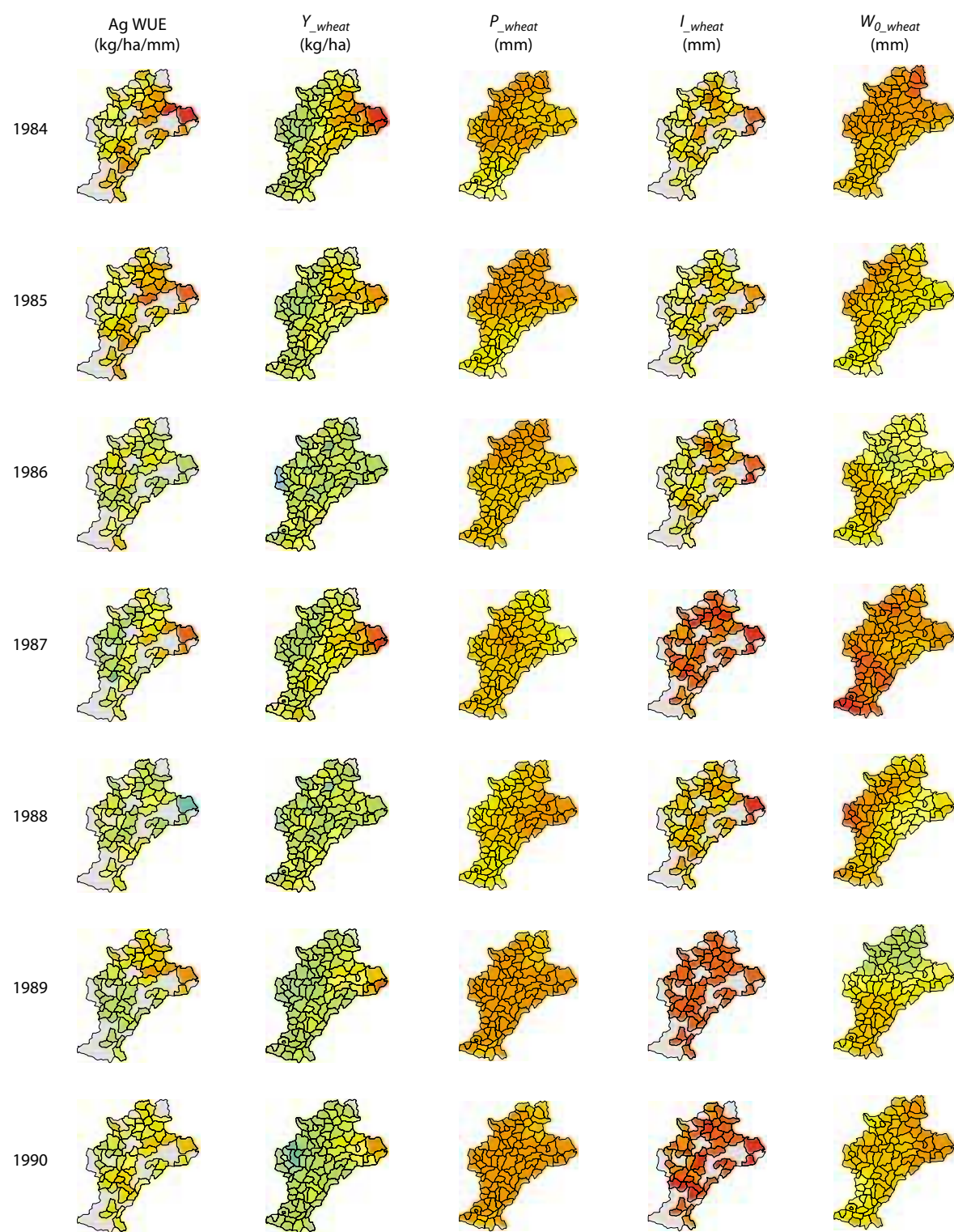


Figure 2. Agricultural water use efficiency for wheat grown on the Hebei Plain study area, 1984–96. The figure shows agricultural water use efficiency (AgWUE) in kg/ha/mm and its components: Y_{wheat} (kg/ha), P_{wheat} (mm), I_{wheat} (mm) and W_{o_wheat} (mm).

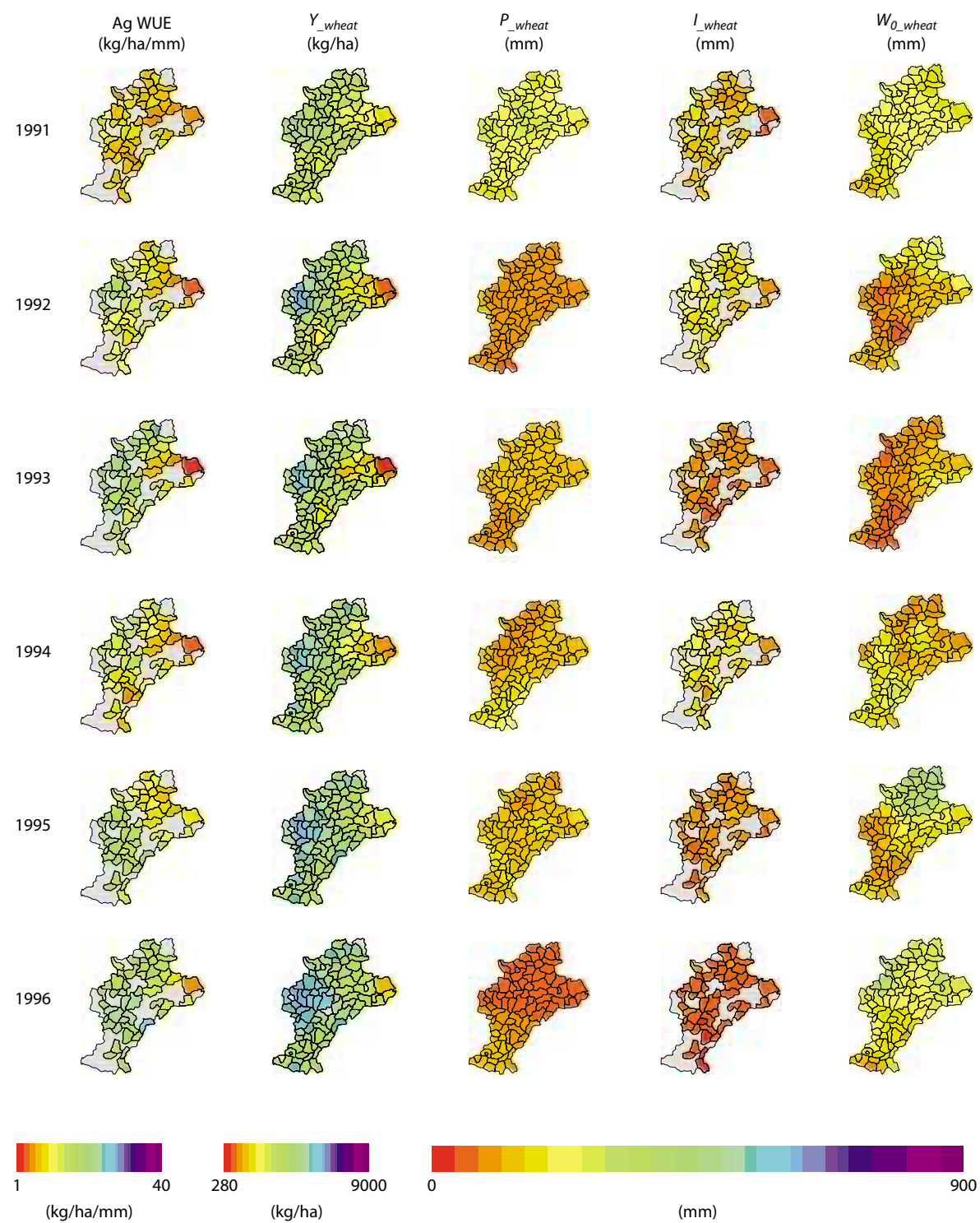


Figure 2. (cont'd) Agricultural water use efficiency for wheat grown on the Hebei Plain study area, 1984–96. The figure shows agricultural water use efficiency (AgWUE) in kg/ha/mm and its components: Y_{wheat} (kg/ha), P_{wheat} (mm), I_{wheat} (mm) and W_{o_wheat} (mm).

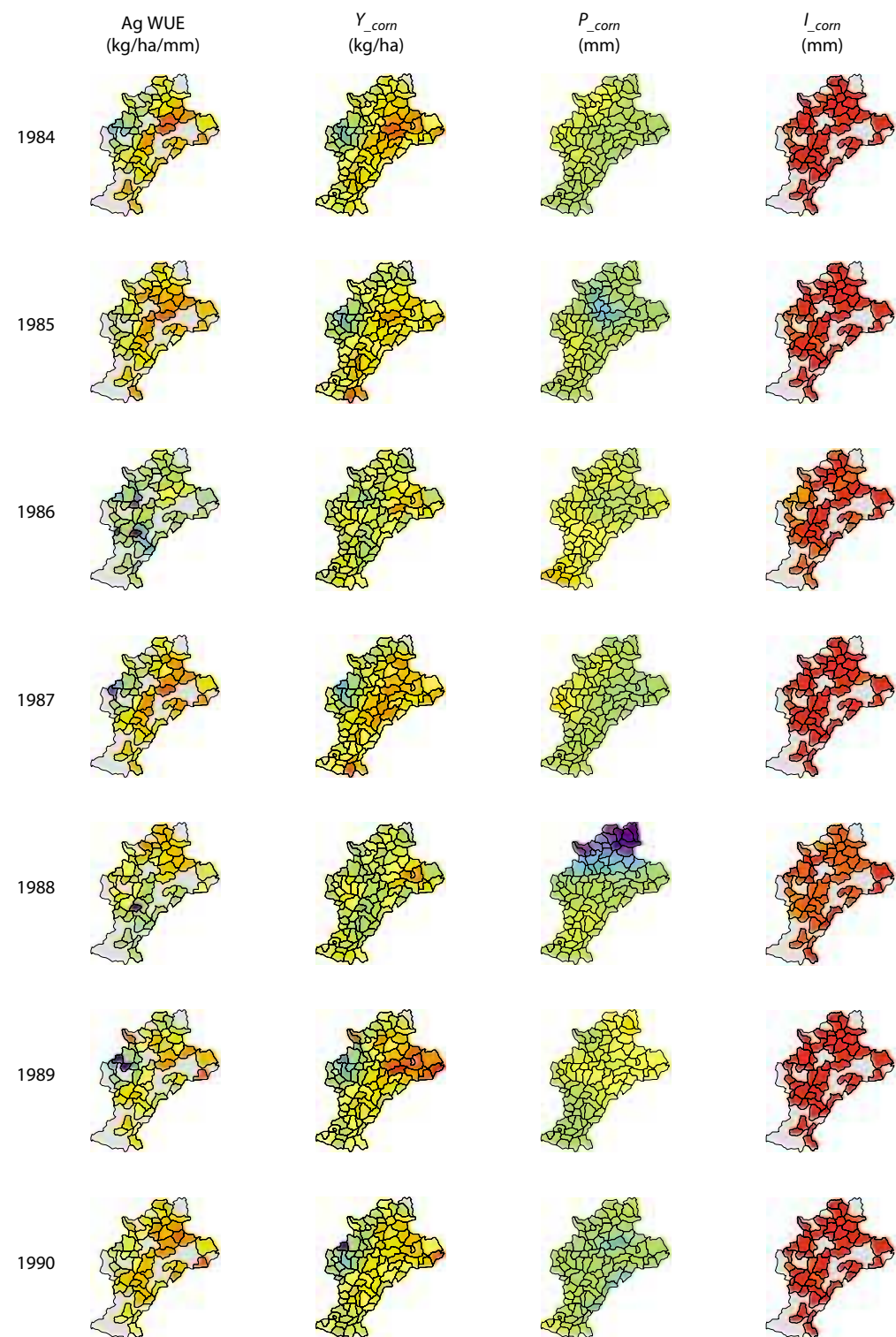


Figure 3. Agricultural water use efficiency for corn grown on the Hebei Plain study area, 1984–96. The figure shows agricultural water use efficiency (AgWUE) in kg/ha/mm and its components: Y_{corn} (kg/ha), P_{corn} (mm) and I_{corn} (mm).

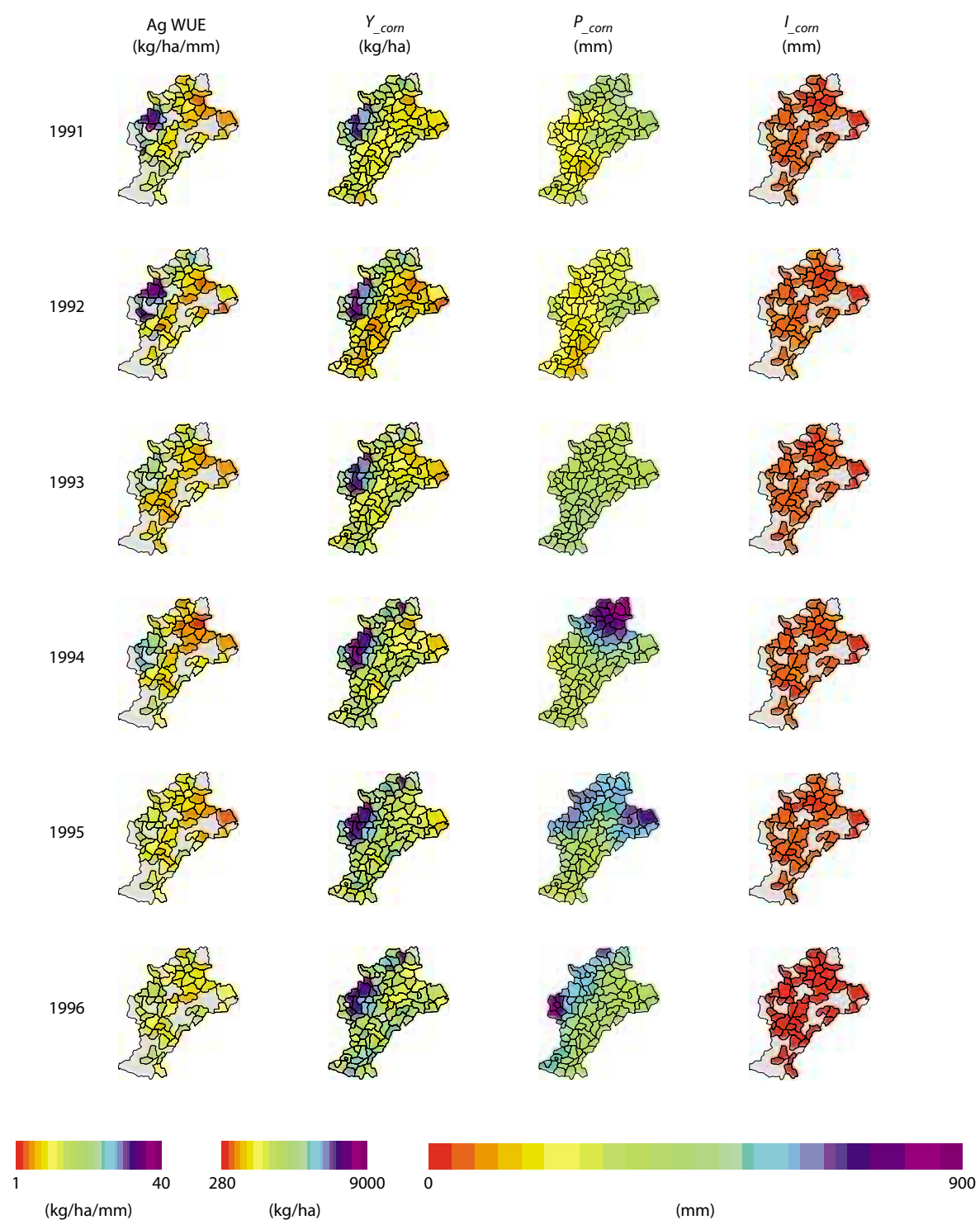


Figure 3. (cont'd) Agricultural water use efficiency for corn grown on the Hebei Plain study area, 1984–96. The figure shows agricultural water use efficiency (AgWUE) in kg/ha/mm and its components: Y_{corn} (kg/ha), P_{corn} (mm) and I_{corn} (mm).

Table 3. Annual agricultural water use efficiency mean and standard deviations for all 49 counties for both the wheat and corn growing seasons (units are kg/ha mm).

Year ^a	Wheat		Corn	
	Mean	SD	Mean	SD
1984	7.0	2.7	9.0	4.4
1985	6.7	2.1	7.7	3.3
1987	10.7	3.6	8.9	5.0
1989	10.0	3.6	10.9	5.4
1990	8.6	1.9	7.4	3.0
1991	6.4	1.1	11.6	6.8
1992	9.5	3.1	12.4	8.1
1993	12.7	4.3	8.9	4.3
1994	8.7	2.5	9.2	5.2
1995	11.3	3.5	8.5	2.8
1996	14.3	3.1	10.1	2.5

SD = standard deviation
^a There are no data for 1986 and 1988

Table 4. Frequency distribution of agricultural water use efficiency for all 538 observations (49 counties by 11 years) for both the wheat and corn growing seasons.

Range (kg/ha/mm)	Wheat		Corn	
	No. of observations	%	No. of observations	%
0–5	43	8	71	13
5–10	270	50	285	53
10–15	169	31	111	21
15–20	53	10	46	9
20–25	3	1	13	2
25–30	0	0	10	2
30–35	0	0	1	0
35–40	0	0	1	0

Note: There are 538 observations, not 539 (11 times 49), as there are no yield data for Xincheng County in 1993.

Table 4 shows that 467 of the 538 corn Ag WUE observations (87%) are also in the range 0–15 kg/ha/mm. In 25 cases, the corn Ag WUE is more than 20 kg/ha/mm, compared to only three cases for wheat (Table 4). It is expected that crops with a C₄ photosynthetic pathway will have higher Ag WUE than C₃ crops² (Beale et al. 1999). However, two cases recorded Ag WUE greater than 30 kg/ha/mm with no obvious errors. Hu (1998), responding to comments from Hill (1997), discussed the issue of China’s agricultural statistics, which may be unreliable for individual counties in some years; as a result, the calculated corn Ag WUE is likely to be greater than 30 kg/ha/mm.

Most Ag WUE values for corn presented here are similar to those reported in other studies. In the northwest of China, Ag WUE was 12.6–23.1 kg/ha/mm for corn, 7.5–20.9 kg/ha/mm for millet, 15.5–15.7 kg/ha/mm for sorghum, and 4.1–5.7 kg/ha/mm for soybeans (Li et al. 2000). These results are similar to those reported for other locations. In the semiarid central and southern high plains of the United States, Tolk et al. (1999) reported values of 12.6–15.8 kg/ha/mm for corn; Stone et al. (1996) reported values of 8.3–15.7 kg/ha/mm for corn and 15.2–16.0 kg/ha/mm for sorghum. In the semiarid Sahel, transpiration WUE for pearl millet was 4.5–16.6 kg/ha/mm (Rockström et al. 1998). For sorghum grown within agroforestry sites along a rainfall gradient ranging from 350 to 2640 mm in Africa, Cannell et al. (1998) reported transpiration WUE of 1.5–9.0 kg/ha/mm. For sorghum in central Queensland, values were 3.4–11.2 kg/ha/mm (Armstrong et al. 1999).

For both the wheat and corn growing seasons, several strong spatial trends can be seen (Figs 2 and

² ‘C₃’ and ‘C₄’ refer to the number of carbon atoms in the first stable product formed during photosynthesis. C₃ plants, including winter wheat on the NCP, are usually active in cooler months. C₄ plants, such as corn on the NCP, are usually active in summer.

3). The Ag WUE and yield data are higher in the western counties than in the east (Fig. 4). The main reason for this is assumed to be that the irrigation water quality and soil conditions in the west are more favourable. For the 11 years of valid wheat yield data (Fig. 2), a gradual increase in Ag WUE from 1984 to 1996 can be seen; this is summarised in Table 3. The increase is most likely to be the result of water-saving agricultural practices; however, no definite conclusions can be reached, because of the lack of regional data.

The relationship between P_{corn} and W_{o_wheat} is illustrated by the similar spatial patterns for P_{corn} in 1984 (Fig. 3) and W_{o_wheat} in 1985 (Fig. 2). For the 13 years of W_{o_wheat} data, temporal and spatial changes that mimic the preceding P_{corn} can be seen. P_{wheat} shows a high degree of temporal and spatial variability, as would be expected (Fig. 3). In 1989, 1990, 1992 and 1996, rainfall was low over most of the study area during the wheat growing seasons. However, in 1989 and 1996, relatively high W_{o_wheat} suggests that there was adequate water to obtain near-average yields, and near-average Ag WUE were recorded in both years. In 1992, irrigation amounts were high, so yields were slightly above average, resulting in a slightly lower than average Ag WUE. Moreover, since 1986, the amount of irrigation applied during the wheat growing season has been reduced, with no loss of grain yield, so Ag WUE has increased (Fig. 2). It is interesting to note that there has been a steady increase of Y_{wheat} in the central western counties of the study area since 1991.

Subtle interactions of the various components contributing to Ag WUE are revealed by close inspection of data for the wheat growing seasons of 1991 and 1992 (Fig. 2). In 1991, W_{o_wheat} was moderate (due to a relatively high P_{corn} in 1990), I_{wheat} was applied at slightly above average rates, and P_{wheat} was also above average. Harvested yields for 1991 were about average; however, Ag WUE was low due to the relatively plentiful supply of water. In comparison, irrigation water was necessarily high in

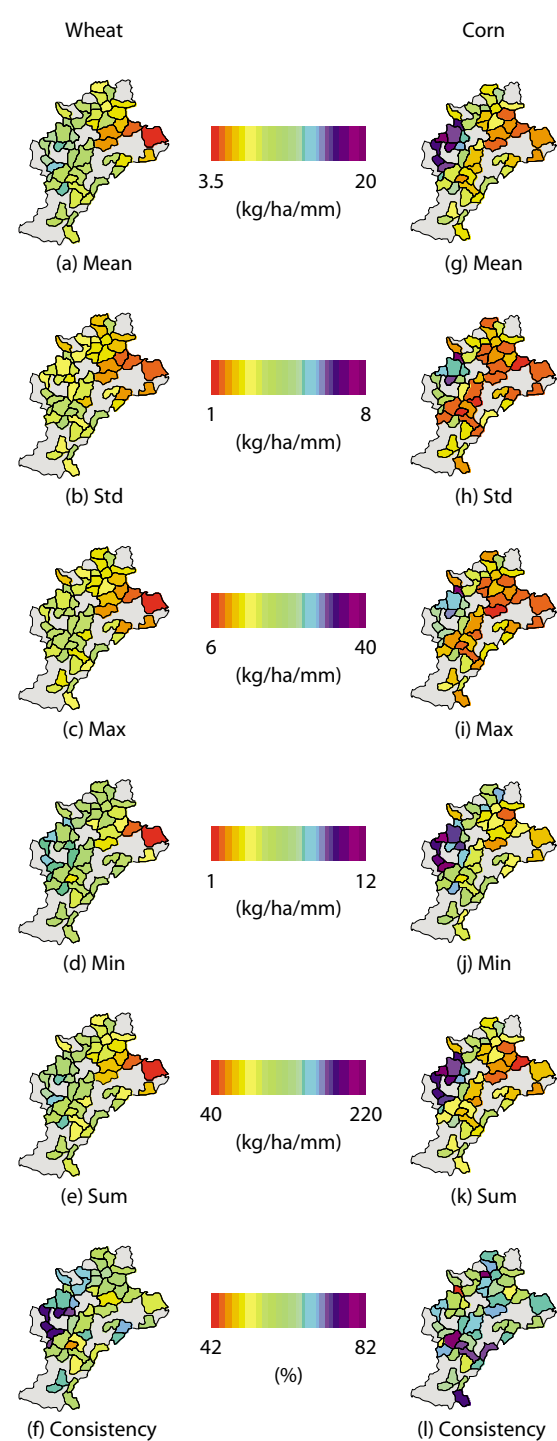


Figure 4. County summary statistics of agricultural water use efficiency for wheat (a–f) and corn (g–l) grown on the Hebei Plain study area, 1984–96. Max = maximum, Min = minimum, Std = standard deviation. Consistency is a measure of year-to-year consistency for each county.

1992, as both P_{wheat} and W_{o_wheat} were relatively low (Fig. 2). However, irrigation timing and amounts were probably optimised for crop growth; this resulted in average yields, so higher Ag WUEs were achieved in 1992 compared to 1991 (Fig. 2).

Figure 4 shows summary maps of Ag WUE for both wheat and corn. For wheat the maximum mean was 14.1 kg/ha/mm, while the minimum mean was 3.7 kg/ha/mm (Fig. 4a). Standard deviations ranged from 1.4 to 4.7 kg/ha/mm (Fig. 4b). The highest maximum was 21.5 kg/ha/mm and the lowest was 6.7 kg/ha/mm (Fig. 4c); the highest minimum was 8.2 kg/ha/mm and the lowest was 1.1 kg/ha/mm (Fig. 4d). Over the 11 years of valid data, the cumulative Ag WUE ranged from 40.3 to 154.8 kg/ha/mm (Fig. 4e). A measure of consistency (C) was developed as:

$$C = \sum_{i=1}^{11} \text{AgWUE}_{country} / 11 * \max \text{AgWUE}_{country}$$

where 11 is the number of valid years of data available. This scales the cumulative Ag WUE for each county by 11 times the maximum Ag WUE for each county and is expressed as a percentage. For wheat, this value ranges from 48 to 76% (Fig. 4f). Counties with a high mean Ag WUE (green to purple) (Fig. 4a) and a low consistency (red to yellow) (Fig. 4f) are those with the highest potential for improving Ag WUE management. A relatively low consistency might be due to variables such as frosts, pests or disease affecting crops. For example, in Figure 4f some of the counties with a low consistency are in a similar location; the reasons for the low consistency need to be better understood before any management action is instigated.

The relative value of Ag WUE consistency is an important measure, but the timing of the maximum Ag WUE used in the calculation must also be taken into account. Figure 5 shows time series plots of Ag WUE and WR for four representative counties (Fig. 1) for the wheat growing season. In Xinhe

county (Fig. 5a), the maximum wheat Ag WUE of more than 18 kg/ha/mm occurred in 1996. This was associated with relatively low county WR (Fig. 5e). However, in other years with relatively low county WR (1987, 1989, 1992 and 1993), Ag WUE did not exceed 14 kg/ha/mm.

One challenge for agricultural managers is to maintain the improvement recorded in 1996 for future dry years by optimising local management practices. For Xinhe County, the generally complementary nature of WR and Ag WUE can be seen by comparing Figures 5a and 5e: years that have a low WR usually have a high Ag WUE. Moving along the time series, improvements can be seen; for example, in 1984, 1985 and 1995, similar WRs were calculated (approximately 150 GL), yet in 1995 Ag WUE was more than 10 kg/ha/mm, whereas in 1984 and 1985 it was less than 3 kg/ha/mm (Fig. 5a). Agricultural practices have probably improved over these 10 years.

From 1984 until 1995, wheat Ag WUE in Heijian county (Fig. 5b) was approximately 6 kg/ha/mm. In 1996, when less than 400 GL was available to this county (Fig. 5f), Ag WUE doubled to 12 kg/ha/mm. However, in other dry years (1984, 1985, 1987, 1992 and 1993), county-level Ag WUE was less than 8 kg/ha/mm. Again, this probably illustrates a general improvement in agricultural practices.

The generally complementary relationship between WR and Ag WUE is seen for most years at Luancheng County. Since 1993, Luancheng County (Fig. 5c) has recorded Ag WUE values of about 18 kg/ha/mm, except in 1994 when there was a sharp decrease to about 11 kg/ha/mm, associated with a local WR maximum (Fig. 5g). However, in 1992 and 1993, which had similar WR values (Fig. 5g), there was not always a similar Ag WUE (Fig. 5c). Differences may be due to seasonal rainfall distribution and management practices such as the timing and amount of irrigation applied at different crop-growth stages (Zhang et al. 1999). Other

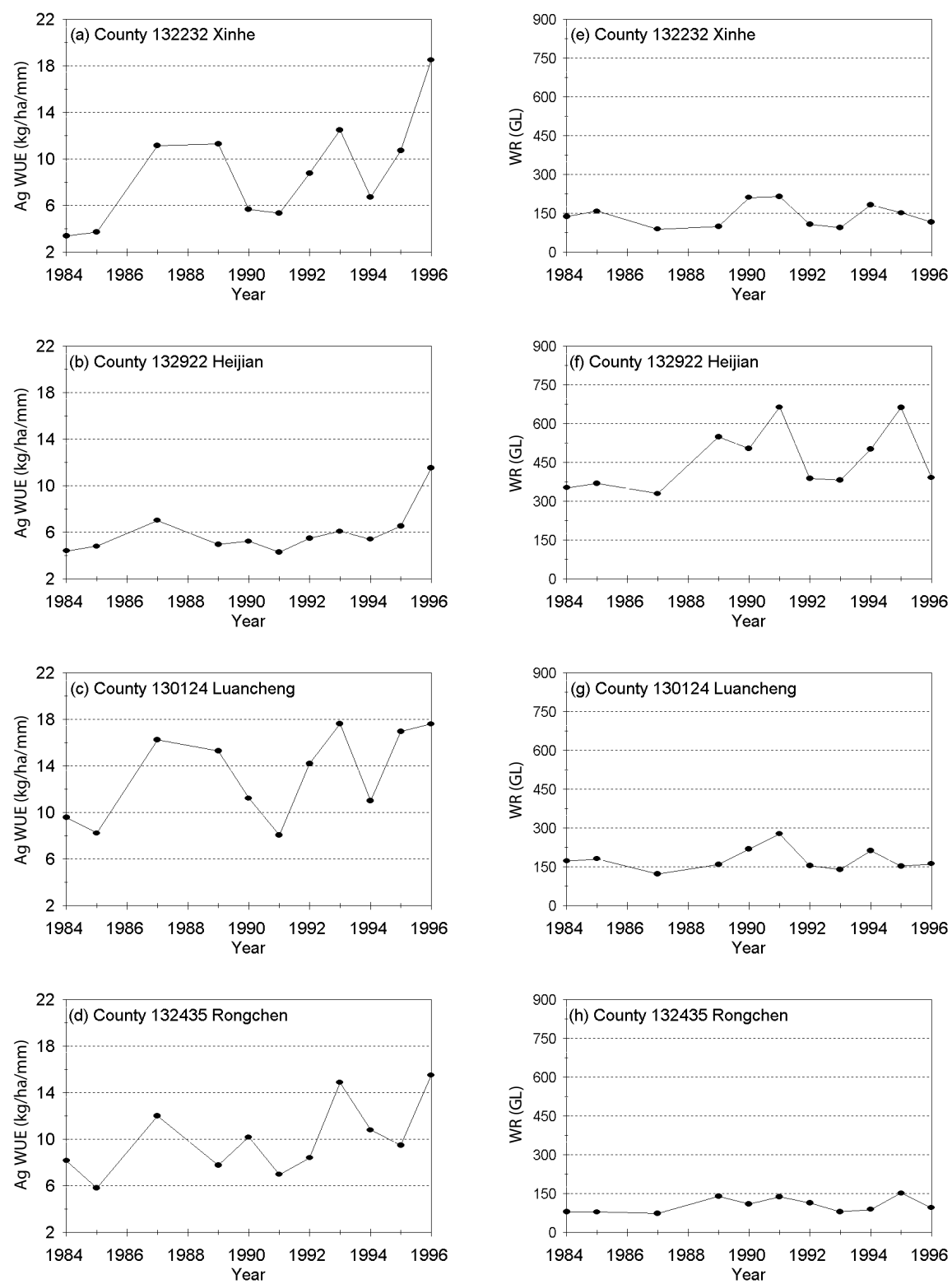


Figure 5. Time series plots for the wheat growing season in Xinhe, Heijian, Luancheng and Rongchen counties: agricultural water use efficiency (Ag WUE) (a–d) and corresponding water resources (WR) (e–h). The location of each county is shown in Figure 1.

constraints on grain yield include the incidence and severity of frosts, disease or pests. At the regional scale there are no figures for these factors, which impact on final yields. In Rongchen, there was a steady increase in Ag WUE (Fig. 5d), modified by the county WR figure (Fig. 5h). The question for local agricultural and water management agencies is whether management practices can be optimised consistently to decrease local variability.

For corn, the mean Ag WUE varied from 20.0 to 4.2 kg/ha/mm (Fig. 4g). Standard deviations ranged from 1.0 to 7.9 kg/ha/mm (Fig. 4h). The highest maximum was 39.0 kg/ha/mm and the lowest 6.3 kg/ha/mm (Fig. 4i); the highest minimum was 11.8 kg/ha/mm and the lowest 1.7 kg/ha/mm (Fig. 4j). Over the 11 years of valid data, the cumulative Ag WUE ranged from 46.4 to 219.5 kg/ha/mm (Fig. 4k). Fig. 4l illustrates that, for corn, the measure of consistency ranged from 43% to 82%. Counties with a high mean Ag WUE (green to purple) (Fig. 4g) and a low consistency (red to yellow) (Fig. 4l) are those with the highest potential for improved management of Ag WUE.

During the corn growing season, the estimates of Ag WUE and WR were generally complementary (Fig. 6). However, sometimes Ag WUE and WR are 'in phase'. For example, for Xinhe county in 1992, low WRs were available (Fig. 6e), a condition associated with low Ag WUE (Fig. 6a). In 1992, Xinhe and several surrounding counties suffered severe drought during the corn season and consequently produced low yields (see Figure 3 for details). In Heijian county, Ag WUE was estimated to be less than 8 kg/ha/mm for the time series (Fig. 6b), but in several years WR was above 600 GL (Fig. 6f). This suggests that there are opportunities for planting larger areas with summer crops. In Luancheng county in 1992 (Fig. 6c), there was a low rainfall during the corn season (Fig. 3), though it may have fallen at optimal times for summer crop growth, leading to high yields. This combination of factors resulted in an estimated Ag WUE of more than 25 kg/ha/mm. From 1993 to 1996, high

average yields were recorded (Fig. 3), while WR increased (Fig. 6g) due to above-average P_{corn} (Fig. 3); consequently Ag WUE for these years was estimated to be lower than the 1992 season. This suggests that when more water is available, its use is less efficient. In Rongchen county (Fig. 6d), the Ag WUE varied from 7 to 14 kg/ha/mm; again there was a general complementary relationship with WR (compare Figure 6d with 6h). There may be little scope to increase Ag WUE at the paddock level in counties like Luancheng; however, increasing county-level Ag WUE may be possible by either planting larger areas of crop or reducing the volume of water used for irrigation.

County total water resources

Figure 7 shows the time series of WR from 1984 to 1996 for both the wheat and corn seasons for each county. To better understand interactions with Ag WUE, both 1986 and 1988 were removed from any subsequent analysis of WR. For the 538 valid observations (49 counties over the 11 years), WR for wheat had a mean of 263.3 GL, with a standard deviation of 130.9 GL. The maximum and minimum wheat WR values were 856.7 and 47.5 GL, respectively. During the corn season the mean WR was 299.6 GL, with a standard deviation of 168.5 GL; the maximum and minimum were 1431.7 and 46.6 GL, respectively.

Table 5 shows the annual WR for both the wheat and corn growing seasons for the 49 counties, including the variability in total WR. For wheat, the maximum occurred in 1991 and can be associated with above-average summer rains in 1990 (Fig. 3), which extended into the 1991 wheat growing season (Fig. 2). For the corn season, the three wettest years were 1994, 1995 and 1996 (Table 5). WR is a function of county area, so variance in WR should be assessed mainly temporally, though counties of approximately equal areas may be loosely compared.

During the wheat season in 1991, many of the northeastern counties had near maximum WR

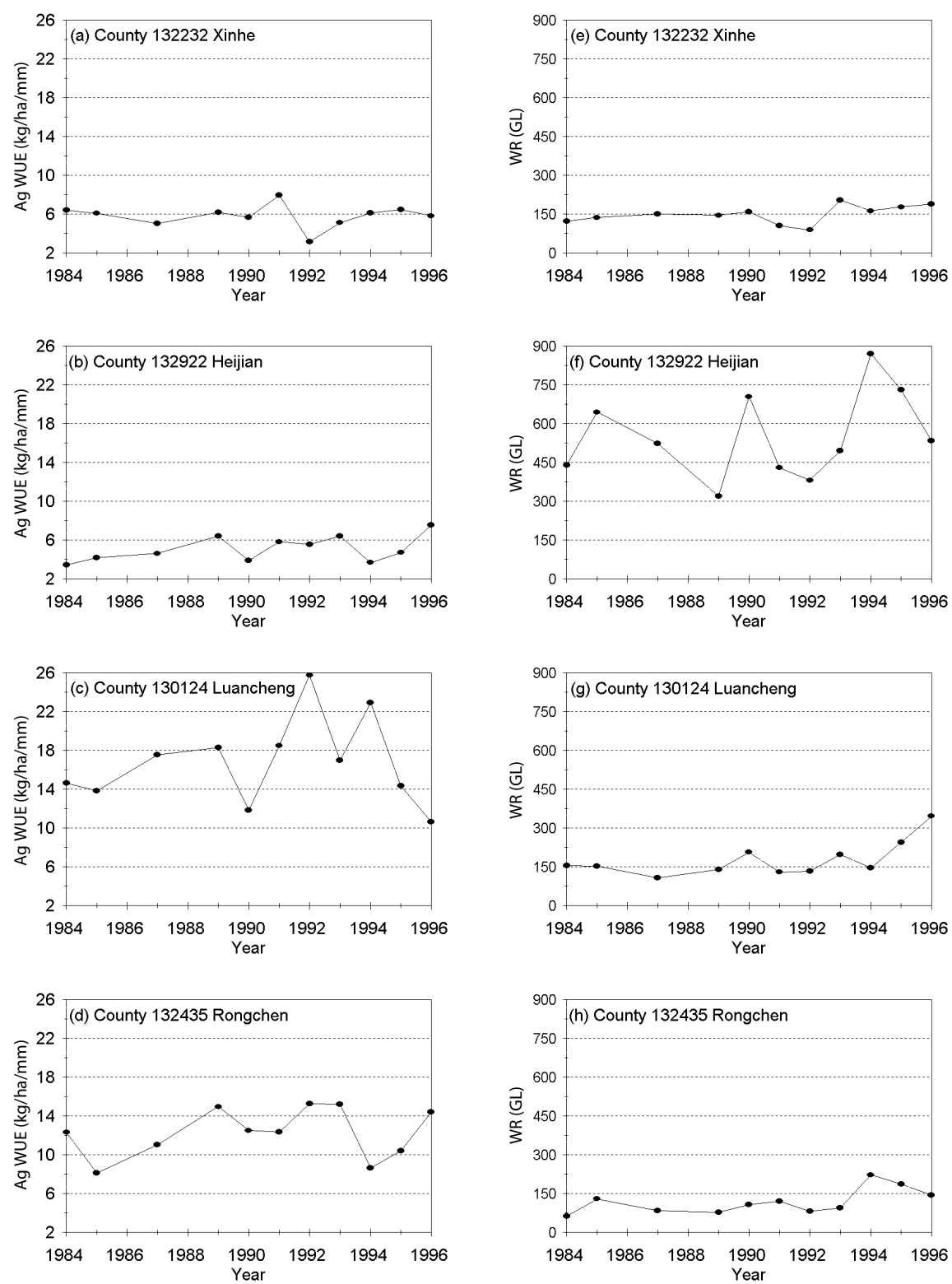


Figure 6. Time series plots for the corn growing season in Xinhe, Heijian, Luancheng and Rongchen counties: agricultural water use efficiency (Ag WUE) (a–d) and corresponding water resources (WR) (e–h). The location of each county is shown in Figure 1.

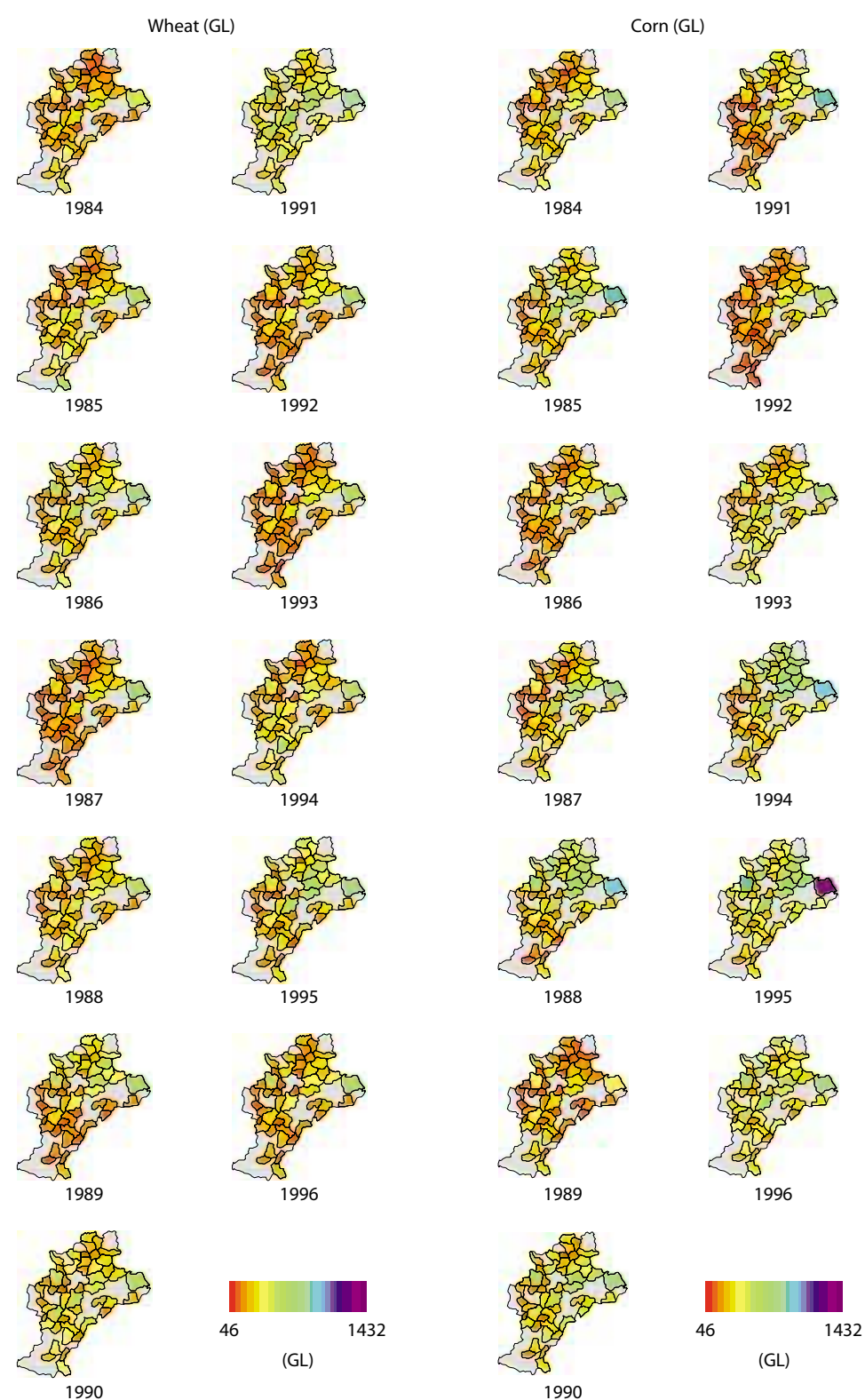


Figure 7. County total water resources for the counties of the Hebei province study area for the wheat and corn growing seasons, 1984–96. Counties of different sizes should not be compared, because water resources values are a function of county area.

(Fig. 7). This was associated with the high rainfall during the 1991 wheat growing season and a moderate 1991 W_0 , which is related to the preceding high P_{corn} . However, in 1991, I_{wheat} was relatively high (Fig. 2). Combining these water sources meant that the resulting WR was high, so a low Ag WUE was estimated during the 1991 wheat season. Two management actions might have been implemented to increase the county-level Ag WUE for the northeastern counties in 1991: a larger area could have been planted with wheat or less irrigation could have been applied. However, it should be noted that we do not know the timing of the irrigation events. Retrospective analysis of irrigation volumes is of some interest, but to actually decide to reduce the amount of irrigation applied during a growing season requires the ability to reliably predict future rainfall events for the entire growing season. Evans (1996) suggests it is not advisable to base such decisions on current short-term climate prediction models of precipitation. A decision to plant larger areas of

crop (or to increase the planting density of areas currently planted) also depends on economic factors (Yang 1998; Yang and Li 2000; Anderson and Peng 1998); political factors (Allan 1999; Frankenstein 1995); environmental factors (e.g. reducing applications of fertilisers or enhancing river flows); and having the capacity to store and process an anticipated increase in grain production.

Figure 8 shows summary maps for both wheat and corn WRs. For wheat, the maximum mean was 660.5 GL, while the minimum mean was 75.1 GL (Fig. 8a). The standard deviations ranged from 18.7 to 119.8 GL (Fig. 8b). Figure 8c indicates that the highest maximum was 856.7 GL and the lowest 108.9 GL, while the highest minimum was 507.0 GL and the lowest 47.5 GL (Fig. 8d). Over the 11 years of valid data, the cumulative WR ranged from 826.1 to 9423.5 GL (Fig. 8e), with a measure of consistency of 49–77% (Fig. 8f).

For corn WR, the maximum mean was 830.0 GL and the minimum mean was 74.2 GL (Fig. 8g). Standard deviations ranged from 23.0 to 240.2 GL (Fig. 8h). The highest and lowest maxima were 1431.7 GL and 121.4 GL, respectively (Fig. 8i) while the highest and lowest minima were 423.5 GL 46.6 GL, respectively (Fig. 8j). Over the 11 years of valid data, the cumulative WR ranged from 815.9 to 9130.5 GL (Fig. 8k). For corn, the measure of consistency ranged from 51 to 77% (Fig. 8l). Several counties located in the northwestern portion of the study area had low consistency values for WR, associated with high maximum WR recorded in both 1988 and 1994 (Fig. 7), a direct result of the high P_{corn} during these two corn growing seasons (Fig. 3).

Normalisation and cross-plotting Ag WUE and WR

Relationships between Ag WUE and WR were generally complementary (Fig. 5 and 6), but there were differences, as discussed above. The relationships were normalised as follows using the county mean and county standard deviation for

Table 5. Annual water resources mean and standard deviations for all 49 counties for the wheat and corn growing seasons (GL).

Year ^a	Wheat		Corn	
	Mean	SD	Mean	SD
1984	225	95	250	130
1985	254	113	307	162
1987	198	105	265	136
1989	275	139	210	88
1990	307	119	334	151
1991	375	154	251	149
1992	229	106	198	103
1993	200	96	304	129
1994	275	118	393	218
1995	310	155	421	223
1996	246	110	366	142

SD = standard deviation
^a There are no data for 1986 and 1988

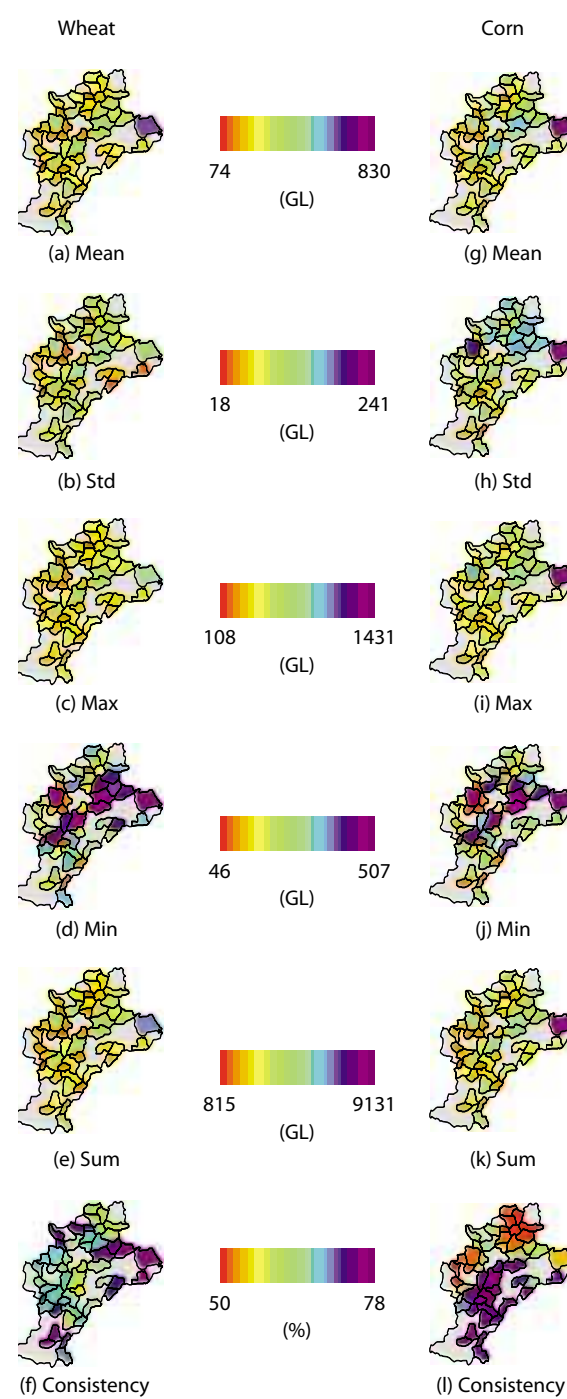


Figure 8. County summary statistics of total water resources for the counties of the Hebei Province study area for wheat (a–f) and corn (g–l). Max = maximum, Min = minimum, Std = standard deviation.

each of the 49 counties (denoted, respectively, NAg WUE and NWR):

$$\text{NAgWUE} = \frac{\text{AgWUE}_{\text{county}} - \overline{\text{AgWUE}_{11 \text{ years, county}}}}{\text{Std AgWUE}_{11 \text{ years, county}}}$$

and

$$\text{NWR} = \frac{\text{WR}_{\text{county}} - \overline{\text{WR}_{11 \text{ years, county}}}}{\text{Std WR}_{11 \text{ years, county}}}$$

Differences in county size inherent in the WR calculation were normalised. For both wheat and corn, data from 1986 and 1988 were excluded from this analysis. NAg WUE and NWR have been cross-plotted for the wheat and corn growing periods (see Fig. 9a and 9b, respectively). For wheat, the lowest NWR is -1.75 (Fig. 9a), whereas for corn it is -2.5 (Fig. 9b); this indicates that there is less variability during the wheat season than the corn season.

Figure 9c provides an indicative schematic explanation for the data plots. Timing of rainfall events and management practices, including the timing and amount of irrigation applied (Zhang et al. 1999), and many other variables (for example, the incidence and severity of frosts, disease or pests) may impact on final yields, so the schematic explanations are indicative only. Observations with both a near-zero NWR and NAg WUE are regarded as ‘near normal’. Counties with both negative NWR and NAg WUE have experienced ‘poor practice and dry’ conditions, whereas a negative NWR and positive NAg WUE implies ‘good practice and dry’ conditions. When county NWR is above average, NAg WUE tends to become negative, suggesting that with more than average water available the water was used inefficiently. This is because WUE becomes less critical in obtaining high yields.

For both wheat and corn, there were few cases when both NWR and NAg WUE were greater than 1.0. The quadrant with both positive NWR and NAg WUE has been deemed ‘good practice and wet’ conditions, whereas when NWR was positive and NAg WUE negative the quadrant was denoted

‘poor practice and wet’ conditions. The NAg WUE and NWR data plots have been stratified and colour coded (Fig. 9d). The stratified cross-plots were then mapped over the time series for both the wheat and corn growing seasons (Fig. 10).

In the wheat growing season of 1984 there was severe drought in the northeast of the study area (Fig. 10); several counties recorded below-average NAg WUE and NWR (yellow). For these counties, it seems likely that the irrigation delivery system did not supply adequate water to the entire county or over the entire growing season. This may also be the reason why one county was located in this stratum during the 1994 wheat season. In 1984, five other northern counties received below-average NWR but recorded near-average NAg WUE (orange). For the 1984 wheat season, many counties had near-average NWR, but some had low NAg WUE (yellow/green) compared to others that recorded near-average NAg WUE (beige). This pattern also existed in the 1985 wheat season. For the remainder of the wheat time series, only isolated counties fell into the strata coded yellow or yellow/green, probably indicating an improvement of agricultural management practices.

During dry years, irrigation was applied in adequate amounts, at near optimal times, to produce yields that suggest the water resources were used efficiently. For example, in 1987 many counties experienced below-average NWR, yet recorded near-average NAg WUE (orange) or above-average NAg WUE (red), indicating good management practices. For the wheat season of 1991, and to a lesser extent in 1989, several counties were located in the low NAg WUE and high NWR strata (green). These years were extremely wet, and opportunities may have existed to plant a larger area with wheat or to irrigate less. Given that when water is plentiful it is usually used less efficiently than when it is scarce, and that it is difficult to predict wet years, it may be difficult to implement these management options. The 1995 wheat growing period was extremely wet, especially in the north; however most counties recorded near-average NAg

WUE (cyan), while two eastern counties recorded above-average NAg WUE (blue). For all northern counties, little irrigation was applied in 1995 (Fig. 2). In these two eastern counties (shaded blue for wheat in 1995 in Figure 10), poor quality groundwater (Zhang et al. 1999), due to the proximity to the Bohai Sea (see Figure 3 of the Overview), would usually be used to irrigate wheat. However, for these two eastern counties in 1995, there was above-average NAg WUE because little, poor-quality groundwater was applied. In 1995 and 1996, many counties recorded above-average NAg WUE and near-average NWR (pink), indicating that good agricultural management was practised during the wheat growing season.

During the corn season, it appears that management practices have improved since the 1990 season, as few counties in particular years have recorded below-average NAg WUE with near-average NWR (yellow/green). In 1989 and 1992, one county each year recorded below-average NAg WUE and NWR (yellow), suggesting that irrigation scheduling (both in timing and amount) may not have been managed optimally. In 1984, 1989, 1991 and 1992, many counties experienced below-average NWR, yet recorded near-average NAg WUE (orange) or above-average NAg WUE (red), indicating good management practice. As with wheat, when above-average water resources were available they were usually used less efficiently, resulting in many counties falling within the low NAg WUE and high NWR strata (green). In the north, corn management practices for wet years have improved, with several counties falling within the green strata in 1994 moving into the cyan strata (near-average NAg WUE and high NWR) in 1995. Only in 1995 and 1996 did any counties record both above-average NAg WUE and NWR (blue). This again indicates that improved management practices have been adopted during wet corn growing seasons. In 1996, most eastern counties received near-average NWR (beige and pink), yet many recorded above-average NAg WUE (pink). This indicates the adoption of improved management practices during these corn seasons.

Conclusions

We have developed a spatial information system that allows water-saving agricultural practices to be assessed. The system is based on the spatial and temporal constructs of the available regional databases, which partly determined our 'input-output' Ag WUE approach. For the wheat growing season, the average Ag WUE for the 49 counties was 7.0 kg/ha/mm in 1984, whereas in 1996 it had risen to 14.3 kg/ha/mm. It is most likely that these improvements in Ag WUE for wheat are the result of farmers adopting water-saving agricultural practices. For the corn growing season, Ag WUE increased from 9.0 kg/ha/mm in 1984 to 10.1 kg/ha/mm in 1996, although values of more than 11.5 kg/

ha/mm were obtained in 1991 and 1992. For both wheat and corn, we have identified counties that have a relatively high mean Ag WUE and yet are somewhat inconsistent from year to year. These counties have the highest potential to achieve improvements in Ag WUE.

The spatial mapping of the time series data for the 'NAg WUE and NWR' stratified data space also showed where recent improvements in Ag WUE had been achieved. For some counties in wet years, there may be opportunities for planting larger areas of crop and thereby increasing county-level Ag WUE. For the study site and the time series of data available, recently introduced water-saving agricultural practices on the NCP seem to have

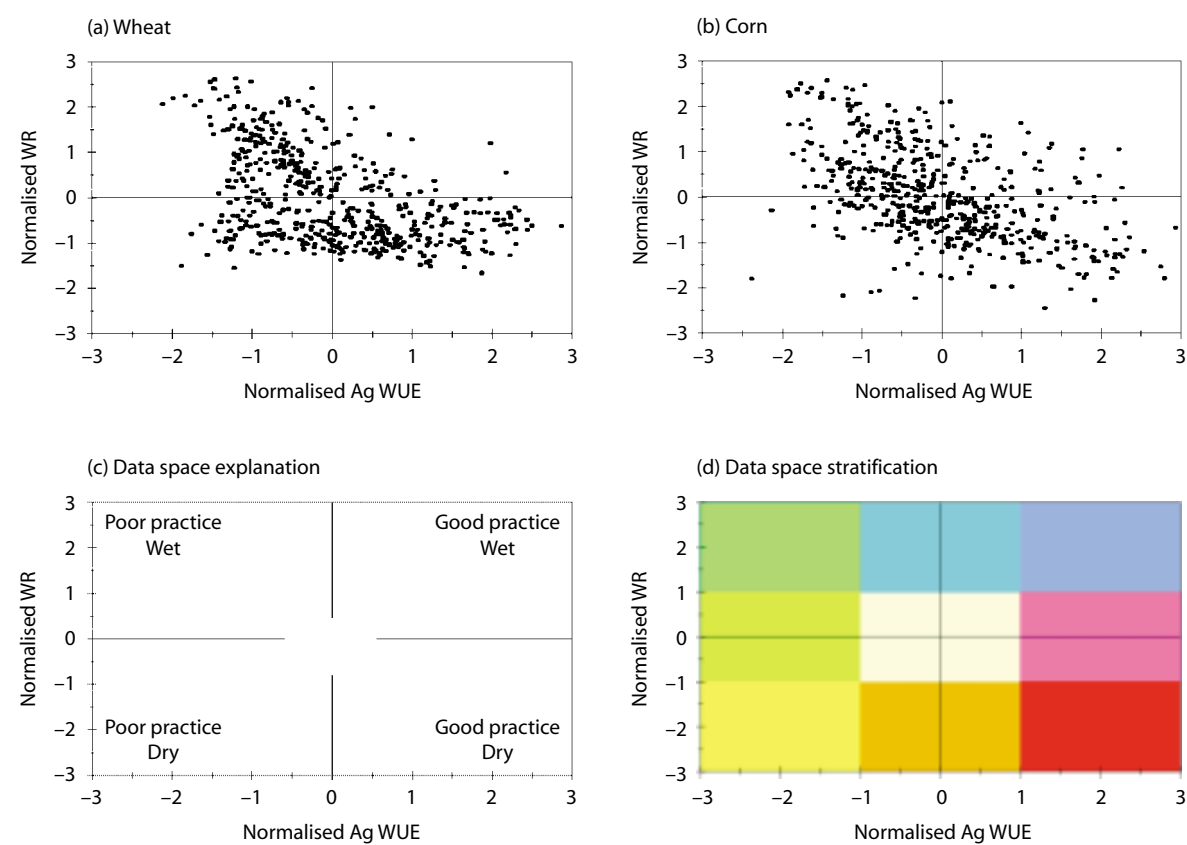


Figure 9. Cross-plots of normalised agricultural water use efficiency (Ag WUE) and normalised water resources (WR) for the wheat and corn growing seasons. Figure shows (a) wheat; (b) corn; (c) a schematic explaining the data space; and (d) the stratification and colour codes used in Figure 10. Starting at the bottom-right corner of (d) and progressing clockwise, the colours are described as: red, orange, yellow, yellow/green, green, cyan, blue, and pink, with beige in the centre.

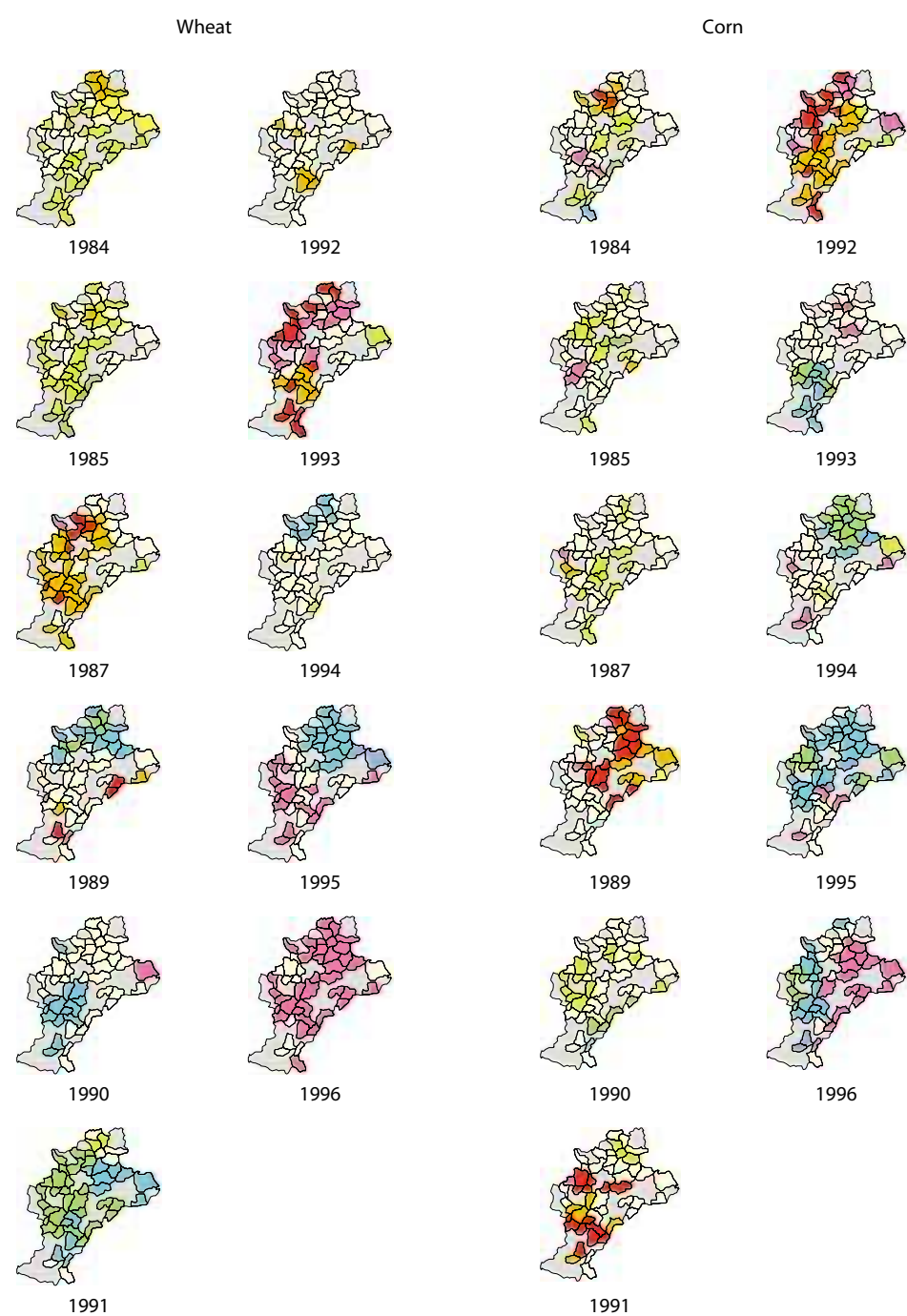


Figure 10. Time series of the cross-plotted stratified normalised agricultural water use efficiency and normalised water resources data space. Figure 9 shows the basis of the colour selection.

resulted in an increase in Ag WUE. This increase may have occurred, in part, due to the widespread application of fertilisers. In this intensively managed agricultural region, it is important to assess the impact of fertiliser on environmental

pollution of both land and water (including surface and ground) resources. Also, if regional groundwater levels are available at appropriate spatial and temporal resolutions, the effects of various agricultural practices (including recent

improvements made to Ag WUE) on the sustainability of regional groundwater can be assessed.

The methods developed here can be used to monitor regional Ag WUE from 1997 onwards and could eventually be extended to the entire NCP, all of China, or other countries. For all geographic regions, spatial and temporal trend analysis of Ag WUE (and other variables) obviously needs to be based on data. It is difficult to infer the causal relationships between Ag WUE and detailed agricultural practices for large areas over long periods, because there is currently a mismatch between available and required data. The collection, quality and availability of such data are major issues facing regional agricultural operational and research organisations. These issues need to be addressed by organisations involved in managing agricultural, water and land resources.

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References

Allan, T. 1999. Productive efficiency and allocative efficiency: why better water management may not solve the problem. *Agricultural Water Management*, 40, 71–75.

Anderson, K. and Peng, C.Y. 1998. Feeding and fueling China in the 21st Century. *World Development*, 26, 1413–1429.

Armstrong, R.D., McCosker, K., Millar, G., Kuskopf, B., Johnson, S., Walsh, K., Probert, M.E. and Standley, J. 1999. Legume and opportunity cropping systems in central Queensland. 2. Effect of legumes on following crops. *Australian Journal of Agricultural Research*, 50, 925–936.

Beale, C.V., Morison, J.I.L. and Long, S.P. 1999. Water use efficiency of C4 perennial grasses in a temperate climate. *Agricultural and Forest Meteorology*, 96, 103–115.

Brown, L.R. and Halweil, B. 1998. China's water shortage could shake world food security. *World Watch*, 11, 10–21.

Cannell, M.G.R., Mobbs, D.C. and Lawson, G.J. 1998. Complementarity of light and water use in tropical agroforests. II. Modelled theoretical tree production and potential crop yield in arid to humid climates. *Forest Ecology and Management*, 102, 275–282.

Cao, M., Ma, S. and Han, C. 1995. Potential productivity and human carrying capacity of an agro-ecosystem: an analysis of food production potential of China. *Agricultural Systems*, 47, 387–414.

Evans, T.E. 1996. The effects of changes in the world hydrological cycle on availability of water resources. In: Bazzaz, F.A. and Sombroek, W.G., eds, *Global Change and Agricultural Production*. Chichester, Wiley, pp. 15–48.

Frankenstein, J. 1995. The Beijing Rules: contradictions, ambiguities and controls. *Long Range Planning*, 28, 70–80.

French, R.J. and Schultz, J.E. 1984a. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research*, 35, 743–64.

French, R.J. and Schultz, J.E. 1984b. Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research*, 35, 765–775.

Garabet, S., Ryan, J. and Wood, M. 1998. Nitrogen and water effects on wheat yield in a Mediterranean-type climate. I. Growth, water-use and nitrogen accumulation. *Field Crops Research*, 57, 309–318.

Gong, J. and Lin, H. 2000. Sustainable development for agricultural region in China: case studies. *Forest Ecology and Management*, 128, 27–38.

Hill, R.D. 1997. Questions for Chinese agriculture. *Land Use Policy*, 14, 335–336.

Hu, W. 1998. Issues for sustaining Chinese agriculture. *Land Use Policy*, 15, 167–170.

Hunsaker, D.J., Kimball, B.A., Pinter, P.J.J., Wall, G.W., LaMorte, R.L., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D. and Brooks, T.J. 2000. CO₂ enrichment and soil nitrogen effects on wheat evapotranspiration and water use efficiency. *Agricultural and Forest Meteorology*, 104, 85–105.

Hutchinson, M.F. 1999. ANUSPLIN Version 4.0 User Guide. Canberra, The Australian National University.

Jin, M., Zhang, R., Sun, L. and Gao, Y. 1999. Temporal and spatial soil water management: a case study in the Heilonggang region, PR China. *Agricultural Water Management*, 42, 173–187.

Karrou, M. 1998. Observations on effect of seeding pattern on water-use efficiency of durum wheat in semi-arid areas of Morocco. *Field Crops Research*, 59, 175–179.

Li, F., Zhao, S. and Geballe, G.T. 2000. Water use patterns and agronomic performance for some cropping systems with and without fallow crops in a semi-arid environment of northwest China. *Agriculture, Ecosystems and Environment*, 79, 129–142.

Li, J., Liu, X., Zhou, W., Sun, J., Tong, Y., Liu, W., Li, Z., Wang, P. and Yao, S. 1995. Technique of wheat breeding for efficiently utilizing soil nutrient elements. *Science in China*, 38, 1313–1320.

Lin, J.Y. 1997. Institutional reforms and dynamics of agricultural growth in China. *Food Policy*, 22, 201–212.

- Liu, Y., Teixeira, J.L., Zhang, H.J. and Pereira, L.S. 1998. Model validation and crop coefficients for irrigation scheduling in the North China Plain. *Agricultural Water Management*, 36, 233–246.
- Loaiciga, H.A., Valdes, J.B., Vogel, R., Garvey, J. and Schwarz, H. 1996. Global warming and the hydrologic cycle. *Journal of Hydrology*, 174, 83–127.
- McVicar, T.R., Zhang, G., Bradford, A.S., Wang, H., Dawes, W.R., Zhang, L. and Lingtao, L. 2000. Developing a spatial information system to monitor regional agricultural water use efficiency for Hebei Province on the North China Plain. *Canberra, CSIRO Land and Water*, 55.
- Muldavin, J. 1997. The limits of market triumphalism in rural China. *Geoforum*, 28, 289–312.
- O’Leary, G.J., Connor, D.J. and White, D.H. 1985. A simulation model of the development, growth and yield of the wheat crop. *Agricultural Systems*, 17, 1–26.
- Oweis, T., Zhang, H. and Pala, M. 2000. Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. *Agronomy Journal*, 92, 231–238.
- Regan, K.L., Siddique, K.H.M., Tennant, D. and Abrecht, D.G. 1997. Grain yield and water use efficiency of early maturing wheat in low rainfall Mediterranean environments. *Australian Journal of Agriculture Research*, 48, 595–603.
- Ritchie, J.T. 1983. Efficient water use in crop production: generality of relations between biomass production and evapotranspiration. In: Taylor, H.M., Jordan, W.R. and Sinclair, T.R., eds, *Limitations to Efficient Water Use in Crop Production*. Madison, American Society of Agronomy, 29–44.
- Rockström, J., Jansson, P.-E. and Barron, J. 1998. Seasonal rainfall partitioning under runoff and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modelling. *Journal of Hydrology*, 210, 68–92.
- Rosegrant, M.W. and Ringler, C. 2000. Impact on food security and rural development of transferring water out of agriculture. *Water Policy*, 1, 567–586.
- Rozelle, S., Huang, J. and Zhang, L. 1997. Poverty, population and environmental degradation in China. *Food Policy*, 22, 229–251.
- Sinclair, T.R., Tanner, C.B. and Bennett, J.M. 1984. Water-use efficiency in crop production. *BioScience*, 34, 36–40.
- Smit, B. and Yunlong, C. 1996. Climate change and agriculture in China. *Global Environmental Change*, 6, 205–214.
- Stanhill, G. 1986. Water use efficiency. *Advances in Agronomy*, 39, 53–85.
- Stone, L.R., Schlegel, A.J., Gwin Jr., R.E. and Khan, A.H. 1996. Response of corn, grain sorghum, and sunflower to irrigation in the High Plains of Kansas. *Agricultural Water Management*, 30, 251–259.
- Tanner, C.B. and Sinclair, T.R. 1983. Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.R. and Sinclair, T.R., eds, *Limitations to Efficient Water Use in Crop Production*. Madison, American Society of Agronomy, 1–28.
- Thomas, A. 2000. Climatic changes in yield index and soil water deficit trends in China. *Agricultural and Forest Meteorology*, 102, 71–81.
- Tolk, J.A., Howell, T.A. and Evett, S.R. 1999. Effect of mulch, irrigation, and soil type on water use and yield of maize. *Soil and Tillage Research*, 50, 137–147.
- Tuong, T.P. and Bhuiyan, S.I. 1999. Increasing water-use efficiency in rice production: farm-level perspectives. *Agricultural Water Management*, 40, 117–122.
- Turner, N.C. 1986. Crop water deficits: a decade of progress. *Advances in Agronomy*, 39, 1–51.
- Turner, N.C. 1997. Further progress in crop water relations. *Advances in Agronomy*, 58, 293–338.
- Wang, H., Liu, C. and Zhang, L. In press. Water-saving agriculture in China: An overview. *Advances in Agronomy*.
- Wang, H., Zhang, L., Dawes, W.R. and Liu, C. 2001. Improving water use efficiency of irrigated crops in the North China Plain—measurements and modelling. *Agricultural Water Management*, 48, 151–167.
- Wei, H. 1997. Household land tenure reform in China: its impact on farming land use and agro-environment. *Land Use Policy*, 14, 175–186.
- Xing, Q.Z. 1997. Urban land reform in China. *Land Use Policy*, 14, 187–199.
- Yang, H. 1998. Trends in China’s regional grain production and their implications. *Agricultural Economics*, 19, 309–325.
- Yang, H. and Li, X. 2000. Cultivated land and food supply in China. *Land Use Policy*, 17, 73–88.
- Yong, L. and Jiabao, Z. 1999. Agricultural diffuse pollution from fertilisers and pesticides in China. *Water Science and Technology*, 39, 25–32.
- Yuan, X., Wang, H., Zhang, X. and You, M. 1992. The relationship between winter wheat yield and water consumption. In: Xie, X. and Yu, H., eds, *The Study of Relationship Between Crop and Water*. Beijing, Beijing Science and Technology Press, 10–18.
- Zhang, C. 1999. Problems on water saving agriculture in China: background issues. In: *Problems on Water Saving Agriculture in China*. Beijing, China Hydrology and Hydroelectric Press, 5–10.
- Zhang, H. and Oweis, T. 1999. Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. *Agricultural Water Management*, 38, 195–211.
- Zhang, H., Wang, X., You, M. and Liu, C. 1999. Water-yield relations and water-use efficiency of winter wheat in the North China Plain. *Irrigation Science*, 19, 37–45.
- Zhang, J., Sui, X., Li, B., Su, B., Li, J. and Zhou, D. 1998. An improved water-use efficiency for winter wheat grown under reduced irrigation. *Field Crops Research*, 59, 91–98.
- Zoebl, D. 2000. Patterns of input-output relations in agro-ecosystems. *Agriculture, Ecosystems and Environment*, 79, 233–244.

19 A ‘Calculate then Interpolate’ Approach to Monitoring Regional Moisture Availability

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Abstract

This chapter describes a method to estimate moisture availability in the 1.1 million km² Murray–Darling Basin (MDB) in southeast Australia. Remotely sensed data from the advanced very high resolution radiometer (AVHRR) are combined with meteorological data to estimate the normalised difference temperature index (NDTI). The NDTI provides a measure of moisture availability, the ratio of actual to potential evapotranspiration. Eighty-five per cent of variation in the modelled NDTI could be explained by surface temperature minus air temperature, per cent vegetation cover and net radiation. These three covariates can be used across the network of meteorological stations to calculate NDTI images, which map changes in moisture availability across the MDB. The method uses a ‘calculate then interpolate’ (CI) approach: the per-pixel variation present in the AVHRR data is used as the backbone for the spatial interpolation. Using the spatially dense AVHRR-based covariates in a CI approach avoids errors that occur between measurement points when interpolating variables for regional hydrological modelling, most significantly the spatial pattern of rainfall. The NDTI provides a link into regional water balance modelling that does not require spatial interpolation of daily rainfall. Assessing spatial and temporal interactions between the NDTI and the normalised difference vegetation index (NDVI) provides useful information about regional hydroecological processes, including agricultural management, within the context of Australia’s highly variable climate and sparse network of meteorological stations.

本文估算了澳大利亚东南部默里达令盆地（MDB）一百一十多万平方公里土地的可利用水分。标准差值温度指数（NDTI）系由气象台站资料和 AVHRR 遥感数据运算而来，用以计算有效水分，即水分蒸发蒸腾实际总量与潜在总量的比例。用地表温度和空气温度的差值、植被覆盖度和净辐射三个变量，可以较好地解释数值变动（决定系数 $r^2=85\%$ ）。通过气象网络各台站的这三种数据，可以计算得到 NDTI 图象，显示 MDB 可利用水分的变化情况。该方法计算后再插值（CI），以逐像元变化的 AVHRR 数据为主干，作

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空间插值运算。因为在 AVHRR 图像上, 变量的空间分布稠密, 使用 CI 法, 可以避免区域水文模型变量插值测点之间的误差, 作降雨空间分布插值时尤其明显。由于澳大利亚的气候多变, 气象台站分布稀疏, 评估 NDTI 和 NDVI (标准差值植被指数) 间的时空相互作用, 可以提供包括农业活动在内的区域性水文-生态过程的有用信息。

HYDROLOGICAL and plant growth models are often developed at points. One way of extending the models to regions is to interpolate the relevant data and then perform calculations on the interpolated measurements. For example, Cole et al. (1993), Kittel et al. (1995), Carter et al. (1996), Nalder and Wein (1998) and Thornton et al. (1997) interpolated the input parameters and driving variables, and then calculated the values at each location. The interpolation can be a daunting task, depending on the complexity of the model, the spatial and temporal resolution and the extent of the modelling. Chapter 16 discusses the idea of 'data construct'. Another way of extending the models to regions is to use some remotely sensed variables with interpolated meteorological variables and then perform the calculations. Moran et al. (1996), Pierce et al. (1993) and Zhang et al. (1995) have used this approach. Raupach et al. (1997) used output from a general circulation model (GCM) as input to a coupled carbon, water and energy flux model. In this approach the GCM is viewed as an 'interpolator' of the required input meteorological variables for the spatially distributed process model. Prince et al. (1998) use high frequency advanced very high resolution radiometer (AVHRR) data to provide estimates of some of the variables needed for a regional plant growth model, which is run at every point. The approach used in all of these methods can be summarised as 'interpolate then calculate' (IC).

A less frequently used approach is to 'calculate then interpolate' (CI). Stein et al. (1991) first introduced

CI procedures to simulate the moisture deficit for a 404-hectare (ha) area in the Netherlands. They used 399 observations in the modelling framework, where seven procedures (four CI and three IC) were performed. Subsequently, the results for each of the seven were compared with another 100 observations, and a mean squared error (MSE) for each was calculated. Overall, the CI procedures provided lower MSE results than the IC procedures, which led Stein et al. (1991) to state that 'in short, CI procedures are to be preferred over IC procedures'. Bosma et al. (1994) simulated the three-dimensional flow of a heavy metal contaminant and used both IC and CI methods, using ordinary point kriging, to predict a parameter for a 20 m² field. They analysed the influence of sample size and concluded that, for the smallest samples, CI procedures performed better than IC procedures. These previous papers provide support for the use of CI in comparison to IC.

Our study integrated data types with very different spatial and temporal scales. AVHRR data are spatially dense, with an at-nadir 1.1 km² resolution, and are recorded over large areas in a matter of seconds, at a specific time, for specific wavelengths. Remotely sensed data are therefore a 'census' at a particular spatial scale, recorded at a specific time. Depending on the amount of cloud coverage and the repeat characteristics of the satellite, optical remotely sensed data may be available only weekly or monthly. Meteorological data are recorded sparsely, with the points often separated by tens to hundreds of kilometres. The variables measured at

these points represent a certain area. However, the exact area being represented by a given point measurement is unknown because the spatial autocorrelation is unknown. Meteorological data from standard long-term, large-area surface networks are usually daily integrals (e.g. rainfall (P) and wind run (U)) or daily extremes (e.g. maximum (T_x) and minimum (T_n) air temperatures) acquired regularly over decades. Thus, remotely sensed data are spatially dense but temporally sparse, while meteorological data are spatially sparse but temporally dense. One aim of our research was to combine the high temporal density of meteorological data with the high spatial density of remotely sensed data. The inherent spatial density of remotely sensed data may be compromised by the IC approach. As a result, geographic information system (GIS) boundaries may lead to artefacts in the final modelled images.

We used covariates derived mainly from spatially dense AVHRR data to spatially interpolate the normalised difference temperature index (NDTI). The approach is very similar to using a digital elevation model (DEM) as a covariate to interpolate surfaces of air temperature. Various numerical approaches can be used to spatially interpolate point data (Lam 1983); two of the most popular are splines and kriging. Several recent papers (e.g. Dubrule 1983; Dubrule 1984; Hutchinson 1993; Hutchinson and Gessler 1994; Laslett 1994; Borga and Vizzaccaro 1997) have compared the outputs from splines and kriging and found little difference between the two in most circumstances, provided the interpolation parameters were selected carefully. Incorporating regular gridded data, usually a DEM, but in this case AVHRR-based variables, as a covariate can be performed routinely using ANUSPLIN (Hutchinson 1997), a commercially available software package. Any spline or kriging package that can utilise covariates can be used to spatially interpolate NDTI.

The Normalised Difference Temperature Index

Jackson et al. (1977) developed the following empirical model to estimate daily actual evapotranspiration (λE_{a_DAY}):

$$\lambda E_{a_DAY} - R_{n_DAY} = A - B(T_s - T_a)$$

where R_{n_DAY} is the daily net radiation in watts per square metre (W/m^2), T_s is the surface temperature (K), T_a is the air temperature (K), and A and B are empirical coefficients. Seguin et al. (1982a, 1982b) extended this approach. Lagouarde (1991) described how the approach could be implemented and noted that the effect of changes in surface cover type and amount (especially roughness length) on the coefficient B were not addressed by the model. Courault et al. (1996) extended the work and provided alternative parameterisations for B . In principle, A and B should be consistent over areas with similar land cover structure.

The crop water stress index (CWSI) was originally developed at the agricultural field and daily time scale (Jackson et al. 1981). AVHRR-based estimates of actual evapotranspiration (λE_{a_AVHRR}) to λE_{a_DAY} are usually related using the approximation of Jackson et al. (1983), which has been extended by Xie (1991). Both are in the context of agricultural field-scale experiments.

There is an alternative to using spatial variance in remotely sensed data to map λE_{a_DAY} . T_s can be linked with meteorological variables if the meteorological data have the same temporal resolution as the remotely sensed data. High temporal resolution (e.g. every minute) meteorological data usually require intensive field campaigns for small, well-instrumented catchments. However, McVicar and Jupp (1999a) have recently shown that meteorological variables at the time of remotely sensed data acquisition can be adequately estimated from daily meteorological data for use with a resistance energy balance model

(REBM). This allows the development of a ‘dual’ approach to the well-known CWSI. Consequently, large regions in an operational framework can be monitored to derive a spatially varying index of moisture availability (m_a , the ratio of actual evapotranspiration to potential evapotranspiration (λE_p)) from daytime T_s . The development of the NDTI undertakes this dual approach. The NDTI is defined as:

$$NDTI = \frac{(T_\infty - T_s)}{(T_\infty - T_0)} \quad (1)$$

The two bounding temperatures, T_0 and T_∞ , are derived by inverting an REBM. T_0 is an REBM inverted surface temperature when r_s (the composite surface resistance) = 0 s/m — that is, when it is assumed $\lambda E_a = \lambda E_p$. T_∞ is an REBM inverted surface temperature when $r_s = \infty$ s/m — that is, when it is assumed $\lambda E_a = 0$ W/m². The methods and assumptions used here are discussed fully in Jupp et al. (1998). In our study, daytime T_s is derived from the AVHRR sensor; however, it could be derived from any other space, or airborne, thermal sensor. If the REBM and the meteorological data — T_a vapour pressure (e_a), shortwave radiation (R_s) and wind speed (u) — estimated at the time of AVHRR data acquisition, are well defined, a time series of T_s should fall within the envelope defined by the limits T_0 and T_∞ . McVicar and Jupp (1998) presented this relationship for five years of AVHRR T_s data recorded at Cobar, Australia.

The NDTI can be regarded as a specific time-of-day version of the CWSI. The NDTI brings the concept of mapping m_a from T_s onto a regional basis and is generic across different land surfaces by using the per-pixel variation present in the AVHRR data as the backbone for the spatial interpolation. This is achieved by developing suitable spatial covariates that incorporate AVHRR per-pixel variation. Both $T_s - T_a$ and R_n are potential covariates (Jackson et al. 1977). Vegetation cover ($VegCov$) is a potential covariate if changes in surface cover type and amount are to be incorporated.

Data Sets

Our requirements for daily meteorological data are modest: only T_m , T_x and P are essential. However, in the 1.1 million km² Murray–Darling Basin (MDB), only 63 Australian Bureau of Meteorology (ABM) stations have measured this data continuously from 1980 until the present. Figure 1 shows the location of the MDB and of the relevant meteorological sites. If available, daily U (km/day) was used to estimate u (m/s) (McVicar and Jupp 1999a). The northwest cloudband is a synoptic scale feature of the Australian region (Colls and Whitaker 1990), so 13 additional ABM stations to the north and west of the MDB were included in the meteorological database. Within the extended NDTI study area, there are 70 ABM stations, of which 57 are in the basin and an additional 13 are to the north and west of the basin.

Remotely sensed data were acquired by the AVHRR sensor on board the NOAA-9 and NOAA-11 satellites. Cracknell (1997) provides an extensive overview of the AVHRR sensor, the NOAA series of satellites and some previous applications of AVHRR data. The data archive that focuses on the MDB consists of 97 AVHRR single overpass afternoon images from June 1986 to January 1994, recorded at approximately monthly time intervals.

Selecting the Spatial Covariates

At Cobar (Fig. 1) daily meteorological data T_m , T_x , P and U were linked using the procedures described in McVicar and Jupp (1999a) to estimate T_a , e_a , R_s and u at the times of AVHRR data acquisition. The data were used with variables routinely derived from AVHRR data (T_s , $VegCov$ and albedo (α)) in the REBM (Jupp et al. 1998) to model NDTI and λE_a . This was performed only for the 73 cloud-free AVHRR overpasses at Cobar.

The utility of each of the three potential covariates ($T_s - T_a$; $VegCov$; and R_n) was evaluated by linearly regressing them against the REBM outputs of NDTI

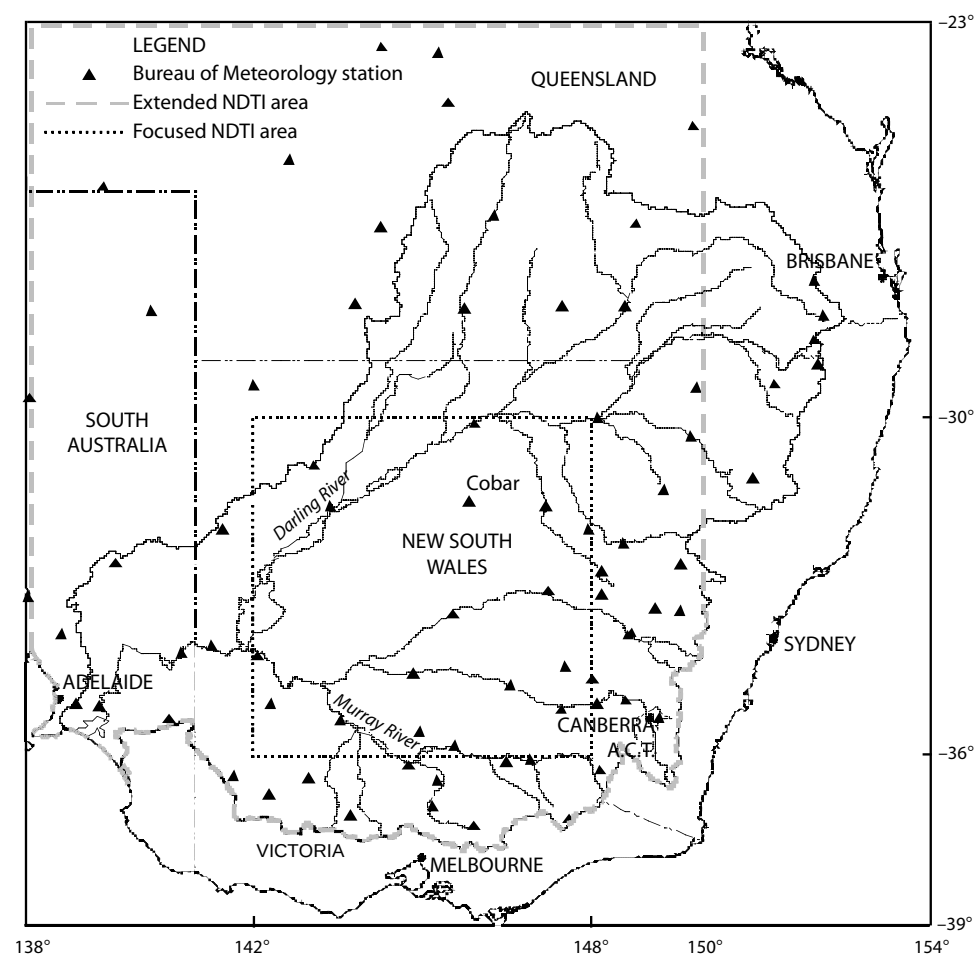


Figure 1. Location of sites in the Murray–Darling Basin, Australia. The sites of the 76 Australian Bureau of Meteorology (ABM) stations are indicated. The focus and extended normalised difference temperature index (NDTI) study areas are shown.

or λE_a . Multiple linear regression was used as required. Table 1 shows the results. Only data with r_s greater than 0 s/m and R_n greater than 125 W/m² were used in the analysis. Increasing the R_n threshold increased the r^2 statistic but reduced the number of observations in the analysis, and vice versa. The threshold of $R_n > 125$ W/m² was a pragmatic balance between the strength of the relationship between the three potential covariates and the REBM NDTI, and the number of observations used (McVicar and Jupp 1999b).

Table 1 shows the results of the regression analysis between the REBM NDTI and one potential

covariate in turn. $T_s - T_a$ had the largest r^2 and lowest standard error of the estimate of Y on X (SEY). Multiple linear regression analysis showed that $T_s - T_a$ and R_n were able to explain 79% of the variance within the NDTI, while $T_s - T_a$ and $VegCov$ were able to explain only 60% (Table 1). When all three potential covariates were used, 85% of the variance within the NDTI was explained and the SEY was less than 0.1.

It is interesting to note that when we regressed λE_a against each potential covariate in turn, R_n provided the highest r^2 and the lowest SEY (Table 1). The r^2 and SEY values when both $T_s - T_a$ and R_n were used

were almost identical to the values when $T_s - T_a$, R_n and $VegCov$ were used (Table 1). This indicates that, if interpolating λE_a rather than m_a , $VegCov$ is not as important as $T_s - T_a$ and R_n .

We calculated regression model estimates of the NDTI and λE_a —denoted NDTI' and $\lambda E_a'$ respectively—based on one covariate ($T_s - T_a$), two covariates ($T_s - T_a$ and R_n) or three covariates ($T_s - T_a$, R_n and $VegCov$). We then cross-plotted them against the REBM NDTI or REBM λE_a , respectively. Figures 2a–c show the results for NDTI when three covariates were used for the modelling. The use of three covariates explained most of the variance of the REBM NDTI (Fig. 2a–c). This confirms that all three potential covariates should be developed as spatial surfaces to interpolate the NDTI. This is not necessary for spatially interpolating λE_a by comparing $\lambda E_a'$ with REBM λE_a ; Figures 2d–f show that this regression can be performed adequately using only $T_s - T_a$ and R_n as spline model covariates.

Developing the Spatial Covariates

We used the CI approach to interpolate the NDTI, which was calculated at the ABM stations (considered points in the MDB) and then spatially

interpolated. We used the following data to develop continuous grids, to be used as covariates, or in the modelling of R_n :

- interpolated meteorological data (T_a , e_a and effective beam transmittance at 0 m (τ_0));
- remotely sensed data (T_s and α);
- supervised classification of AVHRR reflective data used as a GIS stratum with the time series of AVHRR reflective data ($VegCov$); and
- R_n modelled using all of the above six variables as inputs.

Figure 3 illustrates the development of the six input variables required to generate R_n ; Figure 4 shows how R_n is calculated. $T_s - T_a$ and $VegCov$ are developed from some of the six variables. The following discussion provides further details of the methods used to develop the spatial covariates and intermediate variables, and the results we obtained.

Air temperature (T_a)

Continuous grids of T_a for the specific times of AVHRR data acquisition were calculated in a two-step process. First, T_a was temporally interpolated from T_n and T_x to provide estimates of T_a at the 70

Table 1. Regression analysis using REBM NDTI or REBM λE_a as the dependent variable and the potential covariates as the independent variable(s).

Independent variable(s)	Dependent variable					
	REBM NDTI			REBM λE_a		
	r^2	SEY	df	r^2	SEY	df
$T_s - T_a$	0.42	0.17	47	0.01	67.1	47
R_n	0.00	0.23	47	0.38	53.0	47
$VegCov$	0.31	0.19	47	0.21	59.7	47
$T_s - T_a$ and R_n	0.79	0.11	46	0.95	15.4	46
$T_s - T_a$ and $VegCov$	0.60	0.14	46	0.21	60.3	46
$T_s - T_a$, R_n and $VegCov$	0.85	0.09	45	0.97	12.5	45

df = degrees of freedom; NDTI = normalised difference temperature index; r^2 = coefficient of determination; REBM = resistance energy balance model; SEY = standard error of the estimate of Y on X. See text for an explanation of the other symbols. There were 49 observations.

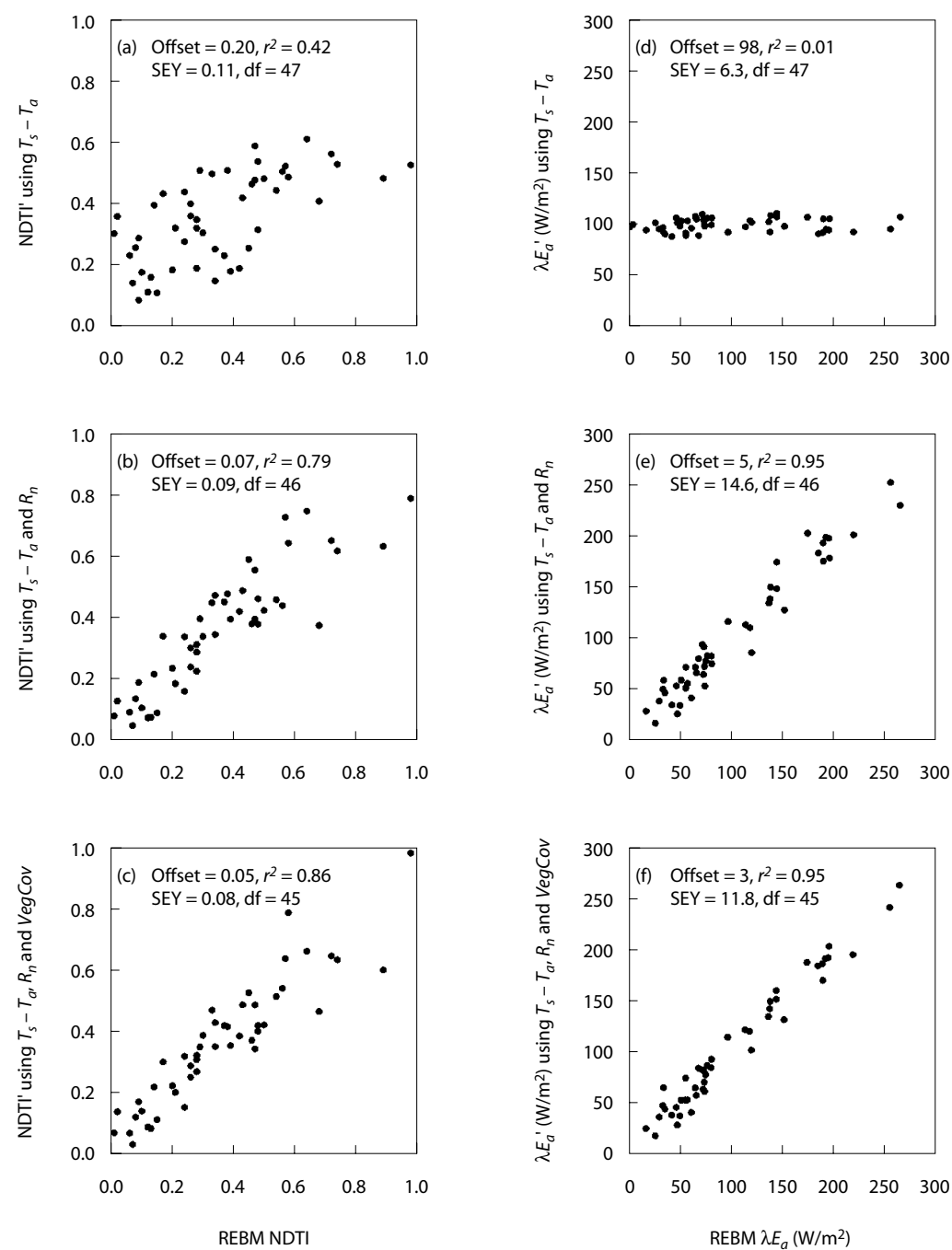


Figure 2. Cross-plots of resistance energy balance and regression models. (a) to (c) show resistance energy balance model (REBM) normalised difference temperature index (NDTI) with regression model NDTI'; (d) to (f) show REBM λE_a with regression model $\lambda E_a'$. The regression models are based on (a) and (d) $T_s - T_a$; (b) and (e) $T_s - T_a$ and R_n ; (c) and (f) $T_s - T_a$, R_n and VegCov. SEY = standard error of the estimate of Y on X. See text for an explanation of the terms used.

ABM stations, denoted $T_{a_AVHRR_PT}$ in Figure 3. Second, the values of $T_{a_AVHRR_PT}$ were spatially interpolated to generate continuous grids of T_a for the extended NDTI study site (Fig. 1), denoted $T_{a_AVHRR_GD}$ in Figure 3.

To select the spline model parameters, we undertook a detailed analysis using $T_{a_AVHRR_PT}$ supporting the AVHRR overpass acquired by NOAA-9 Orbit Number 14301, 22 September 1987 at 1629 local time. The influence of elevation was incorporated into the thin plate spline (TPS) by fitting the data with four variations:

- bivariate TPS function of longitude and latitude;

- trivariate partial thin plate spline (PTPS), incorporating a bivariate TPS function of longitude and latitude and a constant linear dependence on elevation;
- trivariate TPS function of longitude, latitude and elevation, in the units of metres; and
- trivariate TPS function of longitude, latitude and elevation, in the units of kilometres.

When using elevation (or any other variable) as an independent spline variable in a TPS, the units can influence the output surface. Hutchinson (1995) explored the scaling of elevation when interpolating mean monthly rainfall: elevation data expressed as

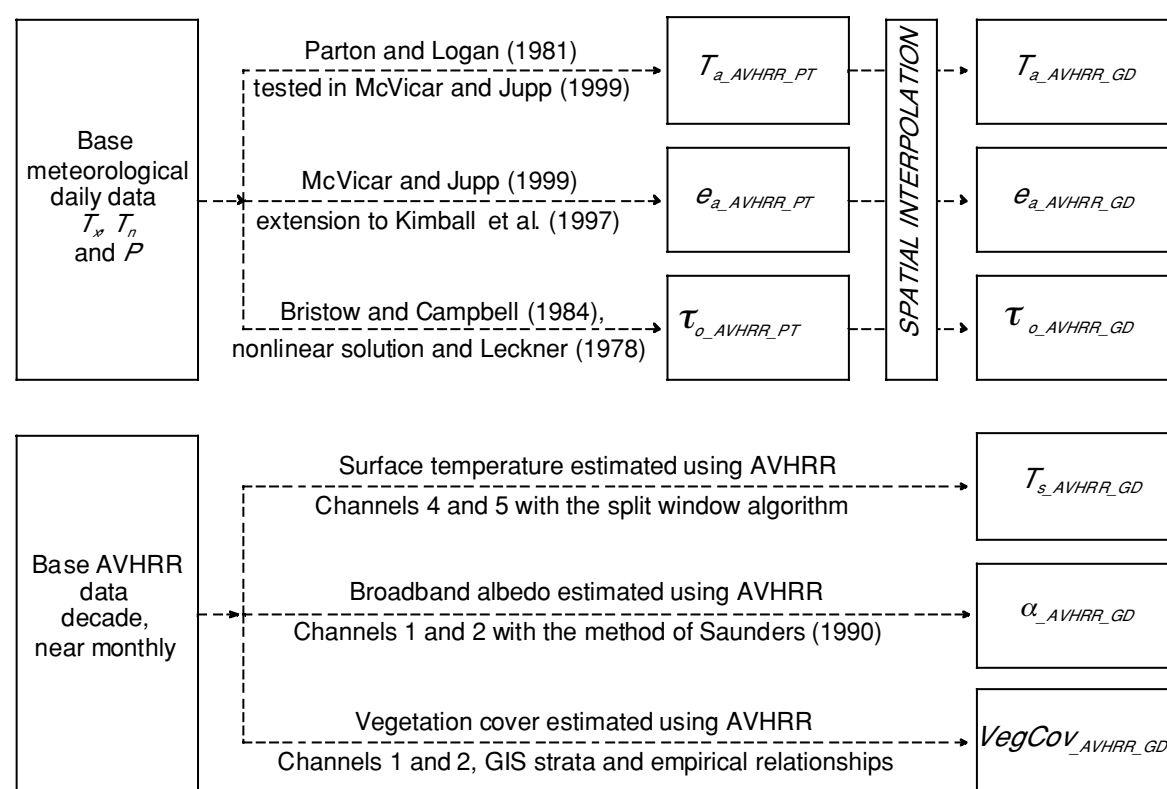


Figure 3. Development of the required variables at the specific time of day when advanced very high resolution radiometer (AVHRR) data are acquired.

The six variables are derived from two main sources. Daily meteorological data (T_n , T_x and P) are used to estimate T_a , e_a and τ_o . Then these three variables are spatially interpolated. AVHRR data are used to estimate T_s , α and $VegCov$. T_s – T_a and $VegCov$ are used as covariates. All six variables are used in modelling the third covariate R_n (see Fig. 4). The subscript *AVHRR* refers to the specific time of day that AVHRR data are acquired; the subscript *PT* refers to measurements made at a ‘point’; the subscript *GD* refers to measurement, or interpolated output, which is a continuous ‘grid’.

kilometres were both convenient and in the range of units that provided a minimal validation residual. For TPS, the range of all independent variables should be approximately equal. However, scaling of elevation does not influence the output statistics if the TPS is extended to a PTPS by including elevation as a linear parametric submodel. This is the case for all covariates. As shown above, we scaled the elevation in metres or kilometres when using a trivariate TPS. The order of the partial derivate (m) was varied from 2 to 4 (three cases) for each of the four cases shown in the above bullet points, resulting in a total of 12 options.

For all 12 spline models, the smoothing parameter (λ) was automatically selected by minimising the generalised cross-validation error, denoted as $GCV(m, \lambda)$. McVicar and Jupp (1999b) present full

statistics for all 12 options. The trivariate TPS with elevation in kilometres $m = 3$ had the lowest $\sqrt{GCV(m, \lambda)}$ (0.792°C) and this spline model was used to spatially interpolate the 97 surfaces of $T_{a_AVHRR_GD}$, using $T_{a_AVHRR_PT}$ as input data (Fig. 3).

Figure 5a shows the output for 22 September 1987. T_a gradually increases from the southeast to the northwest, but this trend is modified by local changes in elevation. The northwest portion is considered semiarid; in the southeast during September (the southern hemisphere spring), if drought conditions are not experienced, there is a spring growth flush of cereal crops (wheat, barley and oats). The 97 continuous grids of T_a were calculated and used with the other variables as required to develop the covariates (Fig. 4).

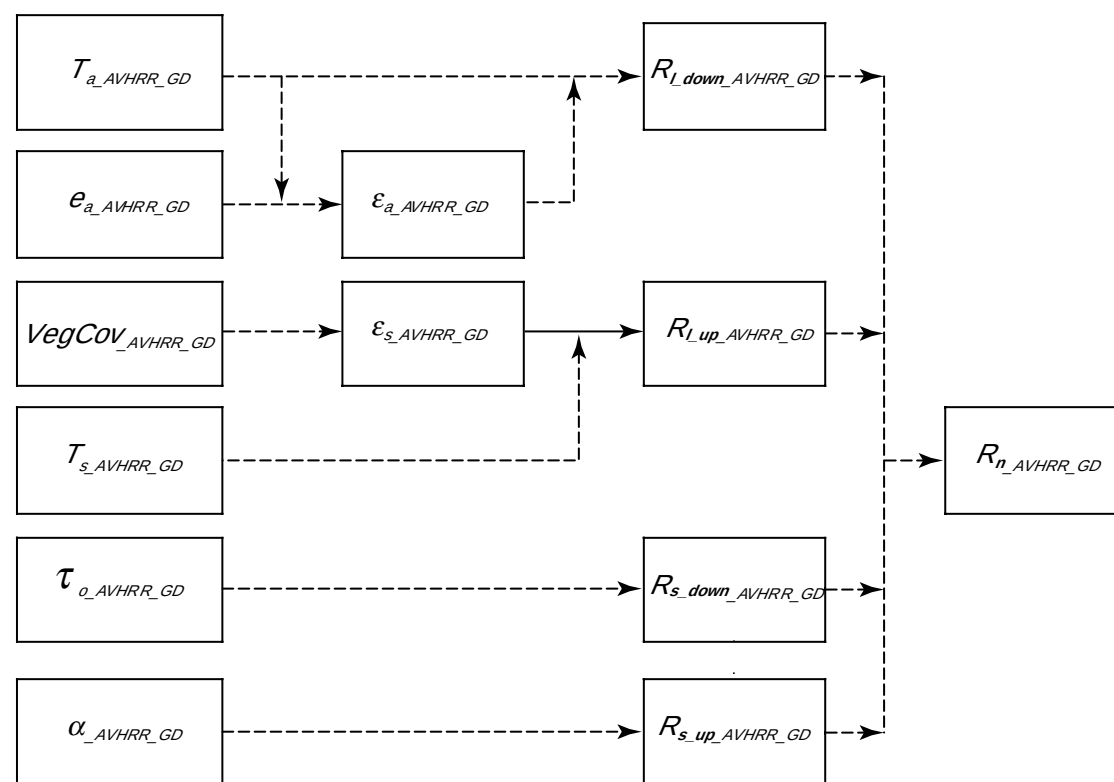


Figure 4. Development of R_n .

R_l and R_s refer to longwave and shortwave radiation, respectively; the subscript 'down' refers to radiative fluxes from the atmosphere towards the land surface; the subscript 'up' refers to radiative fluxes from the land surface toward the atmosphere. Refer to Figure 3 for the development of the six input variables.

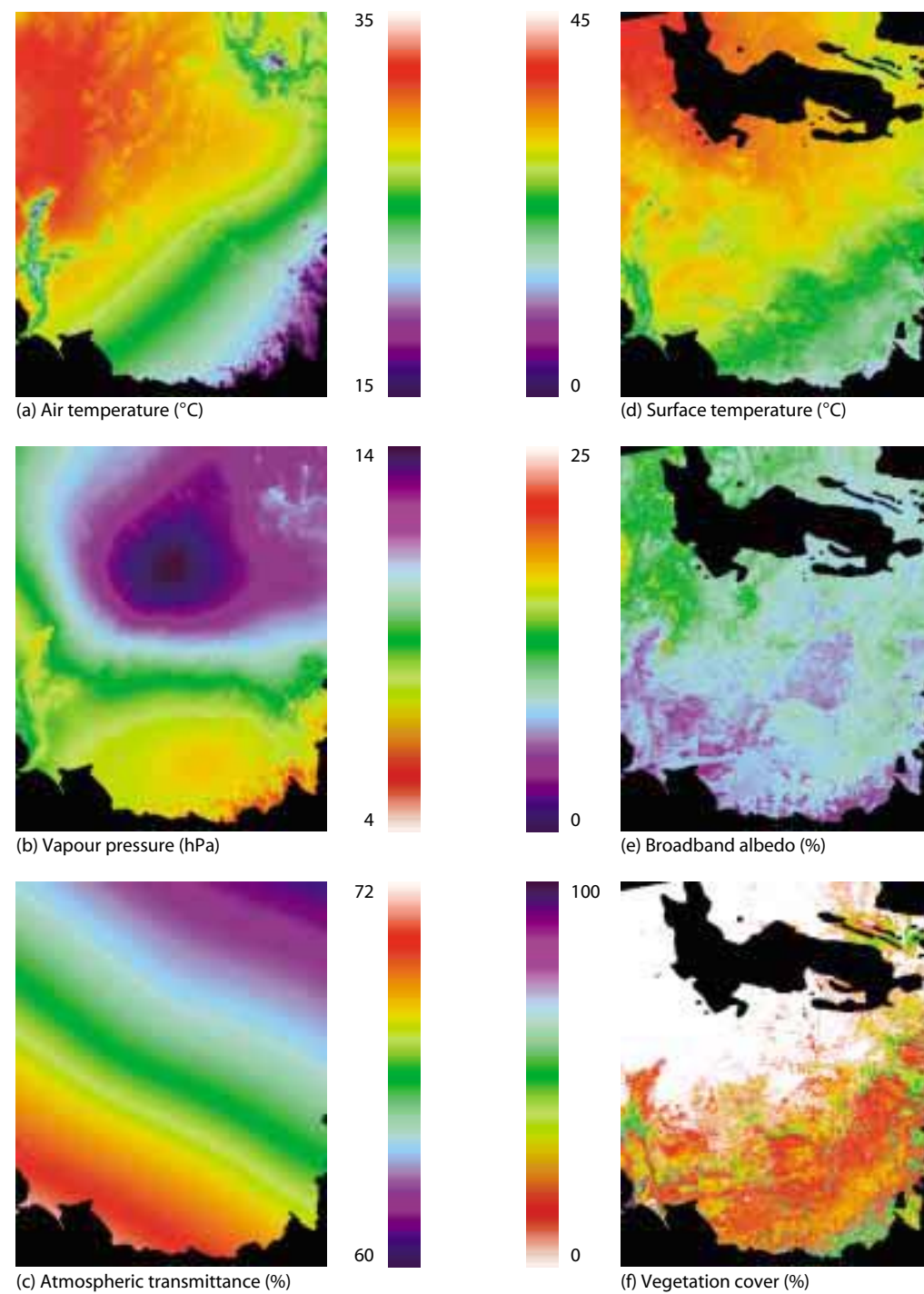


Figure 5. Continuous grids of the six required variables. The required variables are (a) T_a (°C); (b) e_a (hPa); (c) τ_0 (%); (d) T_s (°C); (e) α (%); and (f) $VegCov$ (%) for the extended normalised difference temperature index (NDTI) area shown in Figure 1. Variables (a), (b) and (c) are derived from spatial interpolation based on data recorded at the 70 ABM stations. Variables (d), (e) and (f) are derived from advanced very high resolution radiometer (AVHRR) data, some of which are not reliable because they are cloud affected; these data have been nulled and are shown in black. Note the difference in the smoothness of the output based on the source of the data. Refer to Figure 3 for the development of the six variables.

Vapour pressure (e_a)

Continuous grids of e_a for the specific times of AVHRR data acquisition were calculated using two steps. The first was to temporally estimate e_a . Recently Kimball et al. (1997) estimated dew point temperature based on empirical regressions between T_x and T_m , and an introduced term 'EF', which is the ratio of Priestly–Taylor λE_{p_DAY} divided by annual precipitation. The assumption that e_a remains constant throughout the day was improved upon by linearly interpolating e_a between the times of sunrise for consecutive days, denoted K97 'interpolation' in McVicar and Jupp (1999a). The K97 interpolation method was used to develop $e_{a_AVHRR_PT}$ (Fig. 3) estimates at the 70 ABM stations (Fig. 1). In the second step, the values of $e_{a_AVHRR_PT}$ were spatially interpolated to generate continuous grids of e_a for the extended NDTI study site (Fig. 1), denoted $e_{a_AVHRR_GD}$ in Figure 3. To test the sensitivity of m and the use of and units of elevation as a covariate (Jackson et al. 1985) in developing $e_{a_AVHRR_GD}$, we used the same 12 spline models used for T_a .

For all 12 spline models, λ was again automatically selected by minimising $GCV(m, \lambda)$. The model with the lowest $\sqrt{GCV(m, \lambda)}$ is the trivariate PTPS $m = 2$ (1.11 hPa). McVicar and Jupp (1999b) provide full statistics for all 12 spline models. Figure 5(b) shows the output for 22 September 1987. The area of high e_a in the northern portion of Figure 5(b) approximately conforms to the area identified as cloud in the AVHRR data (Fig. 5d–f). The 97 continuous grids of e_a were calculated and used to model atmospheric emissivity (ϵ_a) (Fig. 4).

Atmospheric transmittance (τ_0)

Calculating continuous grids of τ_0 for the specific days of AVHRR data acquisition is a two-step process. First, we calculated $\tau_{0_AVHRR_PT}$ (Fig. 3), for each of the 97 AVHRR days at each of the 70 ABM stations. McVicar and Jupp (1999b) present full details. Second, we spatially interpolated $\tau_{0_AVHRR_PT}$ to provide continuous grids of τ_0 ,

denoted $\tau_{0_AVHRR_GD}$ (Fig. 3), using a TPS. Detailed results for the spatial interpolation of $\tau_{0_AVHRR_GD}$, using $\tau_{0_AVHRR_PT}$ as the input data, for the bivariate TPS varying m from 2 to 4 were examined. As with T_a , λ was automatically selected by minimising $GCV(m, \lambda)$. The bivariate TPS $m = 2$ has the lowest $\sqrt{GCV(m, \lambda)}$ (0.0157%). McVicar and Jupp (1999b) provide the complete listing of output statistics. Elevation was not incorporated in this spline model as the relationship between τ_0 and elevation is implicitly defined by using a DEM in the calculation of downward short-wave radiation (R_{s_down}). $\tau_{0_AVHRR_GD}$ is assumed constant over the day; the specific time of day, day of year and geographical position of each resampled AVHRR pixel centre are used to determine transmission path length (p) and cosine of the solar zenith angle ($\cos\theta_s$).

Figure 5c shows this output for 22 September 1987; the area of lower τ_0 approximately conforms to the area of higher e_a (shown in Fig. 5b) and is identified as cloud in Figure 5d–f. The 97 continuous grids of τ_0 are used to calculate R_{s_down} (Fig. 4).

Surface temperature (T_s)

$T_{s_AVHRR_GD}$ is calculated using a split-window approach, which takes advantage of the differential atmospheric absorption observed in AVHRR channels 4 and 5. The radiance measured by AVHRR channels 4 and 5 is converted to brightness temperatures, denoted T_4 and T_5 respectively, using Planck's law. An estimate of brightness T_s , denoted Tb_s , has then been developed using the formula $Tb_s = T_5 + 3 \Delta T_{4,5} + 0.5$, where $\Delta T_{4,5}$ is $T_4 - T_5$. The split-window coefficients were determined by simulating the absorption coefficients for the AVHRR channel 4 and 5 bandwidths using Australian atmospheric data (Maher and Lee 1977) and the LOWTRAN6 package (Kneizys et al. 1983). T_s estimates were obtained by correcting the data for emissivity, based on pixel fractional $VegCov$ using 0.98 for vegetation emissivity (ϵ_v) and 0.96 for ground (or soil) emissivity (ϵ_g) (Wan and Dozier 1996). Generating $T_{s_AVHRR_GD}$ does not require any spatial interpolation.

Figure 5d shows the increase in T_s toward the semiarid area in the northwest; lower T_s values to the southeast are associated with an increase in m_a . The increases in λE_a are associated with an increase in $VegCov$ due to the spring growth flush of cereal crops (Fig. 5f). Cloud clearing means that AVHRR data are available only when there was no cloud. The 97 images of T_s were calculated and used with the other variables as required to develop the covariates (Fig. 4).

Broadband albedo (α)

α_{AVHRR_GD} was calculated using the Saunders (1990) model with AVHRR channels 1 and 2 (Fig. 3). Sensor drift degradation was taken in account using the methods provided by Mitchell (1999). The resulting effective reflectance factor is used in the Saunders model to estimate α_{AVHRR_GD} for all 97 AVHRR images. Figure 5e is an example of α ; the high albedo area to the west is Lake Frome, a salt lake; the very small area to the southeast is snow cover on the Australian Alps. Remnant forests and woodlands have the lower albedos. The 97 images of α were calculated and used to model the shortwave radiation reflected upward by the surface (R_{s_up}) (Fig. 4).

Vegetation cover

$VegCov_{AVHRR_GD}$ is calculated as continuous grids for the specific days of AVHRR data acquisition in a two-step process. Firstly, we defined a stratum of woody and nonwoody vegetation by classifying reflective AVHRR data from several dates throughout 1987 into a woody/nonwoody vegetation stratum. Secondly, we developed empirical relationships between in situ leaf area index (LAI) and AVHRR channels 1 (Red) and 2 (NIR). For nonwoody vegetation, $LAI = -1.15 + 0.96 \times (NIR/Red)$ (McVicar et al. 1996a); for woody vegetation, $LAI = -4.65 + 4.22 \times (NIR/Red)$ (McVicar et al. 1996b). Finally LAI_{AVHRR_GD} were converted into estimates of $VegCov$ using the relationship $VegCov = 100.0 \times (1.0 - \exp^{(-LAI/2)})$, assuming random distribution of foliage above the

soil and uniform leaf-angle distribution (Choudhury 1989).

Figure 5f illustrates this output for 22 September 1987. The areas of higher amounts of $VegCov$ are remnant forests and woodlands; the large expanse of moderate values across the southern portion of the image (Fig. 5f) is due to the spring growth flush of cereal crops. The large expanse with 0% $VegCov$ toward the northwest is semiarid (Fig. 5f) and corresponds to the area of high T_s in Figure 5d. $VegCov$ is used as a covariate and is also used to calculate surface emissivity (ϵ_s).

Net radiation (R_n)

R_n can be expressed as the sum of its four components:

$$R_n = R_{s_down} - R_{s_up} + R_{l_down} - R_{l_up} \quad (2)$$

where R_s is short-wave radiation and R_l is longwave radiation. The components can be calculated from the six variables introduced above (see Fig. 4). An IC approach is used for R_n because R_n is strongly influenced by α and T_s , which can be discontinuous due to land use (e.g. when agricultural land is adjacent to remnant forest). Information about α , T_s and $VegCov$ is obtained directly from the spatially dense AVHRR data (Fig. 3). This means that changes in α , T_s and $VegCov$ are accounted for in space—at $1/64^{\text{th}}$ of a degree, the spatial resolution of the resampled AVHRR data—and in time, near monthly, the temporal resolution in the AVHRR data base.

The methods used to model the radiation components are fully documented in McVicar and Jupp (1999b) and are briefly documented below. R_{s_down} is modelled by:

$$R_{s_down} = \tau_0^{\frac{P}{P_0} p/2} \cos \theta_s Q_0' \quad (3)$$

where P is the total pressure (the subscripts denote the altitude above a zero height surface) and Q_0' is

the exoatmospheric normal solar irradiance modified for sun–earth distance. The input variables required are:

- a continuous raster of τ_0 (see above);
- the specific time of day, day of year and geographical position of the pixel centre of resampled AVHRR data (used to determine p and $\cos\theta_s$);
- a continuous raster of height, obtained from AUSTDEM Ver 4.0; and
- slope and aspect, derived from the DEM (used to modify the calculation) (Iqbal 1983).

R_{s_up} is the fraction of R_{s_down} reflected by the surface; this is controlled by α . R_{l_down} is calculated using the method described in Kustas et al. (1989), in which ϵ_a and T_a are variables. The estimate of ϵ_a relies on e_a and T_a (Brutsaert 1975). To calculate R_{l_up} , both ϵ_s and T_s are required (Kustas et al. 1989). ϵ_s is calculated from $VegCov$, using 0.98 for ϵ_v and 0.96 for ϵ_g (Wan and Dozier 1996). The relatively small component of outgoing longwave radiation by reflected sky radiation is ignored (Jackson et al. 1985).

We developed the components of R_n using the methods described above and summarised in Figure 4. In Figure 6a the longitudinal banding of R_{s_down} is due to changes in p and $\cos\theta_s$ when the AVHRR data were acquired at 1629 local time. Modification by elevation, slope and aspect are shown. Figure 6b illustrates the influence of α and banding of R_{s_down} on R_{s_up} . The spatial pattern of R_{l_down} , shown in Figure 6c is dominated by T_a . R_{l_up} (Fig. 6d) follows the spatial variability present in T_s . The components have been added together (Equation 2) to provide continuous rasters of R_n , denoted $R_{n_AVHRR_GD}$, which is used as a covariate. $R_{n_AVHRR_GD}$ for 22 September 1987 is illustrated in Figure 7c.

Applying the Spatial Covariates to the Murray–Darling Basin

We used the CI approach to develop the 97 surfaces of the NDTI for the focus area of the MDB. The NDTI (Equation 1) was calculated at the ABM stations shown in Figure 1. To generate continuous NDTI surfaces, we used a quintivariate PTPS, incorporating a bivariate TPS function of longitude and latitude with constant linear dependencies on $T_s - T_a$, $VegCov$ and R_n (see Figures 7a, b and c respectively). To select the spline model, we varied m from 2 to 4 and assessed its influence (McVicar and Jupp 1999b). We examined detailed results for the spatial interpolation of NDTI for the three options $m = 2$ to 4; full results are presented in McVicar and Jupp (1999b). As with T_a above, λ was automatically selected for the spline models by minimising $GCV(m, \lambda)$. The model with the lowest $\sqrt{GCV(m, \lambda)}$ was the quintivariate PTPS with three covariates $m = 2$.

The high spatial density of AVHRR data is seen in the resulting NDTI images. Figure 8a shows the NDTI image for spring (22 September 1987) and Figure 8b shows the NDTI image for summer (25 December 1987). Changes in the NDTI between the two dates are shown in Figure 8c, where blue is an increase, green fairly constant and red a decrease between the two dates. Figure 8a shows that the Menindee Lakes system is the only area where NDTI is greater than 0.8, with the southern portion of the wheatbelt in the southeast having an NDTI of about 0.5. Some areas around the Menindee Lakes also have an NDTI of about 0.5; these are assumed to have received scattered rainfall. Figure 5d shows the larger extent of this pattern, confirmed by a decrease in T_s . In Figure 8b some areas with an NDTI greater than 0.8 are lakes while others are associated with flood irrigation of crops and remnant river red gum forests (Barham and Gulpa State Forests) along the Murray River. On the Cobar peneplain there are scattered areas with NDTI values of approximately 0.5, which corresponds to

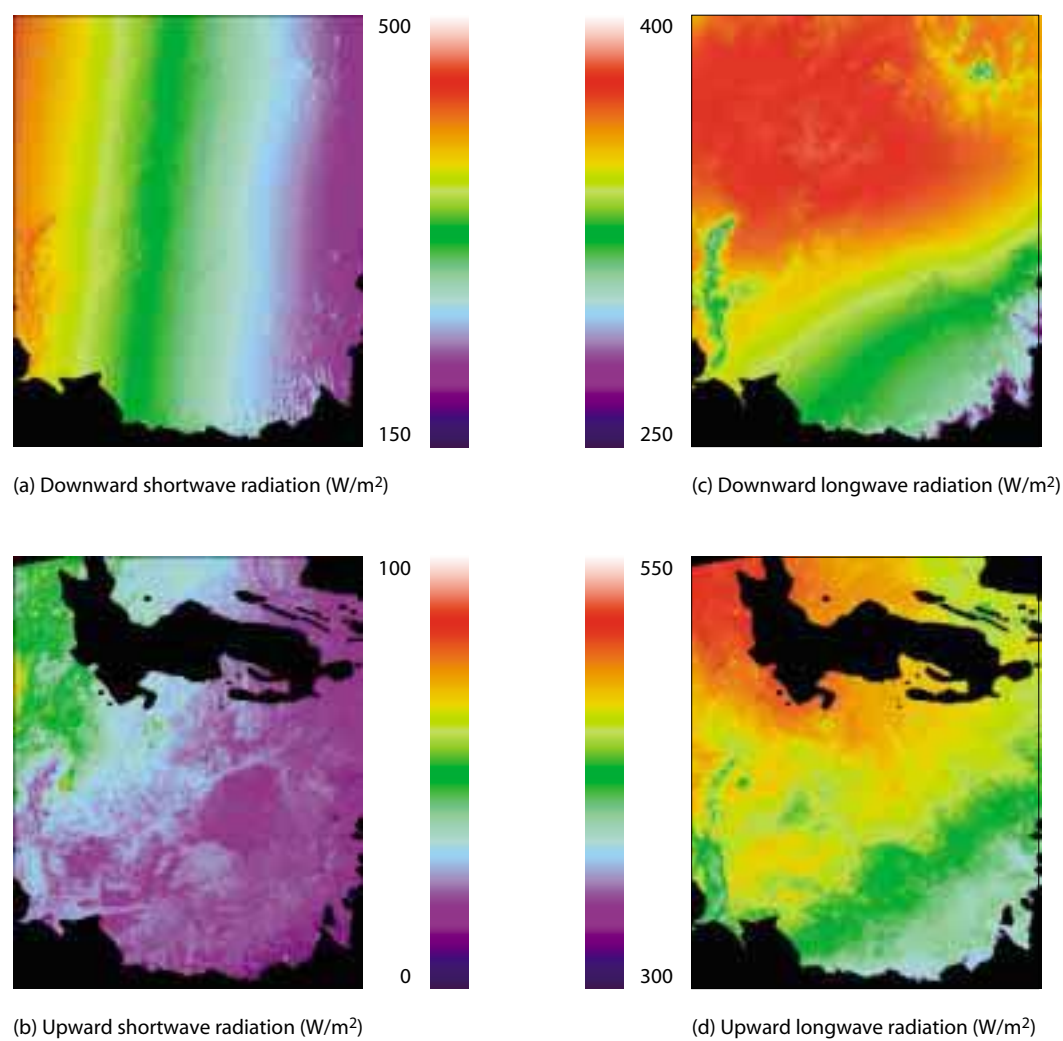


Figure 6. Continuous grids of the four radiation components. The figure shows (a) R_{s_down} (W/m^2); (b) R_{s_up} (W/m^2); (c) R_{l_down} (W/m^2) and (d) R_{l_up} (W/m^2) for the extended normalised difference temperature index (NDTI) area shown in Figure 1 used to calculate R_n . Variables (b) and (d) require input variables from advanced very high resolution radiometer (AVHRR) data (see Fig. 4). Consequently the areas cloud affected in the AVHRR data (see Fig. 5) are nulled and are shown as black for these variables. Refer to Figure 4 for the development of the four components.

areas where the NDTI has increased between the two dates (Fig. 8c); these areas have probably received scattered rainfall.

Figures 8d and 8e show the AVHRR derived estimates of *VegCov* for spring and summer, respectively. The remnant deep-rooted forests are identified by having a stable *VegCov* between the two seasons. This is especially seen for the remnant river red gum forests along the Murray River. In the

woodlands of the Cobar peneplain, *VegCov* is mainly stable. However, there are some areas on the Cobar peneplain—the blue areas in Fig. 8f—where *VegCov* has increased between the two periods. These areas are associated with an increase in the NDTI (Fig. 8c). This increase in *VegCov* is probably associated with an increase in the amount of grass cover. The grasses have adapted to respond to short-term changes in available moisture and will be observable through the relatively open overstorey canopy (10–20%).

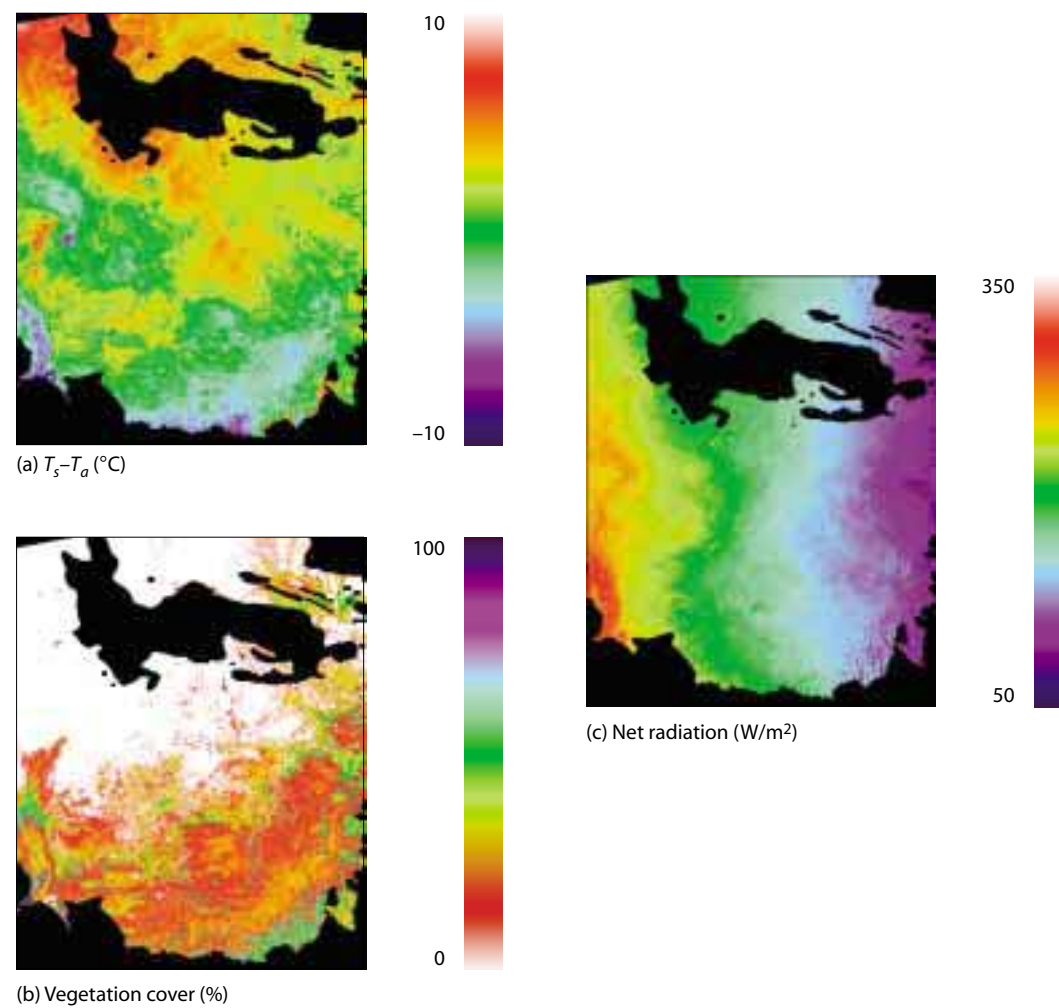


Figure 7. Continuous grids of the three covariates. The figure shows (a) $T_s - T_a$ (°C); (b) $VegCov$ (%) and (c) R_n (W/m²) for the extended normalised difference temperature index (NDTI) area shown in Figure 1. All three covariates use advanced very high resolution radiometer (AVHRR) data; consequently areas cloud affected in the AVHRR data (see Fig. 5 and 6) are nulled and are shown as black for each of the covariates.

The changes between the two dates in NDTI (Fig. 8c) and $VegCov$ (Fig. 8f) are similar, though not identical. For example, along the northeastern border of the two images, there is a large negative change in $VegCov$ due to harvesting of cereal crops, whereas in this area the NDTI remains fairly constant (it is less than 0.2 for both dates). To assist in regional agricultural management, including drought assessment, the resulting NDTI images and reflective-based images, such as $VegCov$ or the

normalised difference vegetation index (NDVI), and their interactions, need to be analysed in a spatial-temporal context. If the NDTI is viewed as an indicator of moisture availability, and the NDVI is thought of as an indicator of moisture utilisation, there is an opportunity to separate variability induced by climate from that induced by management (McVicar and Jupp 1998). For example, in cropping or pasture agricultural systems, if the NDTI reduces during a growing

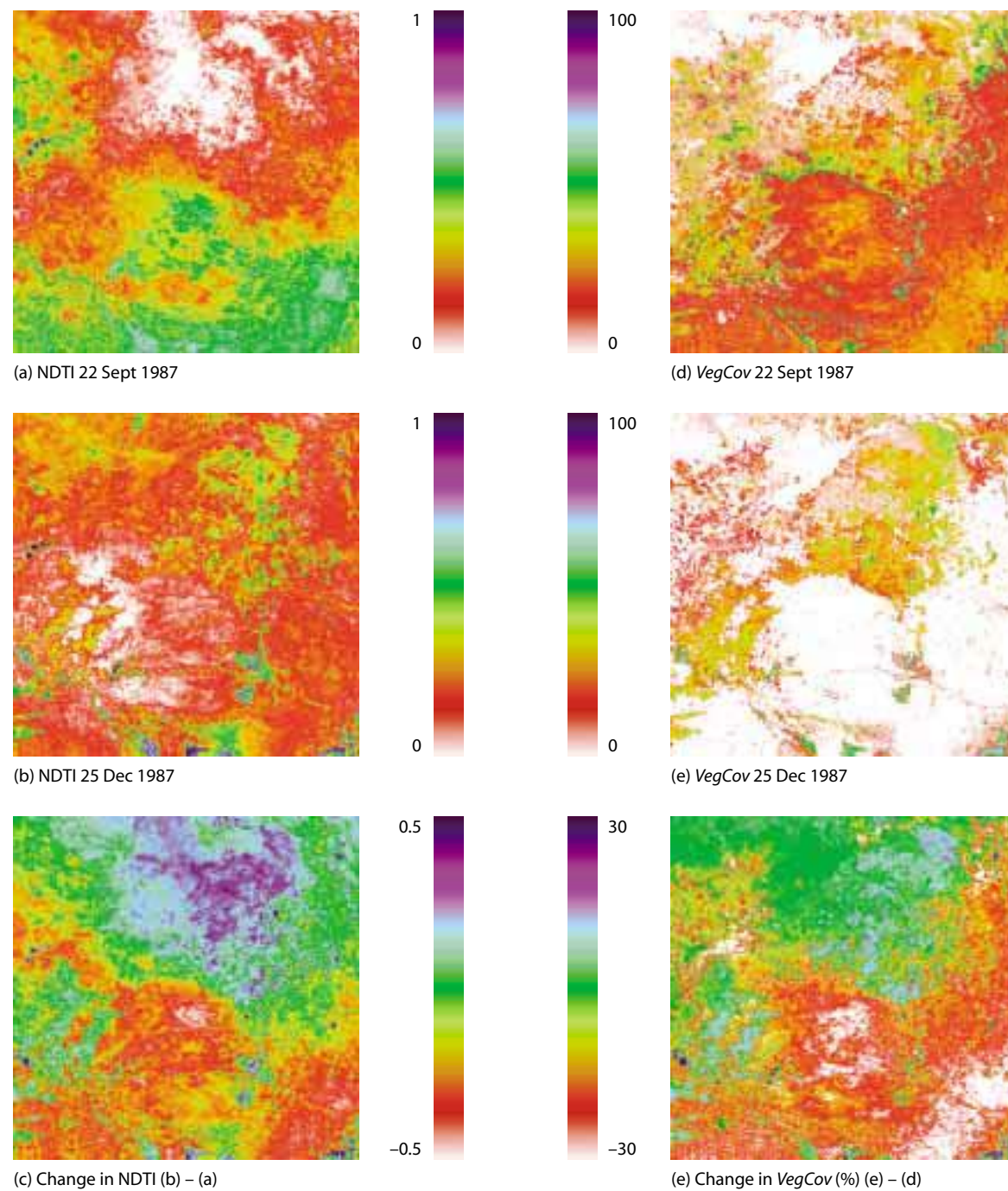


Figure 8. Images of the focus NDTI area shown in Figure 1. The figure shows (a) normalised difference temperature index (NDTI) for 22 September 1987; (b) NDTI for 25 December 1987 and (c) the difference of NDTI between these two dates, calculated as (b) – (a). (d) to (f) as for (a) to (c), except that VegCov is shown.

season while the NDVI increases, this would indicate that some of the decrease in moisture availability was due to transpiration. However, there may be cases where the NDTI reduces during the growing season and the NDVI fails to show any response. Such a case could be the result of disease or insect damage early during the crop growing season and the resulting decrease in moisture availability may be attributable only to soil evaporation. During crop growing seasons these interactions may be best analysed by calculating the integrals under a time series of NDTI and NDVI images. The timing of the maximum NDTI and NDVI during crop growth periods would probably have to be included. McVicar and Jupp (2002) provide a formal sensitivity analysis of the variables used in developing the covariates to interpolate the NDTI.

Conclusions

The NDTI, which can be considered a specific time-of-day version of the CSWI, is calculated using an REBM at the ABM stations where meteorological data are acquired. We have used a CI approach to spatially interpolate the NDTI from these isolated stations to generate a continuous surface in the MDB. Three covariates were required: $T_s - T_a$, $VegCov$, and R_n . They were obtained mainly from AVHRR data and spatial interpolation of selected meteorological variables, with R_n modelled using an IC approach. We are not advocating CI in preference to IC; the underlying issues determine which is most useful in a given situation. We are advocating, and have presented, a CI method that inherently uses the high spatial density of AVHRR data as the backbone for the spatial interpolation.

The NDTI provides a link into regional water balance modelling that does not require spatial interpolation of daily rainfall. Assessing spatial and temporal interactions between the NDTI and $VegCov$ or NDVI will provide useful information about regional hydroecological processes, including agricultural management, in the context of Australia's highly variable climate.

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References

- Borga, M. and Vizzaccaro, A. 1997. On the interpolation of hydrologic variables: formal equivalence of multiquadratic surface fitting and kriging. *Journal of Hydrology*, 195, 160–171.
- Bosma, W.J.P., Marinussen, M.P.J.C. and van der Zee, S.E.A.T.M. 1994. Simulation and areal interpolation of reactive solute transport. *Geoderma*, 62, 217–231.
- Brutsaert, W.H. 1975. On a derivable formula for longwave radiation from clear skies. *Water Resources Research*, 11, 742–744.
- Carter, J., Flood, N., Danaher, T. et al. 1996. Development of a National Drought Alert Strategic Information System. Volume 3. Development of data rasters for model inputs. Final Report to Land and Water Resources Research and Development Corporation, Queensland Department of Primary Industries, 20, Brisbane, 76.
- Choudhury, B.J. 1989. Estimating evaporation and carbon assimilation using infrared temperature data: vistas in modelling. In: Asrar, G., ed., *Theory and Applications of Optical Remote Sensing*. New York, John Wiley and Sons, 628–690.
- Cole, C.V., Paustian, K., Elliott, E.T., Metherell, A.K., Ojima, D.S. and Parton, W.J. 1993. Analysis of agroecosystem carbon pools. *Water, Air and Soil Pollution*, 70, 357–371.
- Colls, K. and Whitaker, R. 1990. *The Australian Weather Book*. Sydney, Child and Associates.
- Courault, D., Lagouarde, J.P. and Aloui, B. 1996. Evaporation for maritime catchment combining a meteorological model with vegetation information and airborne surface temperatures. *Agricultural and Forest Meteorology*, 82, 93–117.
- Cracknell, A.P. 1997. *The Advanced Very High Resolution Radiometer (AVHRR)*. London, Taylor and Francis.
- Dubrule, O. 1983. Two methods with different objectives: splines and kriging. *Mathematical Geology*, 15, 245–257.
- Dubrule, O. 1984. Comparing splines and kriging. *Computers and Geosciences*, 10, 327–338.
- Hutchinson, M.F. 1993. On thin plates splines and kriging. In: Tarter, M.E. and Lock, M.D., eds, *Computing and Science in Statistics*, Vol. 25. University of California, Berkeley: Interface Foundation of North America, 55–62.
- Hutchinson, M.F. 1995. Interpolating mean rainfall using thin plate smoothing splines. *International Journal of Geographic Information Science*, 9, 385–403.
- Hutchinson, M.F. 1997. *ANUSPLIN Version 3.2 User Guide*. Canberra, ANU.

- Hutchinson, M.F. and Gessler, P.E. 1994. Splines—more than just a smooth interpolator. *Geoderma*, 62, 45–67.
- Iqbal, M. 1983. *An Introduction to Solar Radiation*. Vancouver, Academic Press.
- Jackson, R.D., Hatfield, J.L., Reginato, R.J., Idso, S.B. and Pinter Jr., P.J. 1983. Estimation of daily evapotranspiration from one-time-of-day measurements. *Agricultural Water Management*, 7, 351–362.
- Jackson, R.D., Idso, S.B., Reginato, R.J. and Pinter Jr., P.J. 1981. Canopy temperature as a crop water stress indicator. *Water Resources Research*, 17, 1133–1138.
- Jackson, R.D., Pinter Jr., P.J. and Reginato, R.J. 1985. Net radiation calculated from remote multispectral and ground station meteorological data. *Agricultural and Forest Meteorology*, 35, 153–164.
- Jackson, R.D., Reginato, R.J. and Idso, S.B. 1977. Wheat canopy temperature: a practical tool for evaluating water requirements. *Water Resources Research*, 13, 651–656.
- Jupp, D.L.B., Tian, G., McVicar, T.R., Qin, Y. and Fuqin, L. 1998. Soil Moisture and Drought Monitoring Using Remote Sensing. I: Theoretical Background and Methods. Canberra, CSIRO Earth Observation Centre, 96.
- Kimball, J.S., Running, S.W. and Nemani, R.R. 1997. An improved method for estimating surface humidity from daily minimum temperature. *Agricultural and Forest Meteorology*, 85, 87–98.
- Kittel, T.G.F., Rosenbloom, N.A., Painter, T.H. and Schimel, D.S. 1995. The VEMAP integrated database for modelling United States ecosystem/vegetation sensitivity to climate change. *Journal of Biogeography*, 22, 857–862.
- Kneizys, F.X., Shettle, E.P., Abreu, L.W., Anderson, G.P., Chetwynd, J.H., Gallery, W.O., Selby, J.E. and Clough, S.A. 1983. Atmospheric transmittance/radiance: computer code LOWTRAN 6. Technical Report AFGL-TR-83-0187. Massachusetts, United States Air Force Geophysics Laboratory, 200.
- Kustas, W.P., Jackson, R.D. and Asrar, G. 1989. Estimating surface energy-balance components from remotely sensed data. In: Asrar, G., ed., *Theory and Application of Optical Remote Sensing*. New York, John Wiley and Sons, 604–627.
- Lagouarde, J.-P. 1991. Use of NOAA AVHRR data combined with an agrometeorological model for evaporation mapping. *International Journal of Remote Sensing*, 12, 1853–1864.
- Lam, N.S. 1983. Spatial interpolation methods: a review. *The American Cartographer*, 10, 129–149.
- Laslett, G.M. 1994. Kriging and splines: an empirical comparison of their predictive performance in some applications. *Journal of the American Statistical Association*, 89, 391–409.
- Maher, J.V. and Lee, D.M. 1977. *Upper Air Statistics Australia. Surface to 5 mb 1957 to 1975*. Canberra, Department of Science, Bureau of Meteorology.
- McVicar, T.R. and Jupp, D.L.B. 1998. The current and potential operational uses of remote sensing to aid decisions on drought exceptional circumstances in Australia: a review. *Agricultural Systems*, 57, 399–468.
- McVicar, T.R. and Jupp, D.L.B. 1999a. Estimating one-time-of-day meteorological data from standard daily data as inputs to thermal remote sensing based energy balance models. *Agricultural and Forest Meteorology*, 96, 219–238.
- McVicar, T.R. and Jupp, D.L.B. 1999b. Using AVHRR data and meteorological surfaces to spatially interpolate moisture availability in the Murray–Darling Basin. Canberra, CSIRO Land and Water, 45.
- McVicar, T.R. and Jupp, D.L.B. 2002. Using covariates to spatially interpolate moisture availability in the Murray–Darling Basin: a novel use of remotely sensed data. *Remote Sensing of Environment*, 79, 199–212.
- McVicar, T.R., Jupp, D.L.B. and Williams, N.A. 1996a. Relating AVHRR vegetation indices to LANDSAT TM leaf area index estimates. Canberra, CSIRO Division of Water Resources, 33.
- McVicar, T.R., Walker, J., Jupp, D.L.B., Pierce, L.L., Byrne, G.T. and Dallwitz, R. 1996b. Relating AVHRR vegetation indices to in situ leaf area index. Canberra, CSIRO Division of Water Resources, 54.
- Mitchell, R.M. 1999. Calibration status of the NOAA AVHRR solar reflectance channels: CalWatch Revision 1. Melbourne, CSIRO Atmospheric Research Technical Paper No. 42, 20.
- Moran, M.S., Rahman, A.F., Washburne, J.C., Goodrich, D.C., Weltz, M.A. and Kustas, W.P. 1996. Combining the Penman-Monteith equation with measurements of surface temperature and reflectance to estimate evaporation rates of semi-arid grassland. *Agricultural and Forest Meteorology*, 80, 87–109.
- Nalder, I.A. and Wein, R.W. 1998. Spatial interpolation of climatic Normals: test of a new method in the Canadian boreal forest. *Agricultural and Forest Meteorology*, 92, 211–225.
- Parton, W.J. and Logan, J.A. 1981. A model for diurnal variation in soil and air temperature. *Agricultural Meteorology*, 23, 205–216.
- Pierce, L.L., Walker, J., Dowling, T.I., McVicar, T.R., Hatton, T.J., Running, S.W. and Coughlan, J.C. 1993. Ecohydrological changes in the Murray–Darling Basin. III. A simulation of regional hydrological changes. *Journal of Applied Ecology*, 30, 283–294.
- Prince, S.D., Goetz, S.J., Dubayah, R.O., Czajkowski, K.P. and Thawley, M. 1998. Inference of surface and air temperature, atmospheric precipitable water and vapor pressure deficit using Advanced Very High-Resolution Radiometer satellite observations: comparison with field observations. *Journal of Hydrology*, 212, 230–249.
- Raupach, M.R., Finkele, K., Briggs, P.B., Cleugh, H.A., Coppin, P.A., Leuning, R. and Graetz, R.D. 1997. Water and carbon dynamics of the Australian biosphere. In: Munro, R.K. and Leslie, L.M., eds, *Climate Prediction for Agricultural and Resource Management: Australian Academy of Science Conference*, Canberra, 6–8 May 1997. Canberra, Bureau of Resources Sciences, 211–229.

- Saunders, R.W. 1990. The determination of broad band surface albedo from AVHRR visible and near-infrared radiances. *International Journal of Remote Sensing*, 11, 49–67.
- Seguin, B., Baelz, S., Monget, J.M. and Petit, V. 1982a. Utilisation de la thermographie IR pour l'estimation de l'évaporation régionale. I: Mise au point méthodologique sur le site de la Crau. *Agronomie*, 2, 7–16.
- Seguin, B., Baelz, S., Monget, J.M. and Petit, V. 1982b. Utilisation de la thermographie IR pour l'estimation de l'évaporation régionale. II: Resultats obtenus a partir de donnees de satellite. *Agronomie*, 2, 113–118.
- Stein, A., Staritsky, I.G., Bouma, J., Van Eijsbergen, A.C. and Bgegt, A.K. 1991. Simulation of moisture deficits and areal interpolation by universal cokriging. *Water Resources Research*, 27, 1963–1973.
- Thornton, P.E., Running, S.W. and White, M.A. 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. *Journal of Hydrology*, 190, 214–251.
- Wan, Z. and Dozier, J. 1996. A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE Transactions on Geoscience and Remote Sensing*, 34, 892–905.
- Xie, X. 1991. Estimation of daily evapotranspiration (ET) from one-time-of-day remotely sensed canopy temperature. *Remote Sensing of Environment (China)*, 6, 253–260.
- Zhang, L., Lemeur, R. and Goutorbe, J.P. 1995. A one-layer resistance model for estimating regional evapotranspiration using remote sensing data. *Agricultural and Forest Meteorology*, 77, 241–261.

20 Application of a Mean Annual Water Balance Model to the Murray–Darling Basin: Past, Present and Future

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Abstract

Catchment water balance is strongly affected by land-use and vegetation characteristics; generally, trees use more water than pasture and crops. As a result, forested catchments yield less stream flow (water yield). In the Murray–Darling Basin (MDB) there are plans to convert large areas of pasture to forestry plantations in the coming decades; a range of commercial and environmental considerations motivates these plans. This chapter describes how a simple water balance model in a geographic information systems (GIS) framework can be used to assess average annual stream flow under different land-use scenarios. The model only requires percentage forest cover of a catchment and mean annual rainfall. The method is well suited for regional-scale assessment of the impacts of change in land use on water yield.

The case study described here is based on average rainfall data for 1980–95, and vegetation cover data under different land-use conditions obtained from the MDB Commission, the Australian Land Information Group (AUSLIG), and CSIRO Forestry and Forest Products. Estimated mean annual catchment water yields agreed well with measured stream flow data for catchments with medium to high rainfall in the MDB but tended to overestimate water yield for low-rainfall catchments. The model showed that clearing native vegetation in the MDB is likely to significantly increase water yield from most of the catchments within the basin. It also predicted that afforestation in the basin may reduce mean annual water yield by up to 40 mm/year.

土地利用方式和植被类别影响流域水量平衡。一般情况下树木比牧草、农作物消耗更多的水分，因而森林覆盖的流域产生的径流较少。出于环境和商业的考虑，计划在未来的几十年里，把默里达令盆地（MDB）的草地大面积改造成林地。本文介绍了一个简单的水量平衡模型在地理信息系统里如何评估不同土地利用方式产生的径流量。该模型只要求输入流域的森林覆盖率

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和年均降雨量，可用于评估区域范围土地利用变化对产水量的影响。

本项研究基于 1980–1995 年的平均降雨量和不同土地利用下的植被覆盖度。对 MDB 里降雨量高或适中的流域所估算的产水量与实测值吻合很好，但对降水少的流域的估算值偏高。该模型显示原始森林的砍伐很可能使得 MDB 多数流域的产水量大增。它也预测 MDB 完成造林后，年均产水量可减少多达 40 毫米。

LAND use in the Murray–Darling Basin (MDB) has undergone massive changes following European settlement. These changes have significantly modified the hydrological regime of the catchment. The replacement of perennial deep-rooted native vegetation with shallow-rooted vegetation such as perennial grasses, annual grasses and crops has resulted in major changes to catchment-wide evapotranspiration and stream flow (Zhang et al. 1999, 2001; Vertessy and Bessard 1999). These changes to the water balance and vegetation have in turn had major effects on the salt balance and stream salinity within the catchments (Jolly et al. 1997, 2001; Natural Heritage Trust 2001).

There are plans to convert large areas of pasture in the MDB to forestry plantations in the coming decades (e.g. Department of Primary Industries and Energy 1997). A range of commercial and environmental considerations, including the management of dryland salinity, motivates these plans. As this paper demonstrates, the spatial distribution of plantations within catchments greatly influences the resulting change in hydrology.

A number of studies have shown that evapotranspiration from a forested catchment is generally greater than that from a grassed catchment with the same climatic conditions (Holmes and Sinclair 1986; Turner 1991; Zhang et al. 2001). Thus,

land-use management strategies will impact on catchment water balance. The key factors controlling evapotranspiration include rainfall interception, net radiation, advection, turbulent transport, leaf area and plant available water capacity. The relative importance of these processes is likely to depend on climate, soil and vegetation conditions. Zhang et al. (2001) have developed a simple water balance model to assess impacts of land-use changes, which requires only vegetation, annual total streamflow and rainfall data. The model agreed with independent water balance estimates from more than 250 catchments. This paper describes how the model was used within a GIS framework to estimate catchment water yield under different vegetation conditions in the MDB.

Mean Annual Water Balance Model

Zhang et al. (2001) developed the catchment balance model used in this study, based on an examination of annual rainfall and evapotranspiration relationships. It is assumed that, under very dry conditions, potential evapotranspiration exceeds precipitation and actual evapotranspiration equals precipitation; under very wet conditions, water availability exceeds potential evapotranspiration and actual evapotranspiration equals potential evapotranspiration. Based on these assumptions, mean annual evapotranspiration (*ET*)

can be calculated from mean annual rainfall (P) and potential evapotranspiration (E_0):

$$ET = P \left\{ \frac{1 + w \left(\frac{E_0}{P} \right)}{1 + w \left(\frac{E_0}{P} \right) + \left(\frac{E_0}{P} \right)^{-1}} \right\} \quad (1)$$

where w is the plant available water coefficient.

Following Eagleson (1982), we assumed that mean annual evapotranspiration from a catchment is the sum of the evapotranspiration from herbaceous vegetation ($ET_{nonforest}$) (including soil evaporation) and from forest (ET_{forest}), weighted linearly according to their percentage areas. The general equation can be expressed as:

$$ET_{total} = f \times ET_{forest} + (1 - f) \times ET_{nonforest} \quad (2)$$

where f is percentage area of a catchment forested. The nonforest part of a catchment could be further divided into woodland and grasses if such data were available.

To simplify the calculation, the parameters in Equation 1 were established for forested and nonforested catchments:

$$ET_{forest} = \left\{ \frac{1 + 2.0 \times \frac{1410}{P}}{1 + 2.0 \times \frac{1410}{P} + \frac{P}{1410}} \right\} \times P \quad (3)$$

$$ET_{nonforest} = \left\{ \frac{1 + 0.5 \times \frac{1100}{P}}{1 + 0.5 \times \frac{1100}{P} + \frac{P}{1100}} \right\} \times P \quad (4)$$

These relationships are shown in Figure 1, together with observed evapotranspiration from the catchments listed in Zhang et al. (1999). The size of these catchments varied from less than 1 km² to 6 × 10⁵ km², and they span a variety of climates. The vegetation varies from same-aged plantation trees to native woodlands, open forest, rainforest,

eucalypt forest, native and managed grassland, and agricultural cropping.

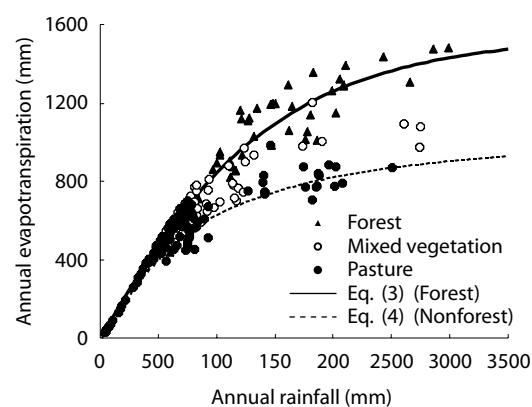


Figure 1. Relationships between annual evapotranspiration and rainfall (Zhang et al. 1999).

It is clear from Figure 1 that most of the forested catchments plot within the upper curve described by Equation 3, nonforested catchments plot around the lower curve described by Equation 4 and mixed vegetation catchments plot in the middle. The relationships described by Equations 3 and 4 are very similar to the empirical curves proposed by Holmes and Sinclair (1986) for catchments in Victoria.

Assuming that the change in catchment water storage over a long period is zero, catchment average water yield is calculated as the difference between long-term average rainfall and evapotranspiration. Figure 2 shows the resulting relationship between water yield and rainfall.

Case Studies

Estimation of the impact of land-use changes on catchment water yield for the main drainage divisions within the MDB (Fig. 3) required spatial data sets of rainfall, catchment boundaries and forest cover. We considered three land-use scenarios — pre-European vegetation, current vegetation and potential future forest plantation. We describe the sourcing and manipulation of these data, which were obtained from various government agencies and

captured for different purposes, and the methods and procedures used to estimate catchment area rainfall and percentage forest cover from these data.

We characterised forest cover for a given catchment using pre-European, current and potential future plantation forest areas of different temporal and spatial scales. Problems associated with initial vegetation classification were overcome by reclassifying the data into two main categories. This process allowed us to compare past, present and potential future vegetation coverage. We wrote ArcInfo programs (ARC macro languages; AMLs) to automate the resampling, the reprojecting of data and the model itself.

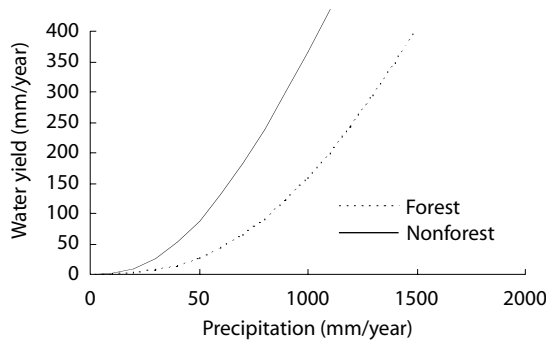


Figure 2. Relationship between catchment water yield and rainfall.

Rainfall surface

Monthly interpolated rainfall surfaces were combined to give a mean annual rainfall surface for 1980–95. Each grid cell is 0.05°, or approximately 25 km² (Jolly et al. 1997). The grid point analysis technique used to derive surfaces provides an objective average for each grid cell and useful estimates of rainfall in data-sparse areas. However, in data-rich areas such as southeast Australia or in regions with a strong rainfall gradient, ‘data smoothing’ will occur, resulting in values at point locations which may differ slightly from the exact rainfall recorded. Figure 4 shows the range and spatial distribution of long-term mean annual rainfall across the MDB.

Catchment boundaries

This project is based on 26 drainage divisions of the MDB with catchments ranging in size from 700 km² to 130,000 km² (Fig. 5). These catchment boundaries were taken from a previous salt load study (Jolly et al. 1997), which delineated catchments using a watershed analysis. Table 1 lists catchment areas and mean annual rainfall.

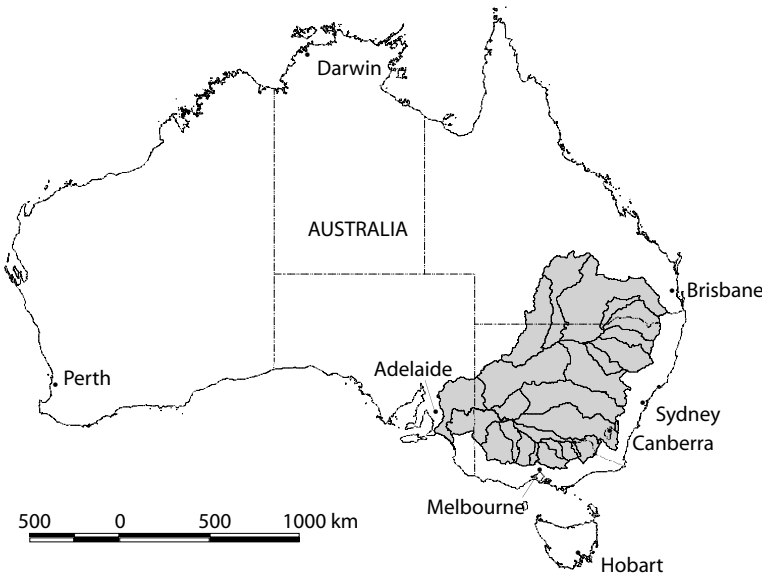


Figure 3. Location of the Murray–Darling Basin (grey area).

M305 vegetation dataset

The m305 multistructured vegetation data set contains attributes characterising land cover and vegetation (Ritman 1995). This study focuses on the woody vegetation component of the land cover

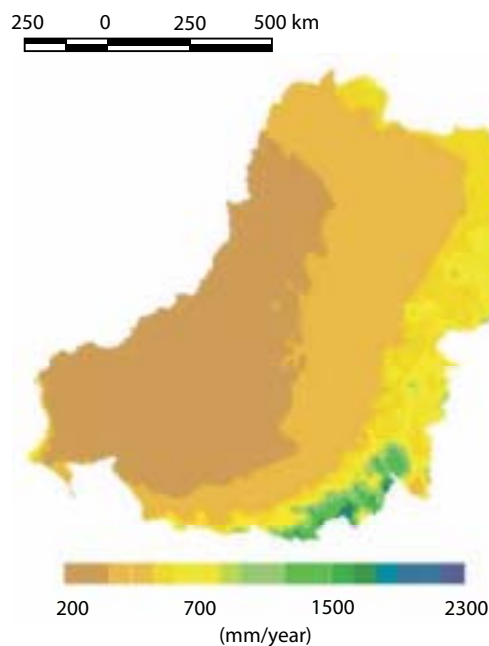


Figure 4. Distribution of mean annual rainfall throughout the Murray–Darling Basin.

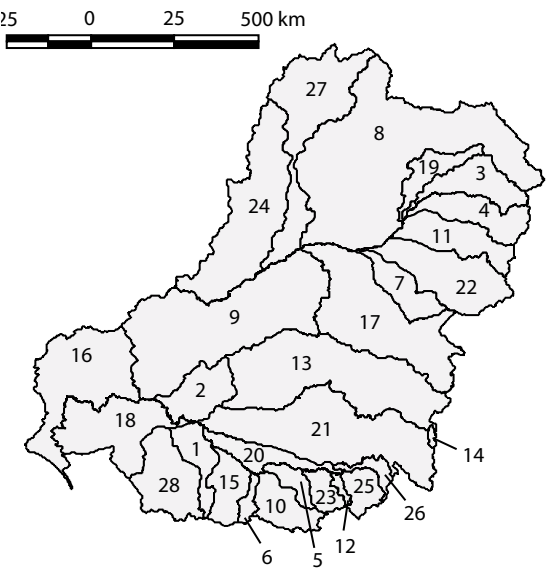


Figure 5. Location of the main drainage divisions within the Murray–Darling Basin (Jolly et al. 1997).

class. The woody vegetation was mapped from Landsat Thematic mapper (TM) imagery at a 30 m ground resolution with six bands per scene from as many cloud-free days as possible. Between late 1989 and 1991, images were chosen to maximise the

Table 1. Catchment area and mean annual rainfall for the 26 catchments within the Murray–Darling Basin.

ID No.	Catchments	Mean annual rainfall (mm)	Area (km ²)
1	Warrego River	408	62,940
2	Condamine-Culgoa	482	162,597
3	Paroo River	281	73,953
4	Moonie River	519	14,342
5	Border Rivers	621	48,041
6	Gwydir	620	26,586
7	Namoi	617	42,000
8	Macquarie	523	74,792
9	Darling River	295	112,832
10	Castlereagh River	537	17,423
11	Lower Murray	281	58,274
12	Lachlan River	470	90,880
13	Benanee	291	21,345
14	Murrumbidgee River	556	81,643
15	Mallee	301	41,488
16	Avoca River	365	14,201
17	Lake George	701	942
18	Wimmera-Avon	405	30,367
19	Murray–Riverina	395	15,039
20	Loddon River	461	15,655
21	Upper Murray River	1,105	15,342
22	Broken River	593	7,099
23	Ovens River	992	7,981
24	Goulburn	829	16,857
25	Campaspe River	590	4,048
26	Kiewa	1,190	1,912

number of cloud-free days. The imagery was initially resampled from 30 m to 25 m. An unsupervised classification into 100 classes was performed on the imagery to derive the woody vegetation. Each map sheet required resampling from 25 m to 250 m because the final mosaic grid would otherwise have been too data intensive. The resulting woody vegetation layer was filtered to minimum clusters of 0.25 ha. Woody vegetation is represented as land cover class 7 and defined as vegetation that has 20% crown cover and is over 2 m in height. A consolidated grid surface was created from the 472 1:100,000 scale map sheets and each map sheet was reprojected from the Australian map grid (AMG) to latitudes and longitudes. New South Wales, Queensland and Victoria had three AMG zones and South Australia had one. The Albers equal area coordinate system (Ritman 1995) is recommended for the basin-wide area statements. However, the model framework discussed does not require any absolute measured areas; it needs only the proportion of catchment under forest.

Carnahan pre-European vegetation data

The Carnahan pre-European settlement vegetation mapping is stored as a 1:5,000,000 scale map covering all of Australia in a geographic projection. The polygon coverage is based on the AUSLIG present vegetation that was created from Landsat multispectral scanner (MSS) imagery at the 1:1,000,000 scale between 1980 and 1985. We derived the pre-European vegetation by modifying current vegetation polygons using historical information, including the diaries of explorers and camel drivers, and soil and vegetation reports that date to the latter part of the nineteenth century. The Carnahan source data are an estimation of what vegetation could have existed prior to European settlement.

The classification attributes of the 1980–85 data were carried across to the Carnahan data set. It was therefore possible to compare the AUSLIG base vegetation data set (1980–85 MSS data) and m305 vegetation data set. Although there are large

differences between the spatial scale of the current m305 and the Carnahan pre-European vegetation data sets, the Carnahan data is the best that is available at this time. From a temporal perspective, the AUSLIG current vegetation coverage (1980–85) and the m305 vegetation data set (1989–91) are comparable. The comparison was undertaken to set classification rules for the polygon attributes when compared to the tree areas of the m305. Finally, these rules were transferred to the Carnahan pre-European data set to model a possible scenario. Three attribute fields were analysed from the current AUSLIG vegetation data set: ‘tallest stratum’, ‘density’ and ‘species growth form’.

Vegetation density foliage cover is expressed in terms of the proportion of the ground that is shaded by the tallest stratum at midday (McDonald et al. 1990). The AUSLIG vegetation data set expresses this in four classes, from < 10% to > 70%. Class 1 is 0–10% (crowns well separated), class 2 is 10–30% (crowns clearly separated), class 3 is 30–70% (crowns touching or slightly separated) and class 4 is 70% or greater (crowns touching to overlapping). The density of foliage cover of the lower stratum is not recorded in the code.

We chose classes 2 to 4 from the foliage cover attribute field. Classes 2 and 3 contain the greatest source of potential error of commission because they cover a broad range of vegetation types and are therefore difficult to compare with the 20% crown cover of the m305 data set. Foliage density was the first class to be investigated, so class 2 was included on the grounds that vegetation height and species would sufficiently discriminate the tree areas for comparison with the m305 vegetation cover. Moreover, when class 2 was omitted, significant areas that were considered ‘tree’ by the m305 data set were not accounted for. In short, more class 2 was considered as ‘tree’ than as ‘no tree’ when comparing to the woody m305 data set.

Species growth form is primarily classified into three vegetation groups: grasses, shrubs and trees.

These three groups are further broken down by vegetation height. Grasses and shrubs less than 2 m high were considered to be nonwoody vegetation and were excluded from the classification because they did not fit the m305 woody vegetation criteria. Table 2 shows which classes were chosen from the AUSLIG present vegetation classes and used in the analysis of the Carnahan pre-European vegetation. Figure 6 shows how the comparison is represented spatially between the two vegetation data sets based on the rules in Table 2.

The tallest stratum is defined as the uppermost stratum in which most of the incoming solar radiation is intercepted (McDonald et al. 1990).

Table 2. The rules used in the vegetation classification of forest for the AUSLIG vegetation data sets.

Rule	Class	Vegetation type
1	Tallest stratum (TS_SD)	Eucalyptus Conifers
2	Density (TS_D)	10–30% 30–70% 70% >
3	Species growth form (GF)	Low trees < 10 m (L) Medium trees 10–30 m (M) Tall shrubs > 2 m (S) Tall trees > 30 m (T)

When the data were tested, the tallest stratum data field was tested against the m305 vegetation data set. Conifers and eucalyptus were found to have the best correlation with the woody component of the m305 data set.

We generated a new grid by merging the m305 vegetation data set and the AUSLIG ‘present vegetation’ cover. With such estimations, there is a chance that errors of omission from the original data will occur. The correlation matrix shown in Table 3 illustrates an 8% error of omission where m305 has forest present and AUSLIG ‘present vegetation’ does not, and an 8% error of commission where m305 has no forest present and AUSLIG ‘present vegetation’ shows forest. This comparison is encouraging, particularly because the m305 vegetation data set was generated from a classification on a cell-by-cell basis and the AUSLIG vegetation is a polygon data set of grouped like-vegetation classes.

Table 3. Correlation matrix of the m305 vegetation data set and the AUSLIG present vegetation data set with regard to tree and no-tree areas.

		AUSLIG present	
		No tree	Tree
m305	No tree	72%	8%
	Tree	8%	12%

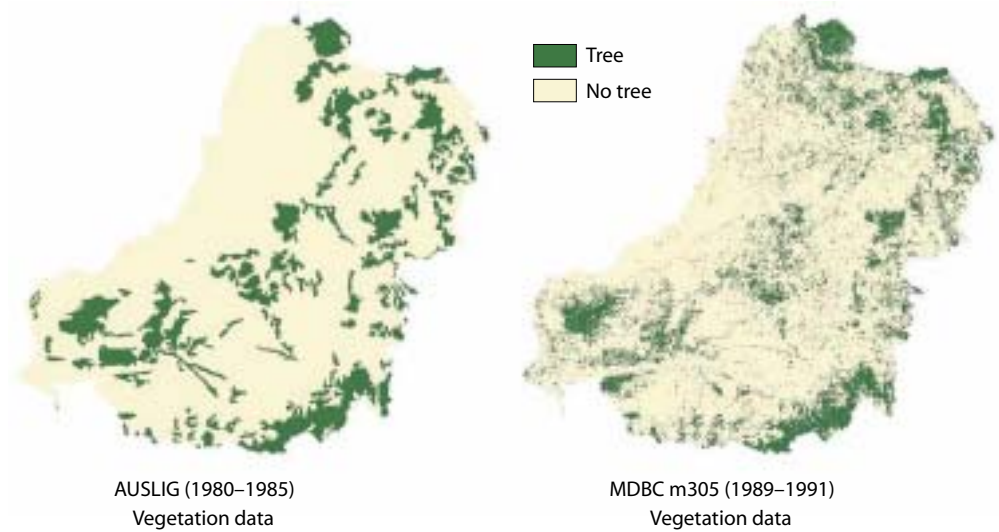


Figure 6. M305 vegetation and AUSLIG present vegetation shown as tree and no tree.

The rules described in Table 2 were applied to the Carnahan vegetation data set. Figure 7 shows the final classified Carnahan pre-European vegetation data set of tree and no tree.

Potential afforestation data

The potential afforestation data set was designed to predict areas suitable for hardwood plantation timbers across Australia. The main source data set used in this analysis considered the environmental factors that favour plantation hardwoods, including precipitation, topography, soils, pests and diseases (Booth and Jovanovic 1991). The potential forest plantation data set involved only the transformation of points to grids and reprojection from AMG coordinates to geographic coordinates. The cell size was 0.05° in latitude and longitude (approximately 25 km²). The resolution was chosen on the basis of the complexity of the analysis, storage requirements and the similarly coarse resolution of other data sets used in the suitability analysis. The attributes of the point data set were carried across to the grid surface. All areas suitable for plantation (i.e. low, medium or high suitability) were considered as the potential afforestation areas (Fig. 8); this represents the total areas currently under forest and the areas that can be reforested.

Results and Discussion

Catchment water yield under current vegetation conditions

The m305 woody vegetation data set of the MDB provides a coherent data set across the basin. Evapotranspiration from each catchment was calculated by combining the vegetation data with the annual rainfall data. In order to compare the results with stream flow measurements, catchment water yield was obtained by subtracting evapotranspiration from rainfall. Figure 9 shows estimates of the catchment water yield in relation to rainfall for all 26 catchments. The calculated catchment-scale water yields ranged from 14 to 335 mm/year, and were within the mean annual water yield relationships defined by Equations 3 and 4. It is clear from Figure 9 that the difference in catchment water yield between forested and nonforested catchments is small (up to 700 mm/year). However, the difference becomes larger as rainfall increases, suggesting that changes in vegetation cover will have a relatively large impact on catchment water yield in high-rainfall areas. This is an important relationship because areas of high rainfall are of great importance for water supply and stream salinity dilution.



Figure 7. Classified tree/no tree data from the Carnahan pre-European vegetation data set.

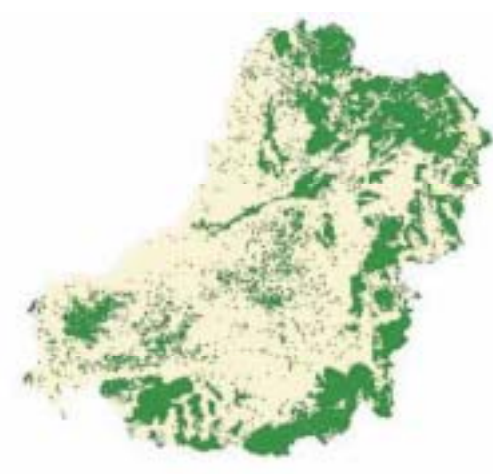


Figure 8. Potential plantation areas and the m305 vegetation data set combined.

Figure 10 shows the modelled catchment-scale water yields compared with long-term stream flow measurements reported by the Department of Natural Resources (1976) and Jolly et al. (1997). The best-fit slope through the origin was 1.03 and the model estimates were statistically consistent with the measurements. However, there were relatively large scatters in the results, and the model tended to overestimate water yield in low-rainfall catchments. When expressed as a percentage of mean annual rainfall, the error in the estimated water yield ranged between 16% and -5%.

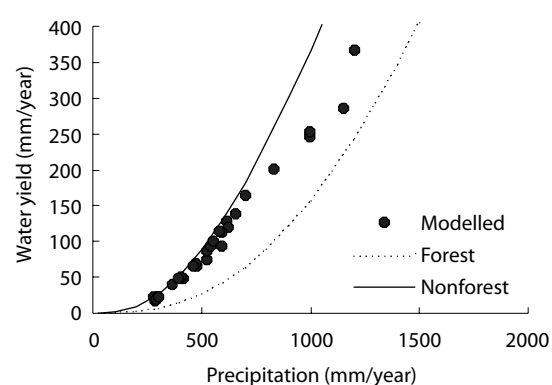


Figure 9. Estimates of water yield under current vegetation cover for the 26 catchments in the Murray–Darling Basin.

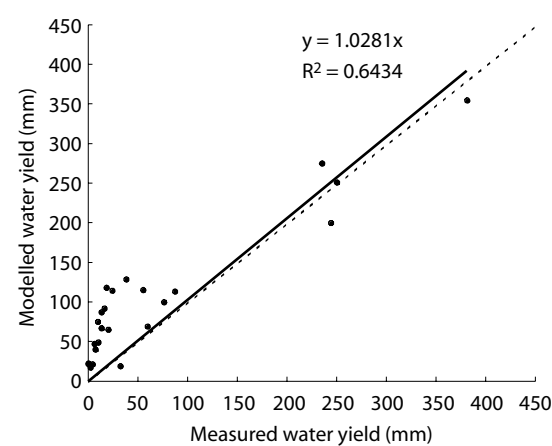


Figure 10. Comparison of calculated and measured catchment water yield for the major catchments in the Murray–Darling Basin. The dashed line is the 1:1 line and the solid line the regression line.

A number of factors could have contributed to the errors in the results. First, estimates of percentage forest cover could affect evapotranspiration modelled by Equation 3. In low rainfall catchments, average percentage forest cover was a small fraction of the total catchment area and some open woodlands were classified as nonforests. This would result in underestimates of evapotranspiration or overestimates of water yield. Second, rainfall distribution could also affect estimates of evapotranspiration and hence water yield. By using mean annual rainfall, the model is likely to underestimate evapotranspiration in catchments with summer dominant rainfall. Examination of the results shows that the model underestimated evapotranspiration in catchments such as Condamine–Culgoa, Moonie and Namoi. Rainfall in these catchments is summer dominant, with 35% of rain falling from December to February. The results from the model can be improved by introducing a seasonality index; this will be investigated in a future study. Finally, diversion of water occurs in many of the catchments in the MDB and it is extremely difficult to account for the effects of diversions on stream flow measurements. This shortcoming will also be investigated in a future study.

The estimated catchment water yields show significant spatial variation (Fig. 11). In the Benanee and Lower Murray catchments, mean annual water yield was less than 20 mm per year; in the eastern catchments, such as the Ovens and Upper Murray catchments, mean annual water yield was above 250 mm per year.

Catchment water yield under pre-European vegetation conditions

We used the model to try to evaluate the effect of clearing native vegetation on mean annual water yield based on current and pre-European vegetation data. Catchment water yields under pre-European vegetation conditions were calculated from the Carnahan pre-European vegetation data

set. We assumed that mean annual precipitation during that time was the same as the mean annual rainfall for the period 1980–95. The results are shown in Figure 12. The large-scale AUSLIG data set estimated average forest cover as 69% before European settlement. This value is significantly higher than the current forest cover of 20%, taken from the m305 woody vegetation data set. Table 4 illustrates the loss in forest cover for each catchment, using the above data set. As a result of loss of vegetation, estimated water yield under pre-

European vegetation conditions was consistently lower than that under current vegetation conditions (Figs 9 and 12). Water yield increased from 0 to 80 mm/year with the most significant changes occurring in the catchments east of the Darling River (Fig. 13). On average, estimated water yield in the MDB has increased from 46 to 69 mm/year.

These results are indicative only and may not represent the actual water yield under pre-European vegetation conditions. However, they provide some estimates of likely changes in catchment water yields resulting from the clearing of native vegetation. There are no gauged stream flow data under pre-European vegetation conditions; the only descriptive information available is written records left by explorers, travellers and settlers. Their view of streams, based on European experience, may be subjective but it provides a qualitative picture of the streams under pre-European conditions. For example, in the Upper Murrumbidgee, ‘It seems the small streams of the catchment were swampy at the time of European exploration, and many were chains-of-ponds.’ (Starr et al. 1999). This information suggests that stream flow under pre-European vegetation conditions would be less than the current stream flow.

Impact of potential afforestation on catchment water yield

Increased groundwater recharge has been identified as a major factor causing dryland salinity in the MDB. A number of land management options have been considered to reduce groundwater recharge; one is forest plantations. Forest can use more water than pasture and hence reduce recharge to groundwater systems. Afforestation can also affect water yield (Vertessy and Bessard 1999). A forest plantation capability scenario was mapped for the purpose of investigating potential commercially viable plantation areas (Booth and Jovanovic 1991). Plantation areas in the MDB were calculated from numerous factors, one of which was the absence of existing forests, which meant that a future scenario of

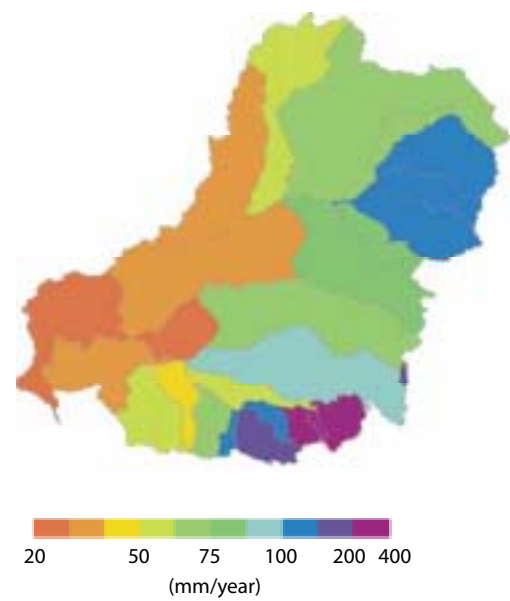


Figure 11. Predicted mean annual water yield distribution across the Murray–Darling Basin under current vegetation cover.

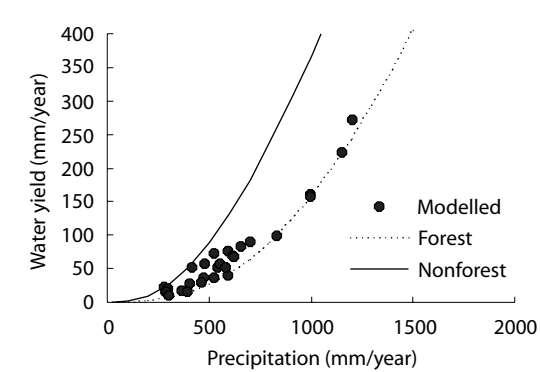


Figure 12. Catchment water yield under pre-European vegetation conditions.

forested areas could only be estimated by combining the potential afforested areas with the m305 vegetation data set. The vegetation scenario was based on the potential implementation of eucalyptus, acacia and pine as commercial plantations. Table 5 lists the criteria on which each species was chosen.

Table 4 illustrates the potential rise in forest cover given full adoption of potential plantation areas. There is opportunity for a significant increase in plantation area in some catchments—such as Condamine–Culgoa Rivers, Moonie River, Border Rivers, Goulburn River, and Wimmera–Avon

Table 4. Current forest cover compared to pre-European forest cover and potential plantation forest cover for the 26 catchments of the Murray–Darling Basin.

Catchment	Current forest (%)	Pre-European forest (%)	Decrease (%)	Potential plantation (%)	Increase (%)
Warrego River	21	21	0	38	17
Condamine-Culgoa	25	40	15	55	30
Paroo River	4	4	0	7	3
Moonie River	31	34	2	70	36
Border Rivers	29	64	35	49	19
Gwydir	14	75	61	32	18
Namoi	24	78	54	38	14
Macquarie	16	88	72	29	13
Darling River	13	23	10	13	0
Castlereagh	16	72	56	37	21
Lower Murray	28	39	12	29	1
Lachlan River	14	71	57	21	7
Benanee	27	48	21	27	0
Murrumbidgee	16	70	54	26	10
Mallee	23	80	57	24	1
Avoca River	8	76	69	46	39
Lake George	17	76	59	36	19
Wimmera–Avon	13	66	53	53	40
Murray–Riverina	10	92	83	14	4
Loddon River	16	84	68	46	30
Upper Murray	69	99	30	85	16
Broken River	18	100	82	24	7
Ovens River	54	99	45	65	11
Goulburn	36	100	64	61	25
Campaspe	15	86	71	20	6
Kiewa	56	89	33	69	13

Rivers. Such plantations would increase catchment evapotranspiration and hence reduce water yield (Fig. 14).

Figure 15 shows changes in water yield from the current vegetation and the potential plantation for all catchments. The southeastern catchments of the MDB would have a low to moderate change in water yield as a result of the afforestation; the catchments at the headwaters of the Murray River, where annual rainfall is relatively high, would experience a reduction in water yield of 20–40 mm/year. Minimal changes in water yield would occur in other catchments that are not considered to be suited for sustainable plantations. Although these changes are not as dramatic as those under the pre-European vegetation conditions, they may have significant impacts on water supply and salinity

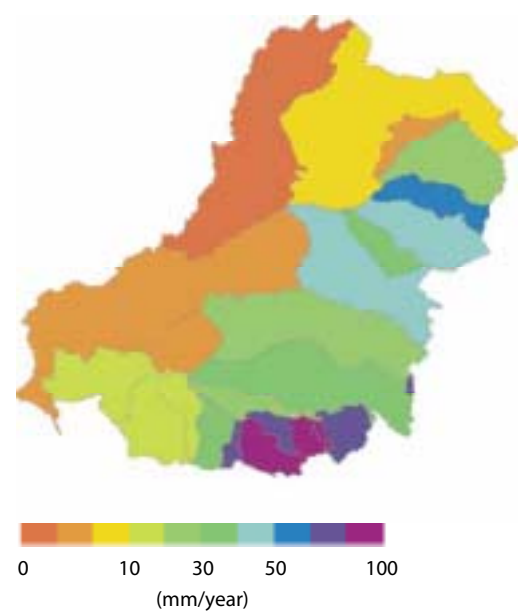


Figure 13. Increase in water yield from pre-European vegetation cover to current vegetation cover.

Table 5. Criteria for the selection of suitable forest plantation areas by species.

Species	Mean rainfall (mm/year)	Rainfall regime	Dry season length (months)	Mean max temp (°C)	Mean min temp (°C)	Mean annual temp (°C)	Soil
<i>Eucalyptus globulus</i>	600–1500	Winter/ uniform	0–5	19–30	2–12	9–18	Fertile loams
<i>Eucalyptus grandis</i>	800–2500	Summer	0–5	25–34	3–16	14–25	Alluvial, volcanic
<i>Eucalyptus nitens</i>	750–1500	All	0–4	20–28	–3–5	7–14	Granite, basalt
<i>Eucalyptus pilularis</i>	750–2000	Summer/ uniform	0–2	22–31	5–12	15–22	Sandy loams
<i>Eucalyptus regnans</i>	900–2000	Winter/ uniform	0–3	17–27	–2–6	7–14	Deep moist
<i>Eucalyptus saligna</i>	700–1800	Uniform/ summer	0–5	22–32	1–14	14–21	Sandy loams
<i>Acacia mangium</i>	1150–3700	Summer	0–5	29–33	12–30	23–28	Acid volcanic
<i>Acacia mearnsii</i>	800–1600	Uniform				16–20	Sands, loams
<i>Acacia melanoxylon</i>	480–2950			19–34	–3–16	9–25	Volcanic soils
<i>Pinus elliotii</i>	750–1700	Summer	0–5	26.5–31	5–12.5	18–23	Phosphorus soils
<i>Pinus radiata</i>	650–1600	Winter/ uniform	0–4	20–30	–2–12	11–18	Mixed

Source: Booth and Jovanovic (1991).

control. Vertessy and Bessard (1999) applied a similar relationship—developed by Holmes and Sinclair (1986)—to the Murrumbidgee catchment and concluded that afforestation in the catchment may significantly reduce mean annual runoff. Reduction in water yield not only imposes costs on users downstream but also affects stream salinity dilution. An important issue is the tradeoff between recharge control and water yield reduction, as these

are likely to vary with rainfall. Such information can help us to make responsible management decisions about land-use changes in the MDB.

Conclusions

This chapter demonstrates how the simple water balance model developed by Zhang et al. (2001) can be used in a GIS framework to estimate the impacts of vegetation changes on mean annual average water yield in a catchment. The model considers the effects of available energy and water on evapotranspiration and requires only mean annual rainfall and vegetation-cover measurements. Comparison between predicted and measured water yield under current land-use conditions agreed reasonably well for catchments with high rainfall; however, the model tended to overestimate water yield for low-rainfall catchments. The model may be improved by introducing a rainfall seasonality index and this will be further investigated. To evaluate the impact of clearing of the native vegetation in the MDB, we estimated water yield under pre-European vegetation conditions. The results showed significant reduction in water yield from most of the catchments within the basin. Although there are no direct stream flow data with which to compare these estimates, some descriptive information seems to indicate that there would be less runoff under pre-European vegetation conditions from the basin. We also attempted to evaluate the impact of afforestation on future catchment water yields and our analysis suggests that broad-scale afforestation in the basin may reduce mean annual water yield by up to 40 mm/year. This may be desirable from a point of view of recharge reduction but its impact on downstream water supply needs to be considered.

Large-scale afforestation affects not only mean annual stream flow, but also flow regime. Results from some paired catchment studies have shown significant changes in flow regime following clearing of forests (Burch et al. 1987; Jones 2000). Further studies are necessary to model these hydrological responses in large catchments.

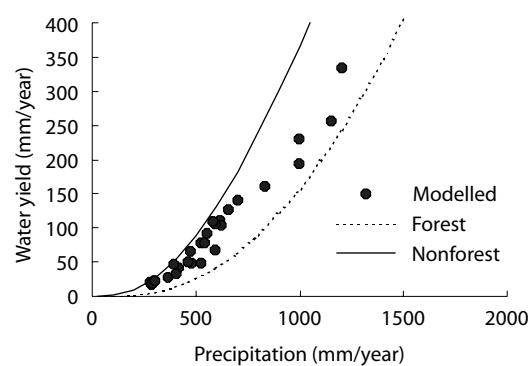


Figure 14. Estimates of water yield under the potential afforestation scenario.

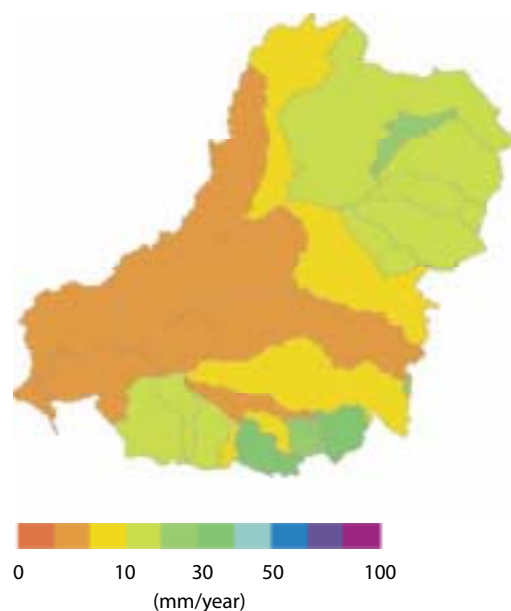


Figure 15. Change in water yield from current vegetation to potential afforested areas.

Acknowledgments

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References

Booth, T.H. and Jovanovic, T. 1991. Identification of Land Capable of Private Plantation Development. Report of the National Plantations Advisory Committee. Canberra, Department of Primary Industries and Energy, Appendix B, 1–86.

Burch, G.J., Bath, R.K., Moore, I.D. and O’Loughlin, E.M. 1987. Comparative hydrological behaviour of forested and cleared catchments in southeastern Australia. *Journal of Hydrology*, 90, 19–42.

Department of Natural Resources 1976. Review of Australia’s Water Resources (1975). Canberra, Australian Government Publishing Service.

Department of Primary Industries and Energy (DPIE) 1997. The 2020 Vision Statement. Canberra, ACT, DPIE.

Eagleson, P.S. 1982. Ecological optimality in water-limited natural soil vegetation systems. 1. Theory and Hypothesis. *Water Resources Research*, 18, 325–340.

Holmes, J.W. and Sinclair, J.A. 1986. Water Yield from Some Afforested Catchments in Victoria.

Jolly, I.D., Dowling, T.I, Zhang, L, Williamson, D.R. and Walker, G.R. 1997. Water and Salt Balances of the Catchments of the Murray–Darling Basin. Adelaide, CSIRO Land and Water Technical Report 37/97.

Jolly I.D., Williamson D.R., Giffedder M., Walker G.R., Morton R., Robinson G., Jones H., Zhang L., Dowling T.I., Dyce P., Nathan R.J., Nandakumar N., Clarke R., and McNeill V. 2001. Historical stream salinity trends and catchment salt balances in the Murray–Darling Basin, Australia. *Marine and Freshwater Research*, 52 (1): 53-63.

Jones, J.A. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basin, western Cascades, Oregon. *Water Resources Research*, 36, 2621–2642.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. 1990. Australian Soil and Land Survey Field Handbook, 2nd edition.

Natural Heritage Trust. 2001. Australian Dryland Salinity Assessment 2000. National Land and Water Resources Audit, Land and Water Australia, Canberra ACT.

Ritman, K.T. 1995. Structural Vegetation Data: a specification manual for the Murray Darling Basin Project M305.

Starr, B.J. 1999. The catchment at the time of European settlement. In: Wasson, R.J. and Caitcheaon, G., eds, *Soil Erosion, Phosphorous and Dryland Salinity in the Upper Murrumbidgee: Past Change and Current Findings*.

Turner, K.M. 1991. Annual evapotranspiration of native vegetation in a Mediterranean-type climate. *Water Resources Bulletin*, 27, 1–6.

Vertessy, R.A. and Bessard, Y. 1999. Anticipating the Negative Hydrologic Effect of Plantation Expansion: Results From a GIS-Based Analysis on the Murrumbidgee Basin.

Zhang, L., Dawes, W.R. and Walker, G.R. 1999. Predicting the Effect of Vegetation Changes on the Catchment Average Water Balance. CSIRO Land and Water Tech Report 99/12.

Zhang, L., Dawes, W.R. and Walker, G.R. 2001. The response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, 37, 701–708.

21 Land Degradation Assessment in the Mount Lofty Ranges: Upscaling from Points to Regions via a Toposequence

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Abstract

Natural resource assessment at regional scales is often time consuming, expensive and reliant upon the local knowledge and judgment of the surveyor. In this chapter we describe the development of an efficient method to assess land degradation (specifically waterlogging and saline and acid soils) at a regional scale. We developed spatial models by integrating knowledge of landscape processes with remotely sensed, terrain and field data, within a geographic information system (GIS). The key to this approach was the linkage of soil and hydrological processes (identified at the point scale) to mapped soil units via toposequences, and the allocation of land degradation classes to each of the units. The data were aggregated to catchment and regional scale to produce maps of land degradation. The results obtained from the modelling were validated by random ground assessments of sites across the region. The method described here could be applied to the assessment of other types of land degradation, and to other regions with comparable landscapes and vegetative covers, where similar soils, terrain and remotely sensed data exist.

区域尺度的自然资源评价既费时又耗资，常常不现实，而且也依赖于评估人员的知识水平、对该地区的了解程度和个人判断能力。本研究提出了评估土地退化（尤其是酸化、盐碱化和渍涝状况）更有效方法，给研究区劳伏特山地各流域的健康状态排名。我们将景观信息、遥感数据、野外数据与地理信息系统相结合，开发出空间模型。该方法的关键在于由布点测量的土壤和水文数据，推算坡面数据，与土壤地图单元联系，确定各单元土壤退化程度。将这些数据再汇总得到流域和区域范围的土地退化图。模型给出的结果

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和在整个地区野外随机检验结果一致。该方法可评估其他不同形式的土地退化，也可以应用到那些具有相似的景观和植被覆盖、存在类似的土壤地形和遥感数据的地区。

IN THE high-rainfall catchments of the Mount Lofty Ranges, South Australia, land degradation and poor quality of stream water contribute to losses in farm production and to off-site environmental impacts. The replacement of native vegetation by pastures and cereals that use less water has led to the development of salinity throughout the southern Australian agricultural zone. This change in land use increases the amount of water recharging to deeper groundwaters, which then rise and mobilise salt stored in soil profiles. The extent of waterlogged saline scalds is increasing. Such scalds are an early indicator of the formation of saline, structureless soils that are prone to water erosion. This land degradation has serious potential impacts on the supply and quality of Adelaide's drinking water, because the region contributes approximately 50–60% of the city's total supply.

There is no consistent method for assessing waterlogging and soil acidification or alkalisation in catchments at regional scale. Organisations or individuals assessing land degradation have developed techniques and expertise best suited to the particular task, adopting methods that are subjective, not clearly defined and often only applied to one particular type of land degradation. This lack of consistency is a major obstacle to the reliable assessment of degradation caused, for example, by poor drainage, salinity and erosion.

Our aim was to develop appropriate methods for assessing potential land degradation at the regional level, by upscaling data from point to catchment scale and using it for spatial modelling in a geographic information system (GIS).

Study Area

The region studied is centred east of the township of Mount Torrens in the Mount Lofty Ranges of South Australia and is approximately 80 km² in extent (Fig. 1). The climate is Mediterranean and representative of the eastern Mount Lofty Ranges, with a mean annual rainfall of 680 mm and a mean annual evaporation of 1170 mm. The generalised topography of the area consists of valley floors surrounded by rolling hills, with Mount Torrens lying to the west and a major faultline range defining the eastern extent of the area. A regional northeast to southwest topographic high, east of Mount Torrens township, bisects the area. Catchments to the west of this high drain into the Onkaparinga and Torrens catchment systems; catchments to the east of it form part of the Murray–Darling Basin catchment system. The topographic morphology of the area is strongly related to the underlying geology of near vertical dipping, north–south trending lineament features associated with Precambrian and Cambrian metamorphic formations.

Soils of the area are typical of the eastern Mount Lofty Ranges, being mostly Xeralfs (Soil Survey Staff 1998), formed from strongly weathered micaceous sandstones and schists of the underlying metasediments. These soils are characterised by abrupt textural boundaries between sandy and loamy textured surface horizons (A and E horizons) and clayey subsurface horizons (B horizons) with mottled and/or sodic properties. The land cover of the area is predominantly pasture, most native tree vegetation having been cleared by the end of the

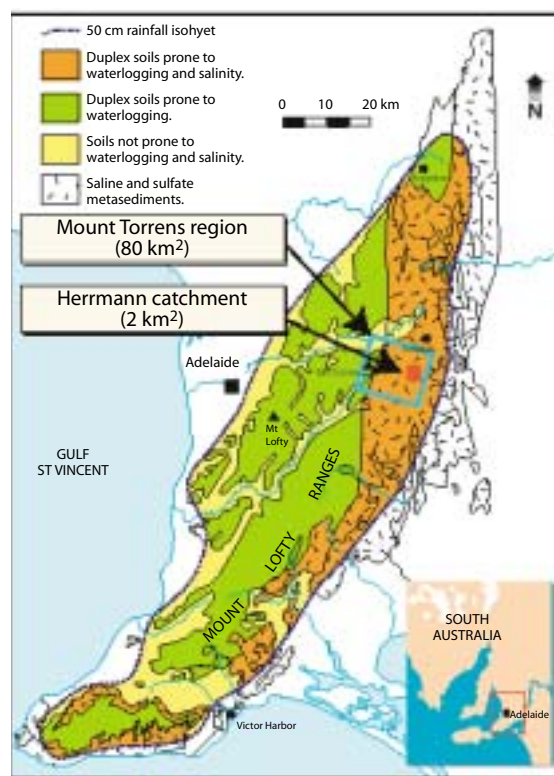


Figure 1. The Mount Torrens study area.

1800s. The remaining areas of remnant vegetation are associated mainly with topographic high points, roadways and watercourses.

To facilitate the process of upscaling, we selected a number of areas within the region for which data on soil, landscape, water quality and remote sensing were available. Detailed information on these studies is reported by Fritsch and Fitzpatrick (1994), Bruce (1996), Cox et al. (1996), Fitzpatrick et al. (1996) and Davies et al. (1998).

Scales and Nature of the Data

This chapter lists and briefly describes some of the various data sets that were used in the analysis. Table 1 summarises the data sets used at each of the various scales within the 80 km² regional area. A more comprehensive discussion of these data and how they were derived can be found in Fitzpatrick et al. (1999).

Herrmann toposequence (~400 m) and key area (~0.2 km²)

Measurements were taken at strategic soil sample points along a 400 m long toposequence within a 0.2 km² key area. They include:

- soil morphology, chemistry and mineralogy
- topography (landform)
- vegetation
- hydrology (perched and groundwater fluctuations)
- geomorphology
- multitemporal aerial photography
- airborne thermal infrared (IR) video.

Herrmann catchment (~2.0 km²)

- 1:5000 scale soil survey mapping
- soil pH measurements
- grid digital elevation model (DEM) and derived topographic index
- airborne synthetic aperture radar (SAR) and derived soil dielectric constant
- airborne thermal IR video
- Landsat Thematic mapper
- airphoto-derived vegetation index
- EM31 derived apparent electrical conductivity (ECa) and discharge index.

Mount Torrens region (~80 km²)

- 1:50,000 scale landscape unit (SLU) mapping and derived aquic index
- 1:50,000 SLU derived acidity classes
- 1:50,000 scale geology and derived geosalinity classes
- DEM and derived topographic index
- airborne SAR and derived soil dielectric constant
- Landsat Thematic mapper.

Description of derived data sets

The vegetation index for the catchment was linked to soil drainage conditions. We developed a computerised classification of multitemporal aerial photography corresponding to the late winter and late summer seasons using information collected for the toposequence and key areas. Native and introduced grass species found in different soil drainage and salinity conditions respond in different ways during these seasons. Thermal IR airborne video showed potential for assessing groundwater discharge sites and remnant stream channels. However, the poor geometry of this imagery only permitted interpretation at the key area scale.

Topographic index ($\ln(A_s/\tan\beta)$) is a secondary terrain attribute. It represents the geomorphic processes associated with soil moisture and its spatial distribution in the landscape. To determine the topographic index for the study area, we created a hydrologically correct, grid DEM using the method of Hutchinson (1989), and evaluated the variables of the index using the procedure of Hutchinson and Dowling (1992).

A soil dielectric constant was derived using data from the National Aeronautics and Space Administration Jet Propulsion Laboratory's airborne synthetic aperture radar. We related the constant to soil moisture status by modelling the radar backscatter. For this study we used the empirical approach of Dubois et al. (1995) to derive a dielectric constant for the entire 80 km² region.

We used ECa, derived from the EM31 survey,¹ to determine the relative distribution of soluble salts in the landscape and preferred pathways of solute and water flow in the subsurface region. ECa was also a

quick and efficient means to interpolate between sites of known soil properties.

A discharge index, used to partition the landscape into zones of recharge or discharge (Cook and Williams 1998), was also derived from EM31 survey data. This index adds an extra dimension to salinity hazard mapping; it provides a numerical value ranging from strongly negative for low salinity/strongly recharging soils to strongly positive for high salinity/strongly discharging soils.

We derived an aquic index from the land classification attributes associated with the digital 1:50,000 scale SLU data mapped by Primary Industries and Resources South Australia (PIRSA). These attributes or land qualities include drainage, water erosion potential, scalding, salinity and recharge potential. The classification ranks each of these qualities on a numeric scale according to eight generically defined class limits. We considered salinity and drainage to be indicative of aquic conditions (i.e. soil landscape units prone to waterlogging).

We constructed geosalinity classes from the digital geology 1:50,000 scale coverage from PIRSA and classified representative units on the basis of inferred landscape salinity effect. Unit classifications ranged from no significant effect, to acting as a potential source of cyclic salt, to being a source of pyritic materials capable of causing aggressive acid weathering and salt generation (sulfate, chloride, magnesium, sodium, calcium and iron).

To predict the distribution of acidity classes over the region, we consolidated the acidity attribute of the 1:50,000 SLU data from the catchment survey into five classes that represent the progression from extreme profile alkalinity (and sodicity) to extreme profile acidity. These classes are associated with susceptibility to dispersion, salinity and erosion in the case of extreme alkalinity and acidification.

¹ EM31-D is an electromagnetic induction instrument (manufactured by Geonics Ltd, Mississauga, Ontario, Canada), used to measure the apparent electrical conductivity of the ground.

Methodology

Upscaling and spatial modelling

Our approach was to extrapolate soil and hydrological process patterns recognised in the field from point scale to catchment and region by aggregating them. Such upscaling is generally difficult due to the lack of relevant and precise data at the broader scale (Wood et al. 1988; King et al. 1998). The problem can be overcome by linking process patterns to mapped soil units via the toposequence and allocating land degradation classes to each of the units. This approach integrates broader-scale soil, geology, terrain and remotely sensed data within a GIS modelling environment.

Most of the nonpoint data used for this study consists of multiclass raster (regular grid cell) coverages. As the objective was to assess potential land degradation at the regional level, we decided to use a weighted index overlay as the spatial modelling technique (Bonham-Carter 1994). This model is linear, additive and suitable for ranking areas according to potential for degradation (i.e. it is predictive). We evaluated each coverage according to a weighted criterion, based on both

trial data and expert knowledge, and scaled the results of the model by applying a classification table of breakpoints to the ranking. The resulting classified data set provided an estimate of potential land degradation that could be verified by limited, random field survey.

The modelling procedures for waterlogged, saline and acid soil conditions are described below for each of the scales. To illustrate the approach we give examples of data models and results for estimates of drainage/waterlogging at each scale. Full details of the procedures and results are reported in Fitzpatrick et al. (1999).

Toposequence/key area

For the toposequence/key area, we analysed a range of detailed point data. The steps outlined below were used to select, describe, distinguish and construct the soil layers in the toposequence. Using this data we could map soil profiles in the key area surrounding the toposequence and thus extrapolate landscape degradation patterns to the catchment and regional level.

Table 1. Summary of data sets used at different scales for different types of land degradation.

Data	Scale											
	Toposequence			Key area			Catchment			Region		
	D/W	SAL	A/A	D/W	SAL	A/A	D/W	SAL	A/A	D/W	SAL	A/A
Soil samples												
Hydrology												
Topography												
Vegetation												
EM31												
Soil dielectric												
SLU												
Geology												

Note: shaded boxes indicate data used for that scale; if boxes are not shaded, data were not used at that scale. A/A = acidity/alkalinity; D/W = drainage/waterlogging; EM31 = conductivity; SAL = salinity; SLU = scale landscape unit

Steps in the process

Select representative catchments and toposequences

- Collate existing information on soil, geology and vegetation.

Describe morphological features in toposequences

- Describe morphological features in soil layers (e.g. soil colour and stone lines).
- Identify soil horizons (e.g. E or Btg) to compare with common scientific terminology.

Group and map morphological features in toposequences

- Group similar morphological features into a smaller number of soil layers (soil systems) using the structural analysis approach (Fritsch et al. 1992), which groups soil features by nested or concordant relationships.
- Develop cross-sections of toposequences for the combined soil layers.

Match soil layers to pedohydrological processes

- Monitor watertable fluctuations (using piezometers and dipwells), soil redox potentials (using Eh probes) and geochemical changes such as EC.
- Link soil and hydrological processes, such as water flow paths and salinity, to each soil layer.

Identify soil mapping units in a key study area surrounding the toposequence

- Collect field survey data from boreholes and representative soil profiles down several toposequences, and analyse soil samples in the laboratory.
- Define landscape and soil mapping units in the key study area using 1:5000 scale aerial photography.
- Determine a range of diagnostic variables for each mapping unit from field observations and soil profile analysis.

Link soil and hydrological processes to the soil mapping units

- Allocate drainage/waterlogging, salinity and acidity/alkalinity classes to each map unit by linking to soil and hydrological processes.

For each type of land degradation (drainage/waterlogging, salinity and acidity/alkalinity), eight classes were allocated to soil layers in the toposequence and five to soil profiles for the key area. Figure 2 illustrates the model used to estimate soil drainage/waterlogging at both scales.

Results—toposequence/key area

Table 2 illustrates the relationships that were developed for each of the three types of land degradation from the toposequence and key area studies. Figure 1 of Chapter 9 shows the estimate of soil drainage/waterlogging for the toposequence and Figure 3 of this paper shows the estimate for the key area. The types of land degradation were verified using soil survey and hydrological data (Cox et al. 1996; Fitzpatrick et al. 1996).

Catchment

Before data modelling and mapping, we developed a GIS for the catchment area to integrate and analyse field and remote sensing data. We digitised the soil survey data at 1:5000 scale, derived from aerial photography and borehole investigations (Fig. 4) and attributed it to the classes defined in Table 2. This information helped us to rank potential drainage/waterlogging, salinisation and acidification at the catchment scale.

We estimated soil drainage/waterlogging from the weighted overlay of vegetation index, topographic index, soil dielectric and EM31-derived discharge index (Fig. 5); salinity from the weighted overlay of topographic index, soil dielectric and EM31-derived EC; and acidity/alkalinity from the weighted overlay of topographic index, geology and soil pH measures.

Table 2. Soil mapping units and associated drainage/waterlogging, salinity and acidity/alkalinity classes for the Herrmann toposequence and key area.

Map unit	Landform elements	Soil description	Drainage/waterlogging	Acidity/alkalinity ^a	Salinity (ECse)/depth to saline water (m)
1a	Flat	Grey sandy loam surface layer over yellow-grey mottled clay	Poorly drained Strongly waterlogged	Moderately acidic (pHw=<6.5) surface, neutral to alkaline at depth	Slightly saline 1–4 dS/m; 1–1.5 m
2n	Flat	Salt efflorescence (halite and gypsum) on surface with grey sandy loam surface over yellow-grey clay	Poorly drained Strongly waterlogged	Mostly alkaline throughout (pHw >7.5)	Very saline >8–16 dS/m < 1 m
3s	Flat/lower slope seepages	Salt efflorescence (halite and gypsum) on surface with loamy black sulfidic material overlying yellow-grey clay	Very poorly drained Strongly waterlogged	Mostly alkaline throughout (pHw >7.5); sporadic occurrences of highly acidic (pHw <5.5) near-surface layers (<5cm), which develop due to oxidation of sulfidic materials	Extremely saline >16 dS/m; < 1 m
4a	Lower slope, open depression	Grey sandy loam surface layer over yellow-red-grey mottled clay	Poorly drained Periodic waterlogging	Neutral throughout (pHw 6.5–7.5)	Slightly saline 1–4 dS/m 1.5–3 m
5s	Lower slope, open depression	Deep grey sand over yellow-grey mottled clay	Poorly drained Periodic waterlogging	Acidic throughout (pHw=<6.5) (low buffer capacity)	Nonsaline <1 dS/m; 1.5–3 m
6l	Crest	Shallow sandy loam over red uniform coloured clay over weathered rock	Freely drained Infrequently waterlogged	Very acidic throughout (pHw <5.5)	Nonsaline <1 dS/m > 3 m
7a	Mid-slope	Brown loam over red and yellow uniform coloured clay. Deep.	Freely drained Infrequently waterlogged	Moderately acidic (pHw <6.5) throughout	Nonsaline <1 dS/m > 3 m
7ag	Crest, upper-slope	Deep well-drained red and yellow soils	Freely drained Infrequently waterlogged	Moderately acidic (pHw <6.5) surface, neutral to alkaline at depth	Nonsaline <1 dS/m > 3 m
7b	Crest, upper-slope	Deep well-drained red and yellow soils	Freely drained Infrequently waterlogged	Very acidic throughout (pHw <5.5)	Nonsaline <1 dS/m > 3 m
7bg	Crest, upper-slope	Shallow well-drained red yellow soils	Freely drained Infrequently waterlogged	Moderately acidic (pHw <6.5) throughout	Nonsaline <1 dS/m > 3 m
7c	Lower slope, open depression	Shallow well-drained yellow soils	Moderately drained Infrequently waterlogged	Neutral throughout (pHw 6.5–7.5)	Nonsaline <1 dS/m 1.5–3 m
Rq	Crest, upper-slope	Shallow well-drained yellow and red soils with quartz fragments	Freely drained Infrequently waterlogged	Moderately acidic (pHw <6.5) throughout	Nonsaline <1 dS/m > 3 m
Rf	Crest, upper-slope	Shallow well-drained yellow and red soils with ferricrete fragments	Freely drained Infrequently waterlogged	Very acidic throughout (pHw <5.5)	Nonsaline <1 dS/m > 3 m
Rs	Mid-slope	Shallow well-drained red soils with micaceous rock fragments	Freely drained Infrequently waterlogged	Moderately acidic (pHw <6.5) surface, neutral at depth, high buffer capacity	Slightly saline 1–4 dS/m > 3 m
E	Flat/stream channel	Gully, tunnel and rill erosion	Very poorly drained Strongly waterlogged	Mostly alkaline throughout (pHw >7.5)	Extremely saline >16 dS/m; < 1 m

^a pHw means that the pH measurement was taken in water

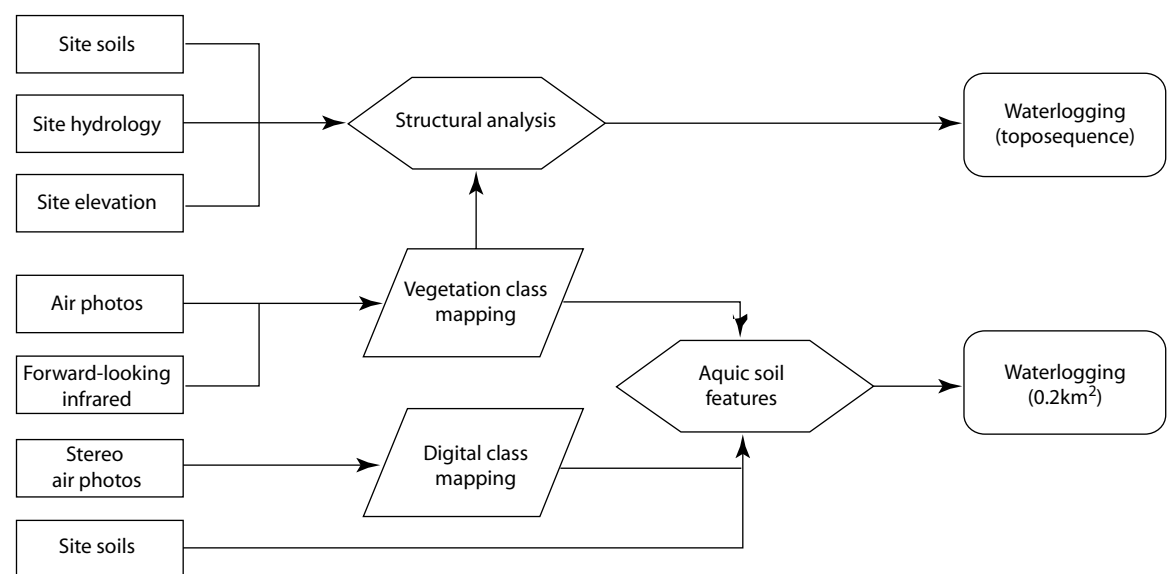


Figure 2. Drainage/waterlogging data model for the toposequence and key area.

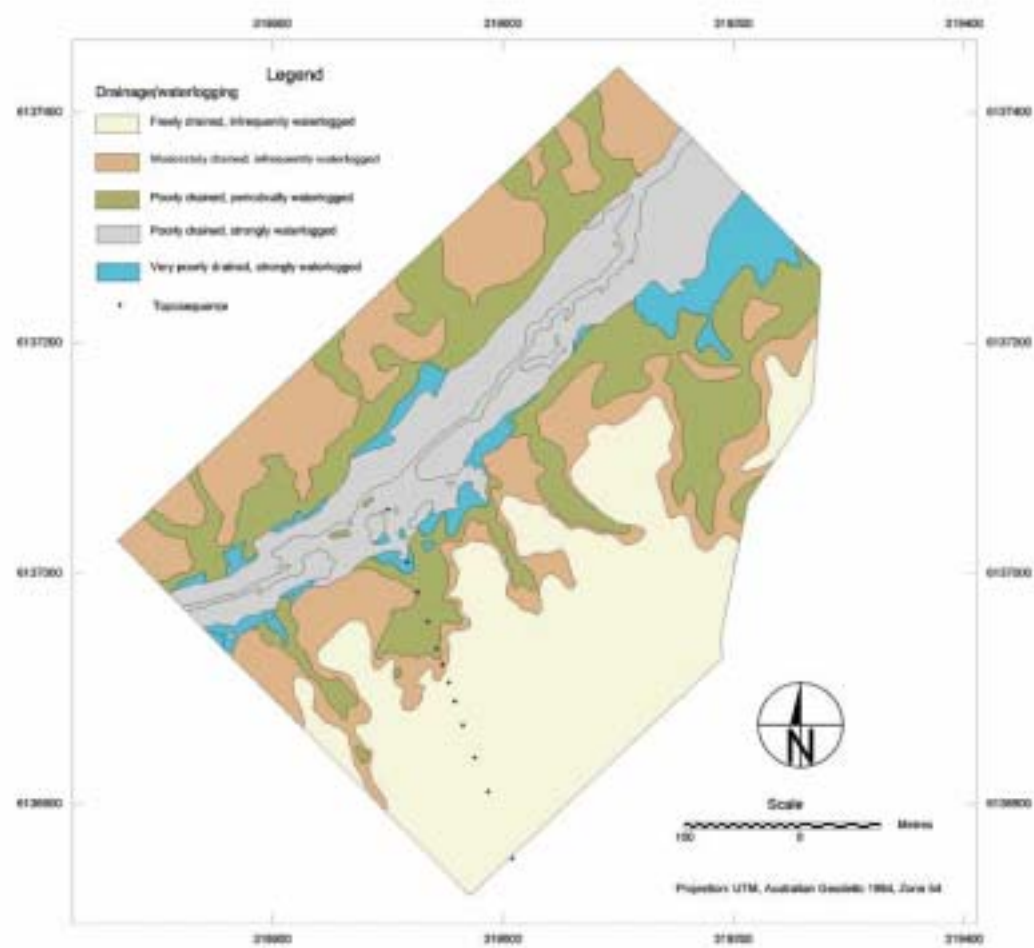


Figure 3 Estimate of drainage/waterlogging for the key area.

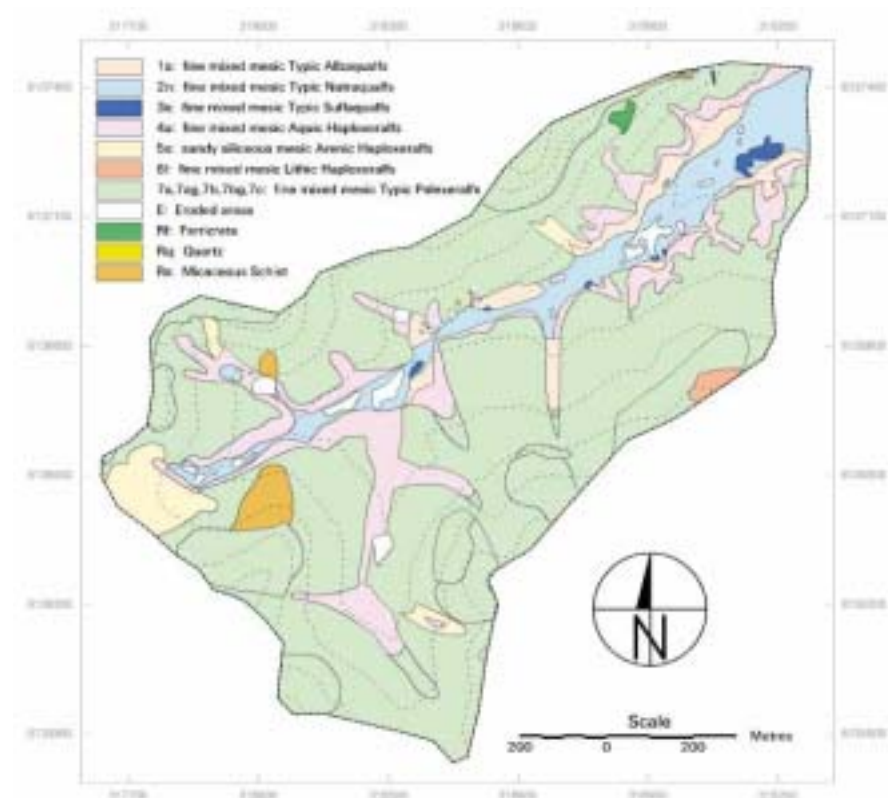


Figure 4. 1:5000 scale soil survey of the Herrmann catchment.

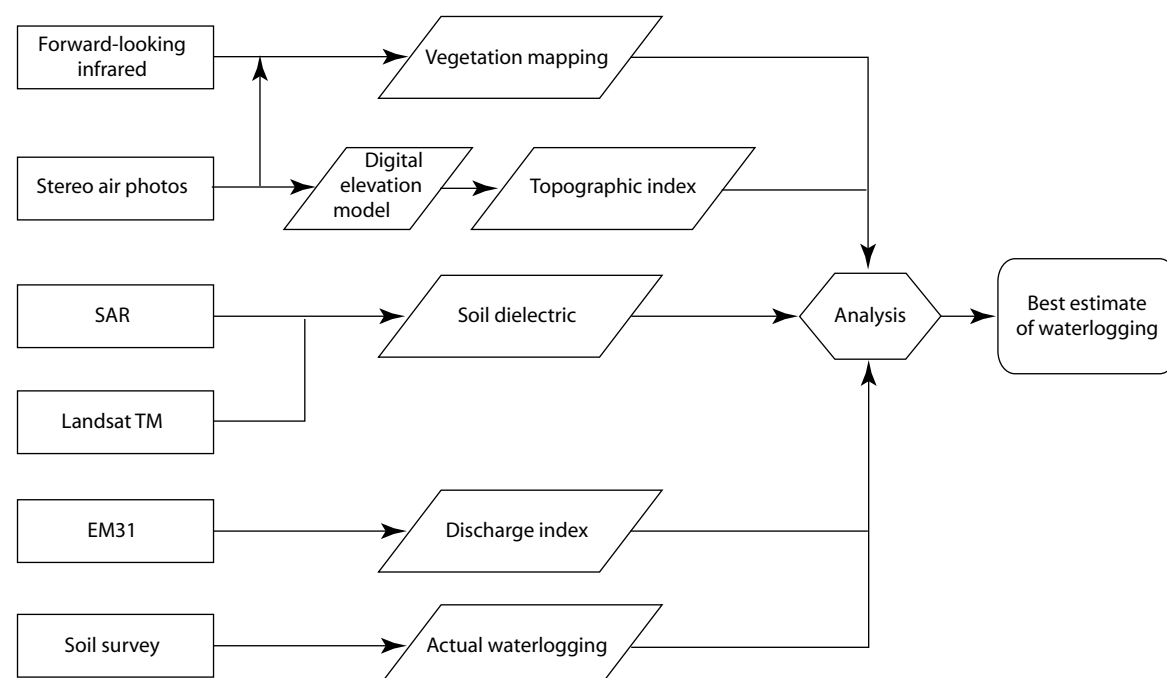


Figure 5. Drainage/waterlogging data model for the catchment. SAR is airborne synthetic aperture radar; Landsat TM is Landsat Thematic mapper; EM31 is derived apparent electrical conductivity.

Results—catchment

Each of the three estimates for the catchment was classified according to the relevant types of land degradation mapped by the 1:5000 scale soil survey. Figure 6 compares the estimate of drainage/waterlogging to mapped information. In general, the estimated results show a positive relationship with the field mapping (Davies et al. 2000). The results of the weighted overlay modelling are affected by any anomalies in the input data. For example, the discharge index showed an area of discharge in the catchment that does not correlate with drainage/waterlogging as mapped by survey. This was explained by field investigations, which indicated an area of clay-rich soil (not previously mapped) that was being incorrectly sensed by the EM31 survey as an area of high ECa.

Region

Some of the higher resolution data used for catchment modelling are not available at regional scale. The weighted overlay model provided a

means to aggregate the appropriate broader scale data with suitable higher resolution data, to allow ranking of the potential for land degradation.

At a regional scale, drainage/waterlogging was estimated from the weighted overlay of topographic index, soil dielectric and SLU-derived aquic index (Fig. 7); salinity from the weighted overlay of geology, soil dielectric and topographic index; and acidity/alkalinity from the weighted overlay of topographic index and SLU-derived acidity index.

Results—region

Figure 8 shows the results of modelling to estimate drainage/waterlogging at the regional scale. Thirty-five independent historical sites and five recently sampled random sites were used to verify the three land degradation estimates at regional scale. The estimates from the model correlated well with the site samples. More detailed analyses of the acidity estimates are included in Merry et al. (2000).

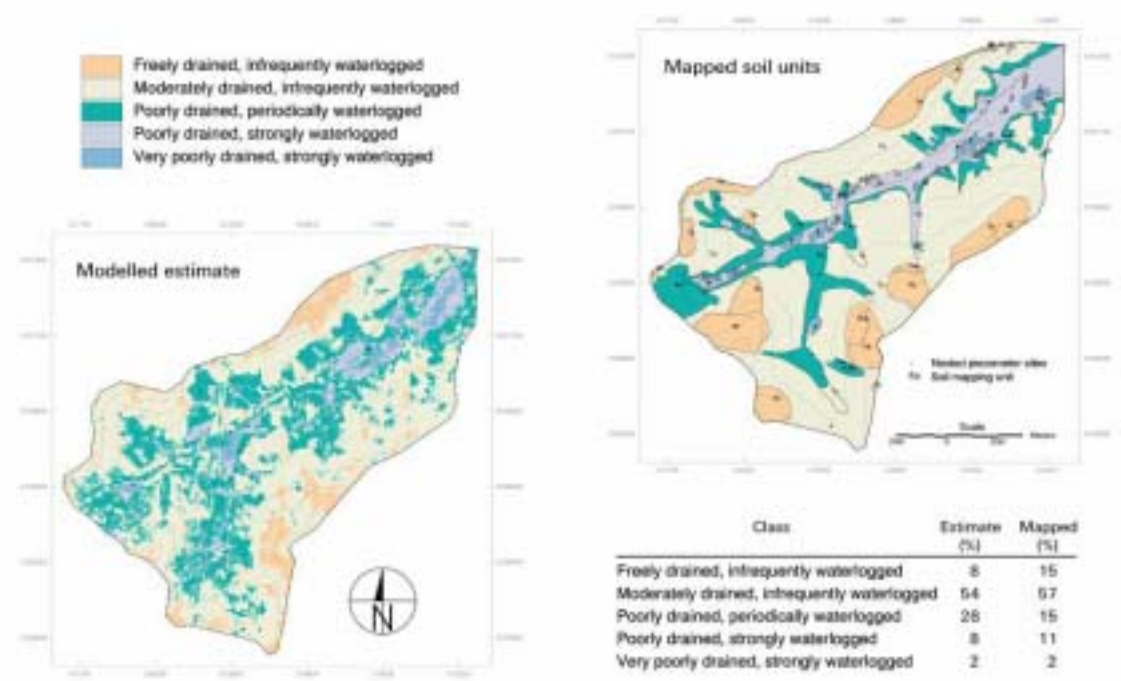


Figure 6. Potential waterlogging in the Herrmann catchment: comparison of map of best estimate data with mapped soil units.

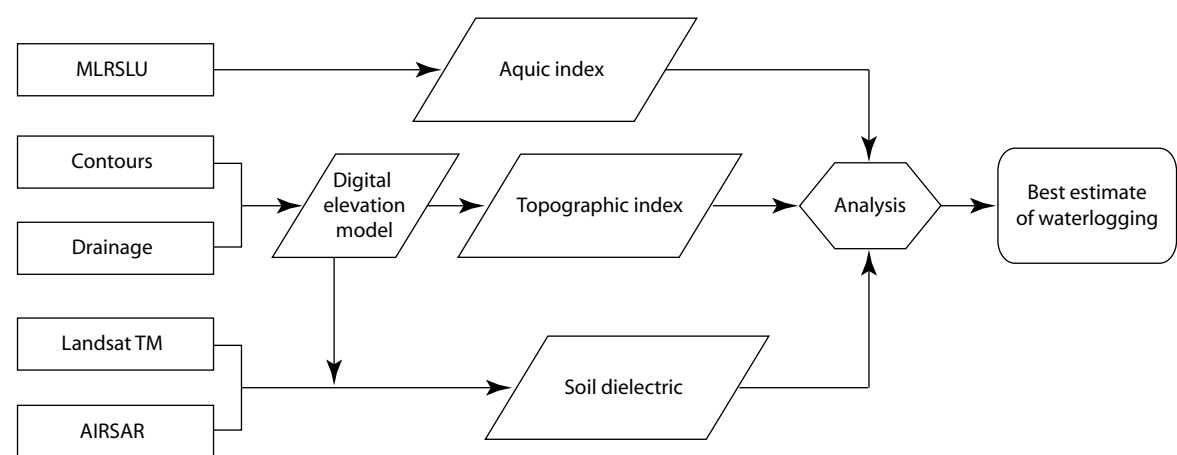


Figure 7. Drainage/waterlogging data model for the Mount Torrens region. MLRSLU = Mount Lofty Ranges scale landscape unit; TM = Thematic mapper.

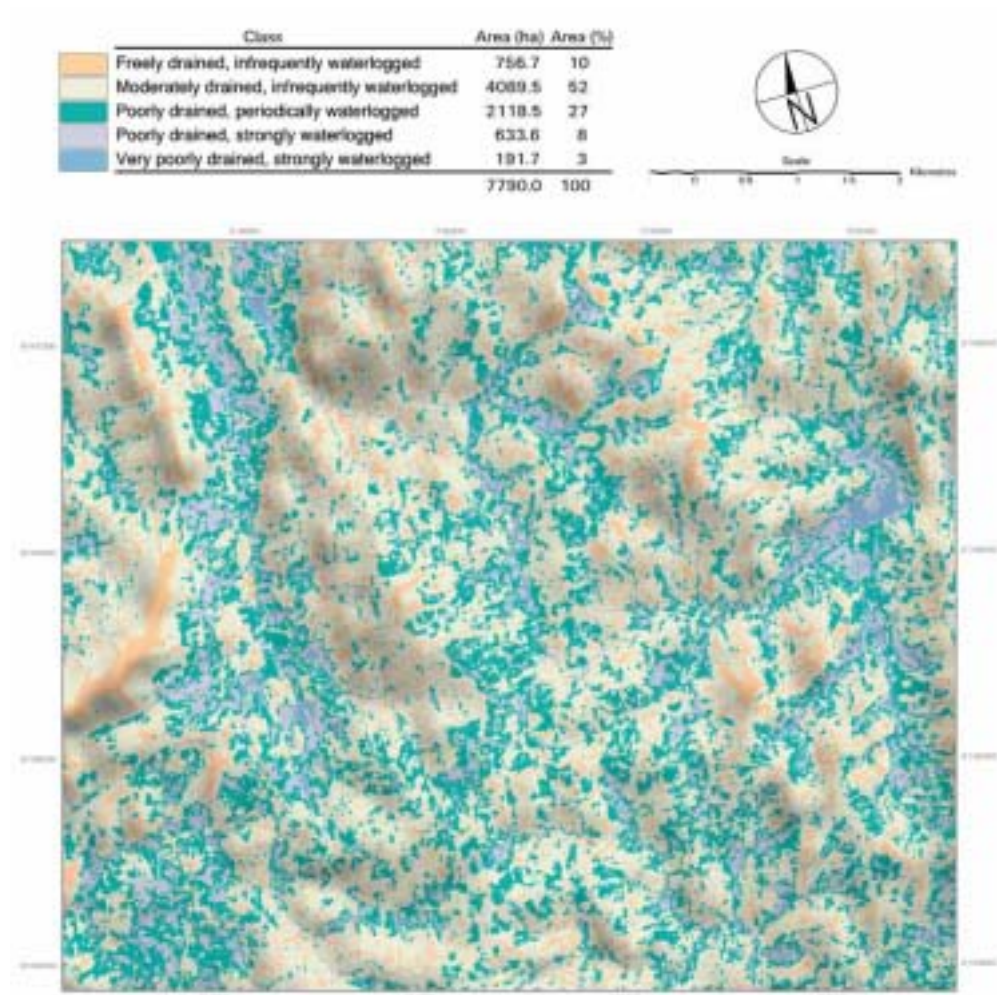


Figure 8. Estimate of drainage/waterlogging for the Mount Torrens region.

Discussion

Using relationships developed from detailed toposquence studies we were able to classify each type of land degradation for the 1:5000 scale soil survey. This classification allowed us to explore the value of broader-scale spatial data in weighted overlay modelling.

Using the models, we could aggregate many of the data sets at the regional scale and rank the potential for land degradation. These rankings could then be classified at the catchment scale using mapped areas and at the regional scale using information obtained from random sites. The extensive use of topography in the form of a grid-based DEM at all scales was a major factor in the ability to aggregate many of the data sets at the regional scale.

The linear, additive nature of the weighted index overlay technique has some disadvantages — any anomalies in the input data tend to modify the results. In such cases, a fuzzy logic method with more flexible combination rules would be advantageous. In this study, anomalies were partially resolved by obtaining appropriate field samples.

The classified ranking provided estimates of waterlogged, saline and acid soils at the regional scale. Although the results have only been analysed qualitatively and have not undergone spatial statistical analyses, they show good agreement with data from independent site checks across the region.

Conclusions

We successfully used a number of different sets of data to upscale assessment of land degradation. The key to translating between scales is to link point-scale process patterns to mapped soil units and allocate land degradation classes to each of the units. We were able to extrapolate point observations to the catchment and regional scale by integrating broader-scale data through weighted overlay modelling within a raster GIS environment.

Using models, we could characterise and assess natural resource status and condition at a scale appropriate for ranking the relative quality of catchments. Regional assessment of land degradation can be used in conjunction with a soil assessment manual (Fitzpatrick et al. 1997) to map problem sites and develop strategies for property management. This approach can help Landcare groups and government agencies to make decisions on resource management based on the knowledge of soil conditions.

The approach described here could be applied to other types of land degradation, and could be used in other regions with comparable landscapes and vegetative covers, where there are similar soils, terrain and remotely sensed data.

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References

- Bonham-Carter, G.F. 1994. Computer Methods in the Geosciences: geographic information systems for geoscientists: modelling with GIS. Oxford, Pergamon.
- Bruce, D.A. 1996. Soil moisture from multi-spectral, multi-polarising SAR. In: Proceedings of 8th Australasian Remote Sensing Conference, Canberra, March.
- Cook, P.G. and Williams, B.G. 1998. Basics of Recharge and Discharge: Part 8 Electromagnetic induction techniques. Collingwood, CSIRO Publishing.
- Cox, J.W., Fritsch, E. and Fitzpatrick, R.W. 1996. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: VII. Water duration. Australian Journal of Soil Research, 34, 803–824.
- Davies, P.J., Bruce, D.A., Fitzpatrick, R.W., Cox, J.W., Maschmedt, D. and Bishop, L. 1998. A GIS using remotely sensed data

- for identification of soil drainage/waterlogging in southern Australia. Proceedings of the International Soil Science Society Congress, Montpellier, France. 20–26 August, 1998.
- Davies, P.J., Fitzpatrick, R.W., Bruce, D.A., Spouncer, L.R. and Merry, R.H. 2000. Use of spatial analysis techniques to assess potential waterlogging in soil landscapes. In: Adams, J.A. and Metherell, A.K., eds, *Soil 2000: New Horizons for a New Century*. Australian and New Zealand Second Joint Soils Conference. Volume 3: Poster Papers. 3–8 December 2000, Lincoln University. New Zealand Society of Soil Science.
- Dubois, P.C., van Zyl, J.J. and Engman, E.T. 1995. Measuring soil moisture with imaging radars. *IEEE Transactions on Geoscience and Remote Sensing*, 33, 4, 510–516.
- Fitzpatrick, R.W., Fritsch, E. and Self, P.G. 1996. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: V. Development of saline sulfidic features in non-tidal seepage areas. *Geoderma*, 69, 1–29.
- Fitzpatrick, R.W., Cox, J.W. and Bourne, J. 1997. Managing waterlogged and saline catchments in the Mount Lofty Ranges, South Australia: a soil-landscape and vegetation key with on-farm management options. *Catchment Management Series*. CRC for Soil and Land Management. CSIRO Publishing, Melbourne. 36 pp. ISBN 1 876162 30 9.
- Fitzpatrick, R.W., Bruce, D.A., Davies, P.J., Spouncer, L.R., Merry, R.H., Fritsch, E. and Maschmedt, D.J. 1999. *Soil Landscape Quality Assessment at Catchment and Regional scale: Mt Lofty Ranges Pilot Project*, final technical report. CSIRO Land and Water Technical Report No. 28/1999, 50 p.
- Fritsch, E., Peterschmitt, E. and Herbillon, A.J. 1992. A structural approach to the regolith: Identification of structures, analysis of structural relationships and interpretations. *Sciences Géologiques*, 45, 2, 77–97.
- Fritsch, E. and Fitzpatrick, R.W. 1994. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: I. A new method for constructing conceptual soil–water–landscape models. *Australian Journal of Soil Research*, 32, 889–907 (colour figs. 880–885).
- Hutchinson, M.F. 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *Journal of Hydrology*, 106, 211–232.
- Hutchinson, M.F. and Dowling, T.I. 1992. A continental hydrological assessment of a new grid-based digital elevation model of Australia. In: Beven, K.J. and Moore, I.D., eds, *Terrain Analysis and Distributed Modelling in Hydrology*. Chichester, John Wiley.
- King, D., Fox, D.M., Daroussin, J., Le Bissonnais, Y. and Daneels, V. 1998. Upscaling a simple erosion model from small area to a large region. *Nutrient cycling in Agroecosystems*, 50, 143–149.
- Merry, R.H., Spouncer, L.R., Fitzpatrick, R.W., Davies, P.J. and Bruce, D.A. 2000. Prediction of soil profile acidity and alkalinity—from point to region. In: Adams, J.A. and Metherell, A.K., eds, *Soil 2000: New Horizons for a New Century*. Australian and New Zealand Second Joint Soils Conference. Volume 3: Poster Papers. 3–8 December 2000, Lincoln University. New Zealand Society of Soil Science.
- Soil Survey Staff 1998. *Keys to Soil Taxonomy*, 8th edition. Washington, US Government Printing Office: USDA, Natural Resources Conservation Service.
- Wood, E.F., Sivapalan, M., Bevan, K.J. and Band, L.E. 1988. Effects of spatial variability and scale with implications to hydrological modelling. *Journal of Hydrology*, 102, 28–47.

22 Regional Evaluation of Soil Erosion by Water: a Case Study on the Loess Plateau of China

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Abstract

This chapter discusses how spatial information techniques can be used to predict and evaluate regional soil erosion. The study, carried out in central China, identified sediment discharge, precipitation, soil composition, gully density and land use as the controlling factors of regional erosion. The authors found that soil erosion can be assessed and predicted quantitatively at a regional scale; that quantitative evaluation can be used to study and describe the soil erosion mechanism at the macro scale; and that soil erosion at the national or provincial scale can be rapidly surveyed using remote sensing, geographic information systems (GIS) and erosion modelling.

本研究以黄土高原为例，在分析了区域水土流失过程、类型和分布特点的基础上，拟订了区域水土流失评价指标体系，包括：沟壑密度、汛期降雨量、土壤团粒含量、植被盖度、坡地面积比等。根据遥感影像划分编制了评价单元图并在 GIS 环境下集成各评价因子建立了评价数据库。根据地理统计方法建立了评价模型。研究表明：区域水土流失宏观趋势的定量评价预测是可能的，基于水土保持类型区的定量评价，可以揭示区域水土流失的宏观规律，进而实现区域水土流失快速调查是可能的。最后对于模型进一步改进方法和途径进行了讨论。

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CHINA suffers severe soil erosion (Xianmo Zhu et al. 1999; Qinke Yang 1994). As the country's economy has developed, soil conservation and ecological rehabilitation have been increasingly taken into account and land-use policy has shifted its focus from small watersheds to large regions (China's Agenda 21 1994; Posen et al. 1996). As a result, policy makers and those responsible for planning soil conservation and environmental rehabilitation measures are demanding systematic information about the current situation and trend of soil erosion, and the benefits of soil conservation and ecological rehabilitation practices. This information is required urgently and will need to be continually updated.

Regional soil erosion and conservation are not just local effects; they also affect the surrounding region, including rivers downstream. Widespread events such as floods, sediment deposition in rivers and reservoirs, dust storms, land degradation and water shortages may result from localised erosion events. Consequently, we must quantify and predict the degree and effects of soil erosion at the regional, national and even global scales.

Spatial information sciences and techniques—including remote sensing, geographic information systems (GIS), global positioning systems (GPS) and related internet technology—have been widely applied to soil erosion monitoring and surveying since the 1980s. In China, the technology for modelling and predicting soil erosion has been developed and applied at the regional scale using GIS and remote sensing (Rui Li et al. 1998; Qinke Yang and Rui Li 1998; Feng Jiao et al. 1998). Usually the study area is divided into several integrated spatial units, so the heterogeneous characteristics or spatial differentiation of the units can be taken into account. Most research into erosion evaluation and prediction has been carried out at the scale of the slope or plot (Renard et al. 1997); there have been relatively few regional studies. Where studies have been carried out, they have usually been based on small areas, with scaling up and/or aggregation being used to extrapolate soil erosion data to a

regional or even global scale (Posen et al. 1996; Kirkby et al. 1996; Qinke Yang and Rui Li 1998).

China has been divided into eight soil erosion areas and the soil erosion trend in each has been predicted by relating sediment discharge to factors such as annual runoff, daily maximum runoff and control area (%) (Peihua Zhou 1988). Soil erosion data can also be obtained by the aggregation method using plot data from the United States Department of Agriculture (USDA) monitoring network (Rui Li et al. 1998). However, the problems of evaluating and predicting soil erosion regionally are not entirely solved.

Methodology

Study area

The study area was the 623,700 km² Loess Plateau, in central China. The plateau includes the southern part of Ningxia Autonomous Region, the whole of Shanxi Province, northern Shaanxi Province, the eastern and central parts of Gansu Province, the southern part of the Inner Mongolia Autonomous Region, and the western part of Henan Province. It borders the Riyue Mountains to the west and the Taihang Mountains to the east; and it extends from Qinling Mountains in the south to the Yingshan Mountains in the north. Figure 1 in the Overview shows the general location of the area.

The Loess Plateau is located in the second of the three grand relief landform terraces in China. The basic geomorphological types include loess hills, sand-loess hills and loess tableland; the gully density is 4–6 km/km² and 40–60% of the area has gullies. The climate is continental monsoonal, with mean annual temperature between 6.6 and 14.3°C and mean annual precipitation between 250 and 700 mm. Rain falls mainly in summer (50–70% of the annual total) and is most intense from July to October. The dominant soils are widely eroded, especially in northern Shaanxi Province, central eastern Gansu Province and western Shanxi Province. Secondary vegetation is limited to only a

few stony hills. For over 2000 years, crop growing has been the main form of land use in the area. The population density is 40–270/km². The relationship between the agricultural activities of people and the natural environment is not harmonious.

Figure 1 shows how erosion can be subdivided according to erosive intensity. According to this classification, the Loess Plateau has three erosion regions: the water erosion region, the wind–water erosion region and the wind erosion region.

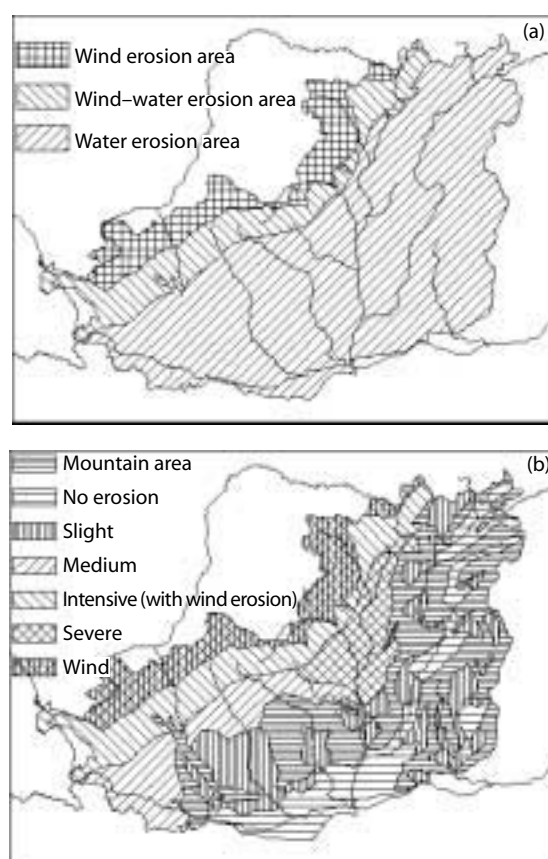


Figure 1. Soil erosion map of the Loess Plateau, showing (a) the types of erosion and (b) the major regions of erosion.

Data and materials

Field surveys and cartographic research by Xianmo Zhu (1981a, b; 1982a, b) show that regional soil erosion is a very complicated process that is affected

by many factors, including geomorphology, soil conditions, meteorology, hydrology, land use, vegetation coverage and soil conservation measures. By analysing these environmental factors and how they affect erosion, we describe the processes of regional erosion and quantitatively evaluate the interactions of the factors and the ability to semi-empirically model the spatial distributions of erosion intensity. In this study, we use the following data.

- **Sediment discharge data** were obtained from the records of 250 hydrological stations covering the period from 1959 to 1986.
- **Precipitation data** measured from 1955 to 1986 at 178 meteorology stations were used to calculate the mean rainfall in the rainy season (July to October).
- **Soil classification data** were obtained from the 1:2,000,000 Loess Plateau soil map produced in 1991 by the Institute of Soil and Water Conservation (ISWC), the Chinese Academy of Sciences and the Ministry of Water Resources. Soil organic matter content data were extracted from monographs that reported the results of the second national soil survey.
- **Gully density data** were determined from gully density annotation points from a 1:500,000 soil erosion map of the Loess Plateau that was produced in 1991.
- **Land-use data.** We estimated the ratio of cropland to forest/grassland from a 1:250,000 land-use map in ArcInfo format, produced by ISWC in 1993 based on the interpretation of Landsat Thematic mapper (TM) data (see Chapter 16 for further details).

Precipitation, sediment and gully density data were in coordinate format (x, y, z) and were spatially interpolated and contoured using ArcInfo. All data were transformed into the Albers projection.

Parameters and database

Table 1 shows the parameters selected for the evaluation. Their choice was dictated by what was needed for prediction and by what was available over the entire study area.

The characteristics of regional soil erosion vary over space and time. Consequently, multilevel areas and classes of erosion can be identified. The study of erosion on a regional scale is based on experimentation and observation at plot and watershed scales, but the data cannot simply be extrapolated from a slope surface or other small area to a larger area using spatiotemporal modelling of the environment (Burough 1998).

To adequately describe the study, the study area must be discretised in space and time. Conventionally, geoentities in space are described by vector data such as points, lines and polygons and other common factors. We divided our study area into 3380 spatial units of uniform map area (UMA) according to Landsat TM imagery.

The parameters were processed into map format and integrated into each of the UMAs, based on the theory and method of the georelationship model. During the process of integration, the data for location and topology were based on the UMA map or base map. The number of data entities on the base map remained constant during data integration.

Results and Analysis

Modelling regional erosion

The general format of the model of regional erosion is:

A = f(Q, S, g, v, c) (1)

Table 1. Parameters used in the evaluation.

Erosion factor	Soil erosion	Climate	Soil	Plant	Land use	Relief
Parameter	Sediment intensity	Rainfall in wet season	The fraction of soil (g/kg) with a diameter > 0.25 mm	Plant cover	Slope to area ratio	Gully density

where *A* is the erosion intensity, *Q* is a hydrological/ climate factor, *S* is a soil factor, *g* is a landform factor, *v* is a vegetation factor, and *c* is a conservation measure factor.

There is an exponential correlation between the amount of erosion, the amount of rainfall in the rainy season, the gully density, the proportion of slope cropland, the coverage of vegetation and the content of aggregate (≥ 0.25 mm) (JunJie Ma 1990; JiYang Liang 1992; QiuSheng Wang 1991). The relationship can be expressed as:

L = 0.4735P^{0.9282} S^{-0.08855} × G^{2.2666} M^{0.07254} e^{-0.00047C} (2)

where *L* is the erosive intensity (tonnes/km²/year), *P* is the precipitation in the wet season (mm), *S* is aggregate content (g/kg), *G* is the gully density (km/ km²), *M* is the ratio of slope cropland (%), and *C* is vegetation cover (%).

The highly significant regression result (*r* = 0.937, *F* = 2984.64 >> *F*_{0.05} = 2.21 where *F* is the *F*-statistic, which is much higher than the level for 5%) indicates that the erosive intensity is positively correlated with rainfall quantity in the wet season, gully density, and the proportion of slope cropland. It is negatively correlated with the content of aggregate and vegetation cover. In other words, the higher the rainfall in the wet season, the greater the erosion intensity; the higher the aggregate content and vegetation covering, the lower the erosion intensity. This accords with general principles of soil erosion, and with other research in this field.

Evaluating the erosion factors

We have identified five variables controlling erosion regionally. These variables can be converted into

specific units and extracted from existing survey or remote sensing information. The variables are suitable for a macro study to evaluate trends, as in our study. Land-use data provide some indication of the extent to which soil and water conservation are practised in the region. For the purpose of analysing erosion potential, the landscape can be categorised into plains, terraces, hills and mountains. There are obvious differences between the categories in patterns of erosion, measures and patterns of soil conservation and types of reasonable land use. Topographic maps and TM imagery have made it possible to determine locations with a high degree of accuracy. As the UMA map has 2230 polygons and the 1:500,000 Loess Plateau erosion map has only 1100 polygons, each UMA can contain values derived from different thematic layers. Thus, erosion levels can differ within UMAs for the same landscape zone.

We applied several algorithms for attribute values from the maps (in digital format) to the databases. We used a flexible method to calculate the relationship between location and descriptive data. Consequently, all variables in the model can be integrated into the UMA map, and a database with multi-items can be built to satisfy the demands of multifactor evaluation (Qinke Yang 2001).

Figure 2 is a GIS map showing soil erosion calculated using Equation 2; it shows the relationships among the different factors affecting soil erosion and accords with the spatial differentiation pattern of soil erosion observed on the Loess Plateau. The result is useful in macro policy making.

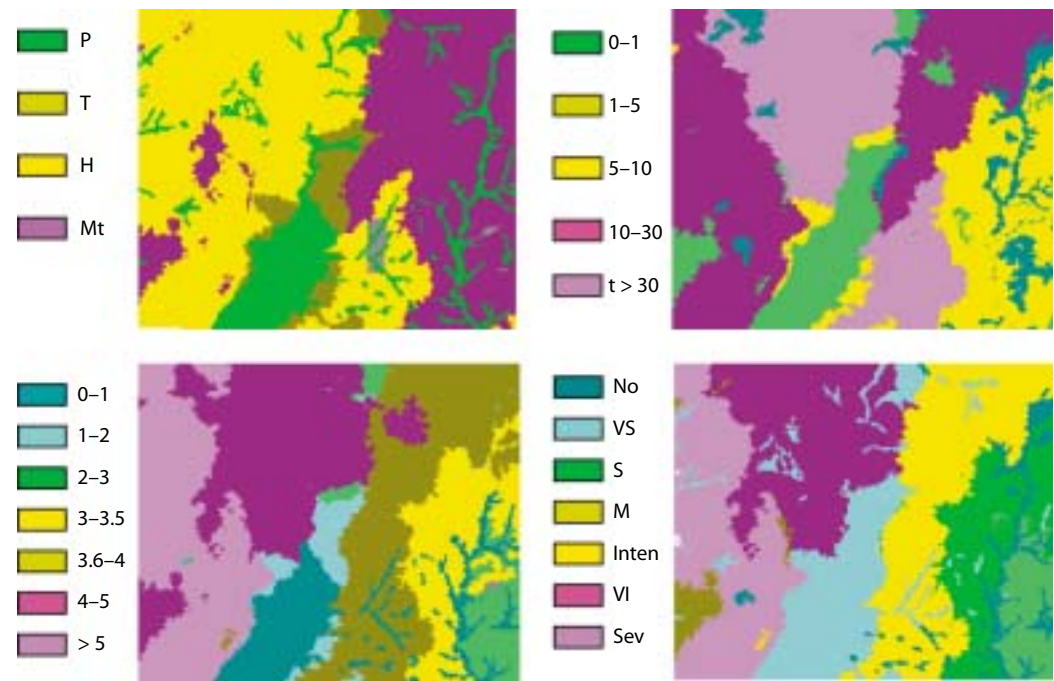


Figure 2. An example of factors influencing regional erosion modelling for a 127 km × 117 km portion of the Loess Plateau situated in Shaanxi Province. The top left image is of landform; P is plain; T is tableland; H is hill; and Mt is mountains. The top right image is the percentage slope of cropland for each polygon. The lower left image shows the density of gullies (km/km²). The lower right image illustrates erosion intensity (t/km²/year), which can be used for regional decision making on soil erosion control and ecorehabilitation; No is none, VS is very slight, S is slight, M is medium, Inten is intensive, VI is very intensive and Sev is severe.

Modelling regional soil erosion

Equation 1 allows runoff modulus ($\text{KL}/\text{km}^2/\text{year}$) to be used as a measure of relevant hydrology factors (Q) and soil antiscourability (kg/KL) as a measure of soil factors (S). Information for the landform factor (g) can be derived from regional DEMs, where the relative relief—the maximum elevation difference in a specified area—is used (Xinhua Liu et al. 2001). The remaining two factors, the vegetation index and soil conservation index, can be derived from advanced very high resolution radiometer (AVHRR) data (see Chapter 16 for further details) and soil conservation statistics, respectively.

Discussion

It is possible and practical to quantitatively assess and predict macro trends in soil erosion at the regional scale, using the theory and methodologies of regional soil conservation and GIS. The methodology involves:

- dividing the study area into discrete units in space and time with homogeneous factors and erosion types based on the analysis of processes and the spatial differentiation of soil erosion and related environmental factors at the regional scale;
- using research on the factors affecting regional erosion and the results of erosion evaluation studies, coordinated with the characters of GIS modelling methods, to identify the relevant parameters of the model;
- extracting the parameters one by one from many kinds of approaches, including field tests, thematic maps, descriptions of observed materials and remote sensing imagery/DEM analysis, and integrating all the parameters into the basic unit map to build up a parameter database; and
- establishing a statistical model for the sediment discharge (the sediment yield from erosion) and each relevant factor using geostatistical and correlative analysis methods.

Our study supports unpublished work of the national soil erosion survey that suggests that remote sensing, GIS and erosion modelling can be used to efficiently survey soil erosion at the national or provincial scale. In the 1980s, it took about 10 years to map soil erosion in China at the national scale using mainly manual methods; in 1998–2000, it took only two years to do the same using a combination of manual and computer methods. When we have all the basic information at the national scale, we will be able to survey erosion quantitatively and annually. The increased timeliness in providing a nationwide overview by performing this massive task in temporal GIS (TGIS, see Chapter 16) will allow cost–benefit analysis of soil conservation and ecological rehabilitation practices to feed back more quickly into policy decisions and directions. The development of this TGIS will not only allow monitoring of the environmental response, but also allow central government officials to determine the effectiveness of money spent in different regions.

Conclusions

This study has shown that soil erosion can be assessed and predicted quantitatively at a regional scale; and that soil erosion at the national or provincial scale can be rapidly surveyed using remote sensing, GIS and erosion modelling. The information so provided will assist macro policy making at the national and provincial levels. The accurate evaluation and prediction of regional soil erosion should be based on systematic research on the genesis and evolution of erosion at the macro scale, and on the factors that cause erosion. The current situation is far from perfect; we are doing more work on this topic.

References

- Burrough, P.A. 1998. Dynamic modeling and geo-computation. In: Karssenber, D. and Burrough, P.A., eds, *Environmental Modeling in GIS*. Utrecht University, The Netherlands, Faculty of Geographical Sciences.

- China's Agenda 21. 1994. White Paper on China's Population, Environment, and Development in the 21st Century. Beijing.
- Feng Jiao, Xiaoping Zhang and Rui Li 1998. Application of GPS in soil and water conservation. *Bulletin of Soil and Water Conservation*, 18(5), 32–34.
- Jiyang Liang 1992. Analysis and simulation of storm, runoff and sediment on the Loess Plateau. *Journal of Soil and Water Conservation*, 6(2), 12–16.
- Junjie Ma 1990. The regression analysis of soil erosion on loess hill and tableland in the middle of Shaanxi. *Journal of Soil and Water Conservation*, 4, 21–28.
- Kirkby, M.J., Imeson, A.G., Bergkamp, G. and Cammeraat, L.H. 1996. Scaling up processes and models from the field plot to the watershed and regional areas. *Journal of Soil and Water Conservation*, 391–396.
- Peihua Zhou 1988. The prediction and prevention of soil erosion in China in 2000. *Memoir of the Institute of Soil and Water Conservation, Academia Sinica*, 1988(7), 57–71.
- Posen, J.W., Boardman, J., Wilcox, B. and Valentin, C. 1996. Water erosion monitoring and experimentation for global change studies. *Journal of Soil and Water Conservation*, 386–390.
- Qinke Yang 1994. The classes and regions of soil erosion in China. In: *Soil Science Study in Modern Time*. Beijing, Agriculture, Science and Technology Publishing House.
- Qinke Yang 2001. Study on overlay and its application of digital map overlay analysis. In Rui Li and Qinke Yang, eds, *Study on Rapid Survey of Region Soil Erosion and Soil Conservation Information System*. Zhengzhou, Huanghe Water Resources Press, 126–134.
- Qinke Yang and Rui Li 1998. Review of quantitative assessment on soil erosion in China. *Bulletin of Soil and Water Conservation*, 18 (5), 13–18.
- Qinke Yang and Rui Li 1999. Application of GIS. In: Li Rui and Yang Qinke, eds, *Research on the Rapid Survey and Management Information System at Regional Scale*. Zhengzhou, Huanghe Water Resources Press, 19–24.
- QiuSheng Wang 1991. The mathematical model for vegetation control of soil erosion and its application. *Journal of Soil and Water Conservation*, 5(4), 68–72.
- Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and Yoder, D.C. 1997. *Predicting Soil Erosion by Water: a guide to conservation planning with the revised universal soil erosive (RUSLE)*. Washington DC, United States Department of Agriculture, Agriculture Handbook, 703.
- Rui Li, Qinke Yang and Yong'an Zhao 1998. Application of spatial information technology in soil and water conservation of China. *Bulletin of Soil and Water Conservation*, 18(5), 1–5.
- Xianmo Zhu 1981a. The main types of water erosion and their related factors in the Loess Plateau (1). *Bulletin of Soil and Water Conservation*, 1981(3), 1–9.
- Xianmo Zhu 1981b. The main types of water erosion and their related factors in the Loess Plateau (2). *Bulletin of Soil and Water Conservation*, 1981(4), 13–18.
- Xianmo Zhu 1982a. The main types of water erosion and their related factors in the Loess Plateau (3). *Bulletin of Soil and Water Conservation*, 1982(1), 25–30.
- Xianmo Zhu 1982b. The main types of water erosion and their related factors in the Loess Plateau (4). *Bulletin of Soil and Water Conservation*, 1982(3), 40–44.
- Xianmo Zhu, Daizhong Cheng and Qinke Yang 1999. 1:15000,000 soil erosion map of China. In: *Atlas of Physical Geography of PRC* (2nd edition). Beijing, Cartographic Publishing House, 200.
- Xinhua Liu, Qinke Yang and Rui Li 2001. Extraction of relief roughness and its application in regional erosion prediction in China. *Bulletin of Soil and Water Conservation*, 21(1), 57–59.

23 Assessing Cropland Using Geographical Information Systems and Land Survey Data: an Example from China

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Abstract

China's current cropland taxation policy is based on the results of a land survey carried out in the 1950s. There is an urgent need to evaluate cropland quality so that land can be taxed and managed using up-to-date information. In China, different agricultural areas are taxed at different rates, based on land evaluation assessment. Farmers on more favourable land pay higher levels of tax. This chapter describes how 15 parameters were integrated into basic polygons to create a database for use in land evaluation. The parameters were obtained mainly from the national land survey and included accumulated annual temperature, annual precipitation, soil organic matter, elevation, slope and soil erosion. We evaluated cropland for each of the polygons using ArcInfo and Foxbase, integrated the database with an aggregated model produced from cropland evaluation of Shaanxi Province and created maps of cropland classes and related tables of statistics.

中国的农业税率因土地质量而异，好地课税率高。现行的税率是根据 50 年代土地详查结果而定的，目前亟需对农地的质量重新评价，以便采用最新数据来征税和管理。本文将 15 个参数集成于地块单元以建立耕地评价数据库。这些参数主要来源于国土详查资料，也包括相关研究中积累的年气温、降水、土壤有机质、海拔、坡度和土壤侵蚀数据。在 ArcInfo 和 Foxbase 环境下评价每个地块的质量等级，将数据库与陕西省农地评价所生成的模型结合，得到农地质量等级图以及有关的统计图表。

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THE QUALITY and quantity of cropland in China was surveyed in the 1950s, soon after the creation of the People's Republic of China. The cropland taxation policy used today is based on the results of this 1950s survey, which evaluated land according to its type (e.g. hills, tablelands and plains) and features (e.g. soil organic matter content, bulk and porosity). In China, farmers pay different tax rates depending on the land evaluation assessment. For example, farmers located on fertile soils close to water sources pay a higher tax rate than those located on relatively infertile soils with lower rainfall or less access to irrigation. Hence, land assessment plays a critical role in agricultural economies at both micro (farmer) and macro (all China) levels.

Since the original survey, farmers and/or government have introduced land improvement measures such as capital works, irrigation networks and improvements to low-quality soils. Because productivity of the land has changed greatly over the intervening years, the 1950s-based land taxation criteria are no longer appropriate. Consequently, it has become necessary to reassess the land in order to adjust the taxation regime in a rational and balanced way that takes into account regional land conditions.

In the early 1990s, aerial photographs were used to construct a nationwide land survey at a scale of 1:10,000 in agricultural areas and 1:50,000 in forest and grassland areas. To date, only the areas of land parcels have been mapped; land quality has not been evaluated. There is an urgent need to evaluate cropland quality so that land can be taxed and managed using up-to-date information.

Three classification systems have been used for nationwide land evaluation in China:

- the land capability classification of the United States Department of Agriculture (USDA) (Klingebiel and Montgomery 1961) (this system was used in 1982 by the central Chinese Government Office of the Second Soil Survey);

- the Food and Agriculture Organization land evaluation system (FAO 1976) (this system has been used to assess the suitability of the land for different purposes); and
- a hybrid system, based on the USDA and FAO methods, modified to suit Chinese conditions (Shi Yulin 1982) (this system was used to report at a scale of 1:1,000,000 for all China).

These systems of land evaluation are designed primarily to help set policies that use land resources sustainably at a regional and national scale, or to gain maximum benefit from land improvement practices (e.g. establishing an irrigation area) for minimal cost. Our aim was to improve the basis for land taxation by using land survey data and geographic information systems (GIS). Two key steps are reported here. First, we identified and mapped the land evaluation units using GIS overlay techniques and readily available regional databases. Second, we developed a land evaluation model in a GIS environment.

Methodology

Land resources are affected by geographical factors (e.g. geomorphology, soil, vegetation, climate and hydrology) and socioeconomic factors (e.g. the infrastructure associated with agronomy, transportation and location). The quality of the land can be represented generally by the following equation:

$$Lq = f(c, g, s, p, e) \tag{1}$$

where *Lq* is a measure of land quality, *c* is a measure of climate, *g* is a measure of geomorphology, *s* is a measure of soil type, *p* is a measure of cropland infrastructure and *e* is a measure of economic conditions.

Land evaluation requires identification and mapping of the evaluation unit (the basic polygon), development of databases to be used in the analysis, and construction of a model to score the land with

respect to different (either real or potential) land uses. Additionally, maps and statistical summaries must be produced for the end user.

In this study, the parameters used, their ranking and their weight were taken from the guide for cropland evaluation of Shaanxi Province (Zhang Qifan 1994). The approach used was based on research from the West and from China. In the light of the information we have accumulated, our data handling capacity and trials in northern, central and southern Shaanxi Province (Zhang Qifan 1994), we believe that 15 parameters are required (Table 1). These parameters cover climate, geomorphology, soil, agricultural infrastructure and economic factors. Cropland quality maps are generally at a scale of 1:10,000, which is suitable for use in the field. The parameters and classes are listed in Tables 1 and 2 and can be expressed as:

$$P = \sum_{i=1}^n A_i K_i \quad (2)$$

where P is the score for the evaluation unit, A_i is a measure of the score for the specified factor, K_i is a measure of the weight of the specified factor, and n is the serial number of the evaluation unit (polygon).

Study Area

The study was performed in Changwu County, which is located in western Shaanxi Province, in the south of the Loess Plateau and covers an area of 565.9 km². Figure 1 shows the location of the study area. The dominant geomorphological types in the Loess Plateau are loess tablelands, loess hills and river plains. Background information about the plateau is contained in the Overview. Mean annual rainfall is 584.1 mm, mean annual temperature is 9.1°C and total annual sunshine is 1659.9 hours. A detailed land survey was completed in 1992 at a scale of 1:10,000 and the information has been upgraded yearly since 1995. The maps, tables and other related data are all managed in paper format and must be accessed manually (Office of the Land Detail Survey

of Changwu County 1994; Committee of the Land Detail Survey of Shaanxi Province 1987).

The six data sets used in this study, and the general data constructs, are described below.

- *Land-use maps* (1:10,000). These were produced from the detailed survey of land resources (Committee of the Land Detail Survey of Shaanxi Province 1987). Each polygon has two items of data: the land-use code, and the number of the polygon. Items recorded in the map table associated with each land-use polygon were the map-sheet code; the administrative region (village, township, county); the type of land use; the area of the polygon and lines (roads, canals, etc.); and the ownership of land. The map also shows a third class of land use classified mainly by environmental factors such as landform, soil type and slope.
- *Cropland slope maps* (1:10,000). These are based on the land-use map and contain data about the cropland slope for each polygon.
- *Land-use change maps* (1:10,000). These are based on the land-use update. Where land use has changed, the old land use, the new land use, and the date of change are recorded for each polygon.
- *Climate condition maps* (1:100,000). These include contour maps of annual precipitation and annual cumulative mean daily air temperature when the air temperature is greater than 10°C. Both were produced by the Meteorological Bureau of Changwu County, based on 40 years data.
- *Soil maps* (1:50,000). These include soil type and soil organic matter maps, based on soil survey data produced in 1980 by the Agricultural Bureau of Changwu, Shaanxi Province.
- *Topographic maps* (1:10,000). These maps are produced by the Survey and Mapping Bureau of Shaanxi Province and are based on aerial photographs from flights conducted in 1976. The contour interval is 10 m.

Table 1. The 15 parameters (bold numbers) used in the land evaluation model, and the weighting factor (Wt), criteria and score used.

	Factor	Wt (%)	Criteria	Marks
Climate	1 ≥10°C accumulated temp	8	> 4600	9
			4600–4300	8
			4300–4000	7
			4000–3700	6
			3700–3400	5
			3400–3100	4
			3100–2800	3
			2800–2500	2
			< 2500	1
	2 Precipitation (mm)	10	> 640	9
640–600			8	
600–560			7	
560–520			6	
520–480			5	
480–440			4	
440–400			3	
400–360			2	
<360	1			
Geomorphology	3 Elevation (m)	4	<400	9
			400–500	8
			500–600	7
			600–700	6
			700–800	5
			800–900	4
			900–1000	3
			1000–1100	2
			> 1100	1
	4 Slope (°)	10	< 2	9
2–6			7	
6–15			5	
15–25			3	
> 25			1	
Soil	5 Erosion	6	None	9
			Slight	7
			Medium	5
			Strong	3
			Severe	1
	6 Depth (cm)	4	> 100	9
			100–70	7
			70–50	5
			50–30	3
< 30			1	
7 Texture	5	Fine sand	9	
		Clay/fine sand	7	
		Clay	5	
		Sandy/stone	3	
		Stone	1	

	Factor	Wt (%)	Criteria	Marks
Soil (continued)	8 Organic (%)	5	> 1.8	9
			1.8–1.6	8
			1.6–1.4	7
			1.4–1.2	6
			1.2–1.0	5
			1.0–0.8	4
			0.8–0.6	3
			0.6–0.4	2
			< 0.4	1
	9 Saline or wet	5	No/no	9
0.6			6	
Slight				
0.6–1.0			3	
Seasonal				
> 1.0			0	
water < 0.5				
10 Pollution	4	None	9	
		Slight	6	
		Medium	3	
Strong	0			
Condition of irrigation	11 Irrigation	12	Irrigation if needed	9
			20% need	7
			Three times	5
			Twice	3
			Once	1
			Not possible ^a	0
			12 Contain water	8
	Better	7		
	OK	5		
	Poor	3		
Worse	1			
13 Distance	7	< 1 km	9	
		1–2 km	7	
		2–3 km	5	
		3–4 km	3	
> 4 km	1			
Economic condition	14 Transport	6	Fair	9
			OK	5
			Poor	1
	15 Location	7	Very large city	9
			Large city	7
Medium city			5	
Small city	3			
County	1			
Rural area	0			

^a There is no infrastructure to irrigate the crops

^a There is no infrastructure to irrigate the crops

Generation of Parameters and Integration of Data

The spatial map unit is the basic polygon of the digital map. Each polygon has uniform attributes of land use, land management, cropping practice and related environmental factors. Figure 1 of Chapter 16 shows this stratification overlay concept. Additionally, each basic polygon has a definite boundary and area (Yang Qinke et al. 1985). In the field, the polygons are bounded by field engineering



Figure 1 Shaanxi Province counties (Changwu County is shaded grey).

or clear line entities such as roads, canals, gullies or cliffs (Zhang Qifan 1994). Research and mapping of these units provided the basis for the scientific and practical evaluations in this study.

We used the land-use map as a basis for identifying and mapping the units, taking into consideration environmental factors and their relationship with land quality. Each unit has a unique identity and is related to one record in the attribute database; Table 3 shows an example of the database for 10 polygons. The overlaying and merging of the polygon attribute table (PAT) and ArcInfo (boundary of polygons) attributes table (AAT) were automated in order to manage the data. In the overlay process, the basic polygon map was used as a base map, with all the other maps overlaid in GIS. For integration, we added an item or parameter into the attribute table of the base map one or more times, as required. Figure 2 shows the steps in this process.

The data were manipulated in three ways:

- Attribute data with ArcInfo were used to map basic polygons and integrate them into multithematic maps. In this way, a database of parameters in the georelational data structure was developed, with multiple items describing each of

Table 2. Stratification of the land evaluation score into classes calculated from the 15 parameters and weighting factors, both introduced in Table 1, using Equation 2.

Class	Subclass	Score	Potential yield (kg/ha)	Class	Subclass	Score	Potential yield (kg/ha)
I	1	900–855	7500–7050	V	10	495–450	3450–3000
	2	855–810	7550–6600	VI	11	450–405	3000–2625
II	3	810–765	6600–6150	VII	12	405–360	2625–2250
	4	765–720	6150–5700		13	360–315	2250–1875
III	5	720–675	5700–5250	VIII	14	315–270	1875–1500
	6	675–630	5250–5175		15	270–225	1500–1125
IV	7	630–585	5175–4350	IX	16	225–180	1125–750
	8	585–540	4350–3525		17	180–135	750–225
V	9	540–495	3525–3450		18	135–0	<225

the basic polygons. Thematic management of data is easier than manual management.

- Cropland evaluation was scripted with SML (simple micro language of ArcInfo) and Foxbase, to calculate the cropland classes automatically.
- A cropland classes map was created by programming with SML according to the guide

to cropland evaluation issued by Shaanxi Province. Three categories and 25 types of table were also created automatically.

In order to avoid creating many erroneous new small polygons due to ‘gaps’ and ‘slivers’ (Burrough 1986) when overlaying two, or more, vector GIS data sources, we developed a new method, which is based on the selection of primary, secondary and

Table 3. An example set of the database for 10 polygons. The score of the 15 parameters (here called A1 to A15) results from the criteria and weighting introduced in Table 1. The final score, class and subclass are derived from Table 2.

Bnd	Poly#	LU	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	Score	Class-Subclass
403	38-2	146	3200	530	1150	3	3	55	5	7	9	9	0	0	4500	1	0	289	VII-14
403	51-0	144	3200	530	1150	5	5	80	9	8	9	9	0	0	4500	1	0	349	VII-13
402	37-1	145	3100	540	1150	9	9	95	7	8	9	9	0	0	4500	1	0	395	VI-12
403	1-4	145	3300	530	1150	9	9	95	7	9	9	9	0	0	4500	1	0	408	VI-11
403	7	145	3300	530	1150	9	9	95	7	10	9	9	0	0	4500	1	0	408	VI-11
401	60	145	3200	540	1150	9	9	95	7	12	9	9	0	0	4500	1	0	413	VI-11
401	61-1	145	3200	540	1150	9	9	95	7	12	9	9	0	0	4500	1	0	413	VI-11
402	39	145	3200	540	1150	9	9	95	7	12	9	9	0	0	4500	1	0	413	VI-11
402	15-1	211	3200	540	1150	7	7	95	7	8	9	9	0	0	1000	1	0	413	VI-11
401	25	135	3200	540	1150	7	7	95	7	10	9	9	0	0	500	1	0	432	VI-11

bnd = administrative area code; poly# = no of the polygon of the parcel map; LU = code of land use

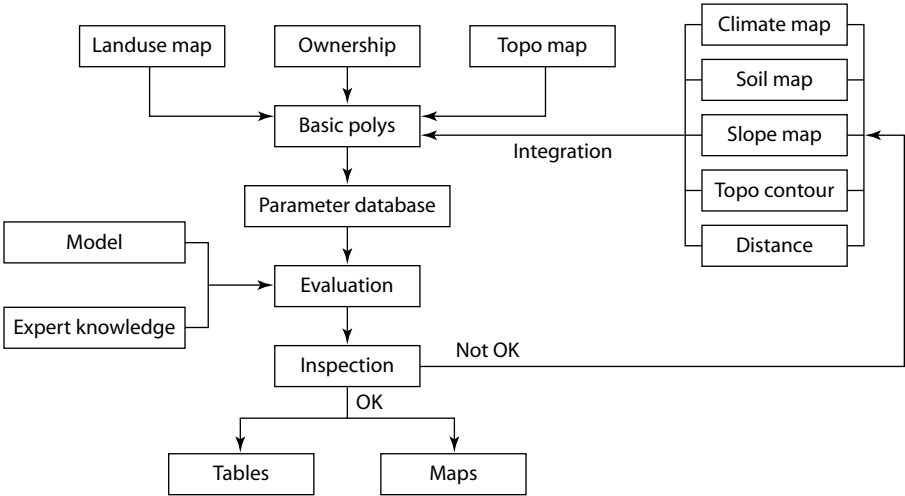


Figure 2. Flow chart of the development of the basic map unit for the land evaluation, the data used in generating the score and the inspection decision point. If the GIS-based land evaluation score, and hence the resulting class and subclass stratification, is deemed not okay, then the process cycles to reviewing the input data.

subsequent data layers in the GIS overlay process. In Figure 3, the upper two data layers are inputs to be overlapped, the primary layer is the top layer and the secondary layer the one below. The top layer has two attributes (A and B); the second layer also has two attributes (a and b). The attributes and areas are shown in 1.pat and 2.pat, respectively. The third layer is the result of overlaying the two input layers; this results in four polygons, which have attributes Aa, Ab, Ba and Bb, as shown in 3.pat. In 3.pat the spurious new polygons (Ab and Ba) are probably the result of slight misregistration of the vectors used in the two input data sets. In the lower data layer, the boundary from the primary data and the area of the resulting sliver polygons are used to assign the slivers to one of the two primary map units (see 4.pat). In addition to misregistration, there are instances where it is unnecessary or impossible for cartographers to locate the same ge- entity with the same geographic coordinates. This

may be due to different input data layers being produced by different mapping programs having slightly different, though related, thematic classes and these having different positional accuracies.

We extracted the parameters from a group of thematic maps, including those for slope, cumulative air temperature, precipitation, soil, soil organic matter, topographic shape, road network and village boundary. After entering the values into ArcInfo, we mapped the field data and other parameters, such as soil depth, texture, salinity, water-holding capacity and pollution, the state of irrigation and the location. The data were inserted into a common GIS, and each of the digital maps was projected using the Gauss–Krug projection — the official projection used in China for scales between 1:10,000 and 1:500,000. The land evaluation was programmed according to the method shown in Tables 1 and 2, with Equation 2,

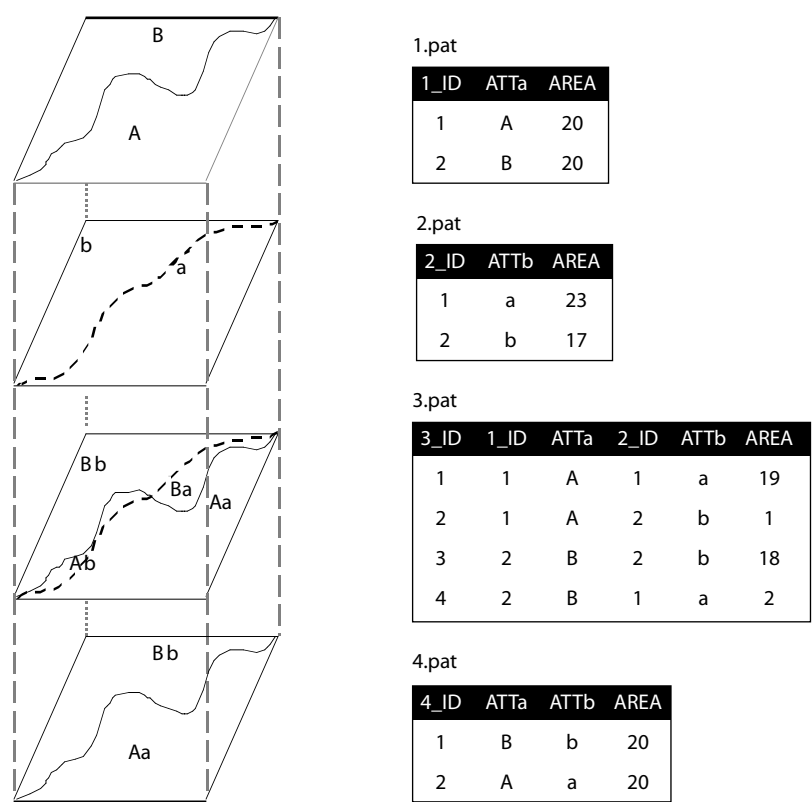


Figure 3. A schematic diagram illustrating the overlay procedure (see text for full details). The spatial data are denoted 1 to 4 from top to bottom.

using an extension developed in ArcInfo to deal with slivers (Figure 3).

The reliability of the land evaluation was verified by comparing the land evaluation map generated by GIS with the actual situation. The local government land surveyor helped to build a simple expert system, through their independent in situ databases. This allowed us to validate the quality of the data ingested and the approach used (specifically, the weighting values selected) for modelling the GIS-based land evaluation.

Analysis

When assessing cropland for local government, the results should be repeatable, should be practical, and should be obtained using the methods specified by local government. This study meets these three criteria. The need for the assessment to be repeatable and transparent is particularly important in China, because land evaluation is used as the basis for tax rates for farming communities. Thus, farmers on high-quality fertile land adjacent to rivers, possibly with access to irrigation water, are taxed at a higher rate than farmers situated on lands with greater slopes or less fertile soils, and relying on rainwater or water that they haul to their farms.

We found that evaluating cropland using GIS gave results that were both theoretically and technically valid. The results of the evaluation, in either map or tabular format, were consistent with the actual situation for more than 95% of the polygons and are accepted by the farmers and local cadastral recorders. The method, the parameterisation, the mapping and the tabular data all closely followed the Shaanxi Province guide. All results, including maps, tables, and related documents, have been approved by scientists and officers of the Bureau of Land Management and Finance of Shaanxi Province. It is important to note that the results from this study have been endorsed by both the taxpayers (the farmers) and the tax collectors (government officers).

Land evaluation can be used not only for taxation management, but also for estimating grain yields, creating policies for cropland building and improvement, land management, and designing and building a practical land information system.

Discussion

To build a parameter database for a region of China, it is more practical to use a spatial unit than to use soil series or land-type data. This is because China has more traditional cropping systems and technologies than the West, and a much greater degree of spatial, physical and socioeconomic variation. For example, the status of fertiliser use, field management and infrastructure is highly dependent on the distances between the land and the owners, and on transport conditions.

Multithematic map data can be integrated automatically by using GIS overlays and database manipulation. This can be achieved without generating spurious polygons, which can be an issue for GIS research and application (Burrough 1986; McAlpine and Cook 1971; Goodchild 1978; Arbia et al. 1998; Smith and Campbell 1989). A parameter database with multiple items for each polygon can be built efficiently using integration processes. The results of the integration reflect the macro features of environmental factors; errors in the land-evaluation GIS-based model were about 2% of the total number of base polygons (Table 4). Producing maps of 98% accuracy is acceptable to policy makers involved in land-evaluation assessment to decide farmer taxation levels. Parameterisation and evaluation can be programmed and integrated with GIS; the evaluation method has been automated and is hence repeatable.

Conclusion

Information technology can be useful in managing land resources, but is in the early stages of development. It is time consuming to digitise land data (maps), and problems with raw data must be

Table 4. Differences in overlaying, shown as both m² and % area of the base map.

Accumulated temperature	Area (m ²)		Difference	
	In base map	In attribute map	Area (m ²)	%
3300	7,944,437	7,797,598	146,839	1.85
3400	11,547,616	11,488,230	59,386	0.51
3500	5,596,422	5,480,886	445,536	2.06

overcome when entering them into the GIS. These include maintaining accurate metadata, geometrically matching maps from different data sources; and keeping track of the temporal changes in GIS data sets. Many of these issues are areas of active research, and practical tools are starting to become available to operational users of GIS technology.

More research is needed on how to handle errors introduced during overlay processing through the removal of spurious polygons. There is also a need to assess the sensitivity of the final results by reducing the number of input GIS data layers from 15 to about four or five (hence simplifying the model). If the results are similar, then the method developed here can be more easily translated to other counties in the Loess Plateau, as the input data requirements will better match the regional data availability.

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References

Arbia, G., Griffith, D. and Haining, R. 1998. Error propagation modelling in raster GIS: overlay operations. *International Journal of Geographical Information Science*, 12, 2, 145–167.

Burrough, P.A. 1986. *Principles of Geographical Information Systems for Land Resources Assessment*. Oxford, Clarendon Press.

Committee of the Land Detail Survey of Shaanxi Province 1987. *Guide of the land detail survey of Shaanxi Province*, Xi'an.

FAO (Food and Agriculture Organization) 1976. *A framework for land evaluation*. Soils Bulletin 32, FAO, Rome.

Goodchild, M.F. 1978. Statistical aspects of the polygon overlay problem. In: Dutton, G., ed., *Harvard Papers on Geographic Information Systems*, 6, Addison-Wesley Reading, Mass.

Klingebiel, A.A. and Montgomery, P.H. 1961. *Land-capability Classification of the United States Department of Agriculture (USDA) Agriculture Handbook 210*. Soil Conservation Service. USDA, Washington, DC.

McAlpine, J.R. and Cook, B.G. 1971. Data reliability from map overlay. In: *Proceedings of the Australian and New Zealand Association for the Advancement of Science*, 43rd Congress, Brisbane, May. Section 21—Geographical Science.

Office of the Land Detail Survey of Changwu County 1994. *The land resources in Changwu County*. Changwu, 1994–6.

Shi Yulin 1982. Guide of the land resources mapping at 1:1,000,000 in China. *Journal of Natural Resources*.

Smith, J.W.F. and Campbell, I.A. 1989. Error in polygon overlay processing of geomorphic data. *Earth Surface Processes and Landforms*, 14, 703–717.

Yang Qinke, Song Guiqin, and Li Rui 1985. The mapping and discussion of basic polygon—a case study in Chang area. *Bulletin of Soil and Water Conservation*, 13, 5, 34–38.

Zhang Qifan (ed.) 1994. *The theory and practice of the cropland evaluation*. Xi'an Map Press, Xi'an.

24 Environmental Indicators and Sustainable Agriculture

Joe Walker*

Abstract

This chapter looks at how indicators can be used to assess agricultural sustainability. Indicators are biophysical, economic and social attributes that can be measured and used to assess the condition and sustainability of the land from the farm to the regional level. Reliable indicators provide signals about the current status of natural resources and how they are likely to change. They can be used to confirm that current farming practices and land-use systems are effective in maintaining the resource base or economic status, identify problems and highlight potential risks. Indicators provide useful information for initiating change or deciding on future on-ground investments.

本文论述健康诊断指标如何应用于农业持续能力的评价。诊断指标是可以量测的生物物理和社会经济特征，用来评价从单个农场到整个地区不同尺度的土地状况和持续发展能力。可靠的诊断指标能体现自然资源的当前状态，及其可能产生的变化。可用于辨别现行的农业生产活动和土地利用系统能否有效维持资源或经济发展水平，确认存在的问题，突出潜在的危机。它能为土地利用方式的修正和未来的土地投资决策提供有用信息。

FARMING practices are changing the environmental resource base. Some changes are for the better (e.g. organic farming), but many are deleterious and could endanger future agricultural activities. Rural and urban environmental changes caused by various human activities, not just farming, are increasingly felt, raising perceptions of the environmental costs of these activities. For example, in the cities, people experience poor air quality; some rivers and beaches are no longer fit for

recreational use; and valued natural areas have been lost to suburban and industrial development. Farmers and rural inhabitants have seen soil loss through wind and water erosion; they are aware of areas that can no longer be farmed because of crop and pasture decline, and gully development in saline areas.

Observation of environmental deterioration in farmed areas is not a recent phenomenon.

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Australian farmers in the early 20th century noticed changes that were detrimental to productive agriculture such as an increase in unpalatable grasses and weeds, the advent of saline flows in previously fresh creeks and streams, the need for increased ploughing to retain a tilth in fallowed paddocks and a decline in crop yields and animal production. The signs were there, both visually and in quantifiably reduced yields.

Visible undesirable changes in the condition of the atmosphere, land and water are ‘indicators’ of degradation brought about through changes in environmental processes resulting from human activity. The changes may be due to the introduction of new processes (e.g. the addition of pesticides to the soil) or to increases or decreases in existing processes (e.g. more recharge leading to rising watertables in Australia and reduced recharge leading to falling watertables in parts of China). Visual indicators such as soil surface crusting, sheet and gully erosion, and stream and river turbidity have alerted us to problems. Thus, we have been using environmental indicators in agriculture for a long time and the concept is nothing new. However, there has recently been greater recognition of the role that indicators of environmental change could have in assessing and monitoring the effect of land use on natural resources. Indicators can be a powerful means for those managing the land to identify potential problems and assess the effect of their management practices on ecosystems (Walker and Reuter 1996; SCARM 1993; US National Research Foundation 2000; Pykh et al. 1999). Provided that indicators are meaningful to a range of users, from farmers to policy makers, they can help to achieve sustainable agriculture. However, indicators must be selected and used carefully if they are to be effective.

Farmers have long used indicators to decide on changes to farm practice. An obvious next step is to develop a more standard, yet simple, way of recording and assessing environmental change that can have immediate application at the farm and

catchment levels. Farmers are already ‘production literate’ but they also need to be ‘environmentally literate’. The two literacies working together can help ensure a sustainable future for agriculture.

How Can We Define Indicators?

Indicators are a subset of the many possible attributes that could be used to quantify the condition of a particular landscape, catchment or ecosystem (Walker 1998). They can be derived from biophysical, economic, social, management and institutional attributes, and from a range of measurement types. Indicators have been defined as ‘measurable attributes of the environment that can be monitored via field observation, field sampling, remote sensing or compilation of existing data’ (Meyer et al. 1992). Ideally, each indicator is precise and accurate in describing a particular process within the environment and will serve to signal undesirable changes that have occurred or that may occur (Landres 1992).

Researchers distinguish several types of indicators. For example, ‘compliance indicators’ identify deviation from previously defined conditions, ‘diagnostic indicators’ identify the specific cause of a problem and ‘early warning indicators’ signal an impending decline of conditions (Cairns and McCormick 1992). It is important to define the purpose of indicators and to select them on the basis of how well they can fulfil the required role.

Indicators are perhaps best viewed as communication tools that can turn scientific knowledge into a form better understood by a range of community groups, policy makers and others (Walker et al. 1996). Questions have been raised about the credibility of indicators for resource assessments, but this applies only if indicators are poorly selected. In selecting indicators it is necessary to look at certain criteria such as reliability, interpretability, data availability, established threshold values (needed to set class boundaries) and known links to processes (Walker and Reuter 1996;

Jackson et al. 2000). There are better grounds to question the aggregation of indicators into an index (e.g. catchment health rating) or subindex (water quality), since this involves the addition of disparate measures, usually in a simplistic way. Fuzzy approaches (Roberts et al. 1997) offer a possible means to be mathematically correct, but the interpretation of any given index is still an issue.

Steps in Using Environmental Indicators

Indicator development starts with defining a problem — identifying the issues and their value to society. We then ask questions to specify the issues more clearly. This involves making balanced and integrated judgments on the economic, social and environmental condition of a region’s rural enterprises (SCARM 1998). The next step is to choose attributes to use as indicators; for example, current condition (or status) and the direction and magnitude of any change in condition. Certain indicators will be influenced by changes in other indicators, and these interactions must be taken into account.

Questions that could be used to determine the specific issues, for example for the grains industry, are:

- Where is farm productivity falling and the natural resource base declining?
- Where is farm productivity increasing or stable and the resource base stable?
- Where is farm productivity improving and the natural resource base declining?

These questions can be asked at individual paddock, catchment and region scales. By using different sets of indicators to answer these questions and by analysing the responses, an assessment report can be produced. If the report shows that current farming practices are having detrimental impacts on the resource base, it can be used as the

basis for remedial action. Indicators can then be used to monitor the outcomes of whatever action is taken. These steps are depicted in Figure 1.

Many of the chapters in this book illustrate the use of indicators in summarising research knowledge. This section examines various issues involved in selecting suitable indicators of catchment and farm health, and in developing appropriate monitoring programs.

Interpreting Indicators at Different Scales

Different spatial scales often require different questions to be asked, requiring different indicator sets and thresholds (Walker et al. 2001). Table 1 illustrates the different kinds of questions asked at different scales. Table 2 lists some of the indicators that are relevant at particular scales. They include single indicators (e.g. soil nitrogen), composite indicators (e.g. cropping on steep slopes as an estimate of erosion risk) and aggregated indexes (e.g. soil moisture index or soil fertility indexes).

Data collected in farm surveys can be aggregated and reported at regional and even national level, provided that sampling intensity and measurement quality are adequate and the indicators reflect regional or farm diversity.

At the national and State scale (Table 1) the interest is mainly on policy development and identifying ‘hot spots’ that require immediate attention. ‘State of environment’ reporting at the national and State levels are examples. The approach is ‘top-down’: the initiative is taken by people from State and national bodies and the results handed over for implementation. The data used are generally readily available data with little attempt to collect detail. These issues are discussed more fully in Chapter 26.

Indicators for regional or local government/provincial scales could also refer to a particular sector, reflecting concerns about the production and

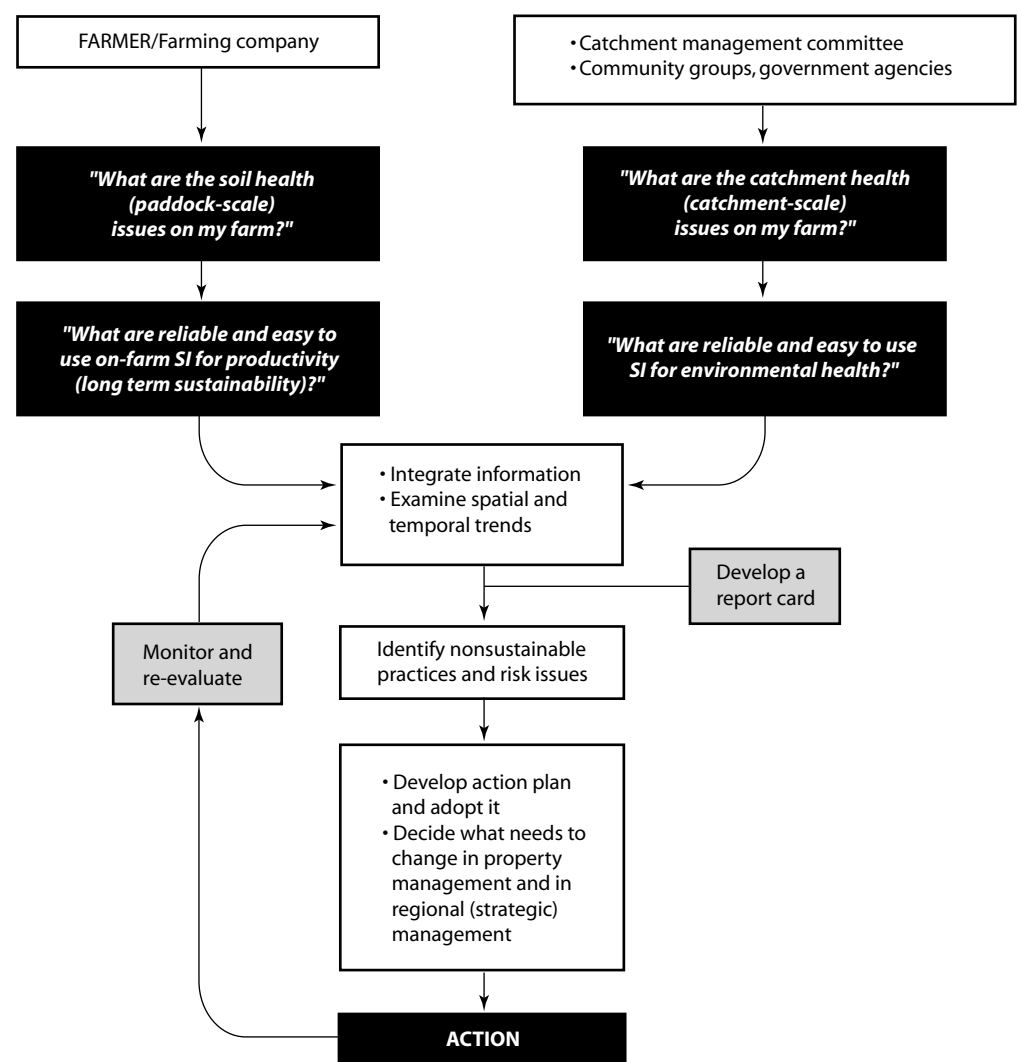


Figure 1. A logical decision tree for using sustainability indicators (SI).

economic future of a region. Examples of the kind of information available for indicator development at this scale are given in Section 3 of this Volume.

At the farm level, questions refer to specific management problems — how to identify undesirable changes and what action to take. The approach is ‘bottom-up’, with emphasis on self-help. The focus is on changing practices at the paddock scale in a way likely to improve farm and catchment health. Examples in this book are found in Chapters 21 and 28.

A Structured Approach to Using Sustainability Indicators

Indicators must be relevant, robust and scientifically defensible. There is little point in using indicators that have known weaknesses or that cannot be interpreted reliably. For example, mean soil worm density is difficult to interpret because of regional and seasonal variability; mean soil pH has little meaning at a catchment scale but is useful at a farm scale or for a particular soil landscape. We need to set criteria against which the merits of an indicator can be judged — for example, by rating

Table 1. The categories of questions asked at different scales.

National scale	Regional/catchment scale	Farm/site scale
Top-down approach	Top-down approach	Bottom-up approach
Purpose of indicators		
National/State assessment	← Two-way linking process → Social–economic–natural resources	Site assessment
Socioeconomics (resource economics)		Socially acceptable economic choices
Policy development		On-ground action
Agricultural sustainability		Condition of the land (paddock)
State of environment (SoE) reporting		Assessing trends for a farm
Agricultural production		Whole environment/conservation urban/rural links
Indicator programs or groups interested in using them		
• DEST (SoE reporting) • State SoE reporting • SCARM (sustainability program) • ABARE (Outlook conference) • ABS (national statistics) • Research and development corporations such as LWRDC, GRDC and RIRDC • State EPAs	• CALP boards • Regional land management boards • MDBC • State water/land/agriculture departments • NLP • Indicators of catchment health developed by CSIRO • ALGA • ABARE	• Farmer groups • Farm planning groups • Land care groups • Providers of extension services • ACF/SAWCAA • Streamwatch • Waterwatch • Farm 500
Questions		
1. How degraded are Australia's natural resources? 2. Where are the urgent problems? 3. How sustainable are our agricultural practices? 4. What are the broad trends in costs versus profits for agricultural enterprises? 5. What policies can be developed to encourage sustainable agriculture?	1. How can production, quality of life and profits be increased? 2. What methods need to be developed to better manage natural, social and economic resources? 3. What effects are agricultural practices having on natural, social and economic resources? 4. What impacts are social and economic events having on resource management?	1. How can I best manage my farm? 2. How can I make a living on my farm? 3. What sort of life can I have? 4. How can I assess land and water health on my farm? 5. How much will it cost to fix a biophysical/resource depletion problem?
ABARE = Australian Bureau of Agriculture and Resource Economics; ABS = Australian Bureau of Statistics; ACF = Australian Conservation Foundation; ALGA = Australian Local Government Association; CALP boards = catchment and land protection boards; DEST = Department of the Environment, Sport and Territories; EPA = environmental protection agency; GRDC = Grains Research and Development Corporation; LWRDC = Land and Water Resources Research and Development Corporation; NLP = National Landcare Program; MDBC = Murray–Darling Basin Commission; RIRDC = Rural Industries Research and Development Corporation; SAWCAA = Soil and Water Conservation Association of Australia; SCARM = Standing Committee on Agriculture and Resource Management; SoE = State of environment		

Table 2. Examples of linkages between issues, sustainability indicators and scales.

Scale	Issue	Sustainability indicator
National	Average real net farm income	Farmer's terms of trade
	Access to key services	Distance to regional centres
State	Health of river basins	Trends in water quality
Agricultural industry	Meeting commodity market specifications	Trends in silo protein levels for wheat
	Farmer's skills	% farmers using property management plans
Region	Health of rural environments	% land affected by salinity
		Condition and extent of native vegetation
Catchment	Meeting water quality targets	Trends in water quality
		% area with protected riparian vegetation
Farm	Optimising farm returns	Disposable income per family
	Planning the annual farm business	Forecast trends in commodity prices
Paddock	Yield performance	% potential yield or \$ water use efficiency
	Soil health assessment	Reliable soil tests

each indicator in terms of relevance, ease of capture and reliability. Table 3, which broadly follows Jackson et al. (2000) and Walker et al. (2000), summarises the criteria for selecting reliable sustainability indicators.

Threshold guidelines for resource condition

Figure 2 shows how a hypothetical resource indicator in an agroecosystem might change with time. Initially, sample values vary within accepted thresholds. For example, even if a system has been changed from a natural to a managed agroecosystem, it may be performing within acceptable limits. Such a system is considered stable (e.g. not leaking nutrients or water to streams or groundwater systems) within the set thresholds. This is the concept of ‘conditional stability’ developed by Walker (1999). In later years, values

may move outside threshold limits. For example, increased electrical conductivity could signal increasing salinity in soil or streams, or decreased soil nitrogen levels could indicate nutrient depletion under intensive cropping regimes. The main problem is in setting threshold values that apply nationally. Some thresholds are well defined (e.g. some water quality measures are related to human health), but values are more difficult to set in landscapes and catchments. Values are known to vary regionally and thresholds vary with spatial scale. This variability makes the idea of setting environmental targets difficult to define absolutely.

A suite of indicators is needed to examine changes in resource condition. For example, commercial soil sampling services offer clients multiple tests on each sample submitted. The results can then be

Table 3. Challenges for selecting reliable sustainability indicators (SIs).

Criteria	Challenges
Reliability	Is a standard method available to measure the SI?
	Are low errors associated with measurement?
	Is the SI measurement stable?
	Can the SI be interpreted and ranked reliably?
	Does the SI respond to change or disturbance?
	Is the SI accepted by farming communities?
Data capture and cost	Can SI data be easily captured?
	Is the data capture at low cost?
	Does the SI need to be monitored regularly?
Ranking and assessment	Can the SI data be mapped or graphed?
	Can SI assessments be integrated soundly in space and time?
	Do previous SI data exist?

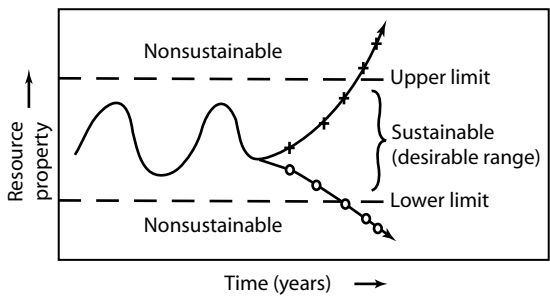


Figure 2. Conceptual diagram showing the requirement for validated upper and lower limits to assess temporal trends (A, B) in a resource property (indicator values) (Reuter 1998).

compared to relevant guidelines¹ and used to summarise trends. Farmers and their advisers can carry out these tests themselves at relatively low cost using practical ‘do-it-yourself’ test kits. Kits are available through the Western Australian Farm Management Society and Charles Sturt University. Rengasamy and Bourne (1997) have also developed a kit for assessing soil salinity, acidity and sodicity.

¹ For example, there are Australian guidelines for interpreting soil (Peverill et al. 1999), plant (Reuter and Robinson 1997) and water quality tests for assessment of stream condition (Ladson and White 1999).

Benchmarking farm business health

The Australian Bureau of Agricultural and Resource Economics (ABARE) has defined economic indicators of farm performance (ABARE 1999). These are derived as complex national or industry indexes, or estimated from aggregated data from various sources such as annual ABARE farm surveys, the Australian agricultural census and agricultural financial surveys from the Australian Bureau of Statistics (ABS). ABARE and ABS publish regular updates showing trends for economic indicators.

Dealing with large annual variations

When there are large annual variations in indicator values, it is important to know the trends over time. Many economic indicators, such as disposable income per family or profit at full equity, vary greatly from year to year through the combined effects of seasonal weather conditions, shifts in commodity prices and other market forces (e.g. interest rates). For these indicators, trends in data, acquired annually, should be assessed at constant dollar value over several years or decades to understand the magnitude and direction of longer term changes. The impact of rainfall on economic indicators can be partly circumvented by expressing data in units of

rainfall received in any given season — the so-called dollar water use efficiency (\$WUE) indicator.

National assessments of sustainable agriculture

The Standing Committee on Agricultural Resource Management (SCARM) published a series of reports during the 1990s. These culminated in a pioneering but incomplete report on the assessment of sustainable agriculture in Australia’s 11 agroecological zones. Initially, ‘sustainable agriculture’ was defined and guiding principles were developed for assessing the level of sustainability achieved by the agricultural sector (SCA 1991). Subsequently, an indicator framework was devised for making these assessments (SCARM 1993). A pilot feasibility study was undertaken to evaluate the validity and availability of data for these indicators (SLWRMC 1996). A final report

(SCARM 1998) documented the data and trends. Table 4 lists the indicators used by SCARM to assess sustainability in Australian agriculture. It also lists possible indicators that were not identified in the report but are now acknowledged to be important for a complete assessment of sustainable agriculture in Australia. Some of these indicators are now used in the National Land and Water Resources Audit.

Comparing Different Condition or Sustainability Assessments

It is often useful to compare agricultural performance with catchment condition or with other indexes (e.g. economic or social indexes). Figure 3 shows a cross-comparison matrix of ranked assessments of farm production and ranked assessments of catchment condition. The focus in the figure is on combinations that do not conform to expected (i.e. the diagonal). For example, if a

Table 4. Composite indicators and attributes used by SCARM (1998) to assess sustainability in Australian agriculture, together with some additional attributes required for a more complete assessment.

SCARM indicators	Attributes assessed by SCARM (1998)	Attributes not assessed by SCARM (1998)
Long-term real net farm income	• Real net farm income • Total factor productivity • Farmer’s terms of trade • Average real net farm income • Debt servicing ratio	• Costs of land degradation • Costs and benefits from remediating degraded resources • \$ water use efficiency (for rainfed and irrigated farms)
Natural resource condition	• Phosphate and potassium balance • Soil condition: acidity and sodicity • Rangeland condition and trend • Diversity of agricultural plant species • Water use by vegetation	• Nitrogen and sulfur balances • Extent of soil structural decline • Level of groundwater reserve exploitation • Extent of land salinisation • Assessment of catchment condition
Off-site environmental impacts	• Chemical residues in products • Salinity in streams • Dust storm index • Impact of agriculture on native vegetation	• Impacts of soil erosion on river water quality • Extent of nonreserve native vegetation on farms
Managerial skills	• Level of farmer education • Extent of participation in training and Landcare • Implementation of sustainable practices	• Adoption by industry of best management practices • Extent of farmer access to the internet
Socioeconomic impacts	• Age structure of the agricultural workforce • Access to key services	• Capacity of rural communities to change • Extent of diversification within rural regions • Extent to which current infrastructure, policies and laws support sustainable agriculture

catchment is biophysically in poor condition and production is high, the system is probably maintained by high inputs of fertiliser and may not be environmentally sustainable. The matrix, which was developed by Walker et al. (2000), is not meant to show causal relationships, but suggests where more investigation is needed. It is particularly useful in broadly comparing biophysical indexes with production, economic and social indexes and in interpreting sustainability at catchment and regional scales. The matrix is based on a list of core indicators for benchmarking economic and resource health within catchments (Walker and Reuter 1996). The initial list was drawn up in 1996; other indicators were added following a national workshop (see Table 3 in Reuter 1998).

Conclusion

Most programs involved in monitoring and assessing environmental condition are ultimately associated with issues of sustainability. The word ‘sustainability’ has many connotations, including longevity, continuity, function and stability. There are thus different questions to ask and different approaches available. Process-based models have a place and also have limitations; so do indicators. Process-based models, as illustrated in other chapters in this book, can be useful to develop a range of scenarios, but in the context of indicators they can be particularly useful in setting workable threshold values. Unfortunately, many process modellers and reductionist scientists have relegated environmental indicators to the soft sciences, little

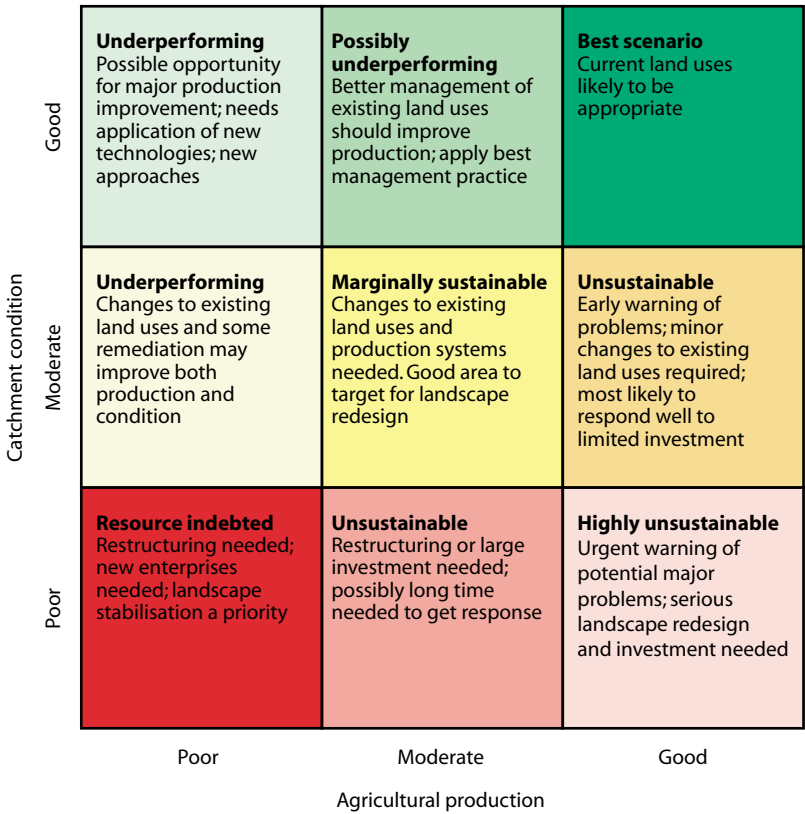


Figure 3. Possible interpretation of the catchment condition–agricultural production cross-comparison matrix.

realising that indicators have a process base. This attitude is usually based on ignorance about the derivation and use of indicators. The establishment of the new journal *Environmental Indicators*² will help to establish indicators as a credible systems approach to sustainability issues.

References

- ABARE (Australian Bureau of Agricultural and Resource Economics) 1999. Performance indicators for the grains industry. In: Australian Grains Industry Performance by Grains Research and Development Corporation Agroecological Zones, 15–21.
- Cairns, J. and McCormick, P.V. 1992. Developing an ecosystem-based capability for ecological risk assessments. *The Environmental Professional*, 14, 186–96.
- Jackson, L.A., Kuartz, J.C. and Fisher, W.S. 2000. Review of EPA evaluation guidelines for ecological indicators. EPA/600/3-90/060.
- Ladson, A.R. and White, L. 1999. An index of stream condition: reference manual. Victoria, Waterways Unit Department of Natural Resources and Environment.
- Landres, P.B. 1992. Ecological indicators: panacea or liability? In: McKenzie, D.H., Hyatt, D.E. and McDonald, V.J., eds, *Ecological Indicators*, Vol. 2. New York, Elsevier Applied Science, 1295–318.
- Meyer, J.R., Cambell, C.L., Moser, T.J., Hess, G.R., Rawlings, J.O., Peck, S. and Heck, W.W. 1992. Indicators of the ecological status of agroecosystems. In: McKenzie, D.H., Hyatt, D.E. and McDonald, V.J., eds, *Ecological Indicators*, Vol. 2. New York, Elsevier Applied Science, 628–58.
- Peeverill, K.I., Sparrow, L.A. and Reuter, D.J. 1999. *Soil Analysis: an Interpretation Manual*. Melbourne, CSIRO Publishing.
- Pykh, Y.A., Hyatt, D.E. and Lenz, R.J.M., eds 1999. *Advances in Sustainable Development: Environmental Indices Systems Analysis Approach*. Oxford, EOLSS Publishers.
- Rengasamy, P. and Bourne, J. 1997. Managing sodic, acid and sodic soils. Co-operative Research Centre for Soil and Land Management SAS 8/97, Adelaide.
- Reuter, D.J. 1998. Developing indicators for monitoring catchment health: the challenges. *Australian Journal of Experimental Agriculture*, 38, 637–48.
- Reuter, D.J. and Robinson J.B. 1997. *Plant Analysis: An Interpretation Manual*, 2nd edition. Melbourne, CSIRO Publishing.
- Roberts, D.W., Dowling, T.I. and Walker, J. 1997. FLAG: A Fuzzy Landscape Analysis GIS Method for Dryland Salinity Assessment. CSIRO, Land and Water Technical Report 8/97, Canberra, July 1997.
- SCA (Standing Committee on Agriculture). 1991. *Sustainable Agriculture*. SCA technical report series No. 36. Melbourne, CSIRO Publishing.
- SCARM (Standing Committee on Agricultural and Resource Management) 1993. *Sustainable Agriculture: Tracking the Indicators for Australia and New Zealand*. Melbourne, CSIRO Publishing.
- SCARM 1998. *Sustainable Agriculture: Assessing Australia's Recent Performance*. Melbourne, CSIRO Publishing.
- SLWRMC (Sustainable Land and Water Resource Management Committee) 1996. *Indicators for Sustainable Agriculture: Evaluation of Pilot Testing*. SLWRMC, April 1996, CSIRO Publishing.
- US NRC (National Research Council). 2000. *Ecological Indicators for the Nation*. Washington, DC, National Academy Press, 180 pp.
- Walker, J. 1998. Environmental indicators of catchment and farm health. In: Williams, J., Hook, R.A. and Gascoigne, H.L., eds, *Farming Action Catchment Reaction: the Effects of Dryland Farming on the Natural Environment*. Melbourne, CSIRO Publishing, 99–117.
- Walker, J. 1999. Conditional health indicators as a proxy for sustainability indicators. In: Pykh, Y.A., Hyatt, D.E. and Lenz, R.J.M., eds, *Advances in Sustainable Development: Environmental Indices a Systems Analysis Approach*. Oxford, UK, EOLSS Publishing Co. Ltd, 349–362.
- Walker, J. and Reuter, D.J. (eds) 1996. *Indicators of Catchment Health: A Technical Perspective*. Collingwood, Victoria, CSIRO Publishing.
- Walker, J., Alexander, D., Irons, C., Jones, B., Penridge, H. and Rapport, D. 1996. Catchment health indicators: an overview. In: Walker, J. and Reuter, D.J., eds, *Indicators of Catchment Health: A Technical Perspective*. Melbourne, CSIRO Publishing, 3–18.
- Walker, J., Veitch, S., Braaten, R., Dowling, T., Guppy, L. and Herron, N. 2000. *Catchment Condition in Australia: an Assessment at the National Scale*. A discussion paper for the National Land and Water Resources Audit (Project 7/8).
- Walker, J., Veitch, S., Braaten, R., Dowling, T., Guppy, L. and Herron, N. 2001. *Catchment Condition in Australia*. Final Report to the National Land and Water Resources Audit, November, 2001.

² www.elsevier.com/locate/ecolind

25 Testing Readily Available Catchment-Scale Indicators as Measures of Catchment Salinity Status

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Abstract

This study compares a biophysical index of catchment salinity status based on readily available indicators with field measures of stream salinity. It also looks at the time required to compile a data set from readily available data, and whether meaningful results can be obtained from averaged data for third-order catchments. The catchments studied form the entire Upper Murrumbidgee catchment (approximately 12,000 km²).

The study outlines a systematic approach to selecting relevant, appropriate and readily available indicators. The indicators selected were per cent forest cover, forested areas greater than 50 ha, road density per unit area, per cent agriculture on slopes greater than 5%, number of roads crossing streams/rivers per unit area and the hypso-metric integral per catchment. The indicators were compiled and collated in 10 days. The field data comprised stream salt concentration, salt load and two measures of macroinvertebrate group richness—the number of families of macroinvertebrates and the number of families observed compared to the number expected (O/E). The field work required nine months to complete. The biophysical and field indexes were calculated using a simple additive model. The data were placed in three classes using threshold values equivalent to best, intermediate and worst, weighted as 3, 2 and 1 respectively.

Significant relationships were detected between stream salinity and the biophysical index, and between the biophysical and field indexes. A lesser but significant relationship was detected between O/E biota and the biophysical index. These relationships suggest that the readily available data ranked the salinity status of the catchment in a credible way. We suggest that coarse-scale data are grossly undervalued in developing comparative scenarios; indicators carefully selected from readily available data can be used to quickly derive big picture scenarios.

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本文对比了反映流域盐化状况的生物物理指标和反映河流盐分状况的野外量测指标，前者基于从现有资料中选择出来的环境指标，后者由野外测量得到。也讨论了从现有资料中收集整理出一套指标数据所用的时间，以及平均数据能否得到对第三级流域有用的结果。此项研究覆盖了整个默如比基流域的上游地区（约一万两千平方公里）。

作者概述了从现有资料中选择相关、适当的诊断指标的一个系统化的方法。选择的指标有森林覆盖率，面积大于 50 公顷的林地，单位面积的道路密度，坡度大于 5% 的农地比例，单位面积内跨越河流的道路数量，以及每个流域的高程积分。健康诊断指标数据在十天内完成编辑汇总。野外数据包括河流盐分浓度，排盐量和反映大型无脊椎动物群丰度的两个值——大型无脊椎动物门数及其调查值与预期值的（O/E）的比值。野外作业需九个月完成。生物物理指标和野外量测指标由简单的加法模型计算得出。数据被分为三个等级，其阈值分别相当于好、中、差，权重分别是 3、2、1。

研究发现河流盐分和生物物理指标之间以及生物物理指标与野外量测指标之间有着明显关联。O/E 和生物物理指标间的关联比它们稍弱但仍很明显。这些联系表明简单易得的诊断指标对流域盐分状况的反映可信度很高。我们认为写意式粗线条数据的价值总的来说被低估，在作对比项目中，采用认真挑选的诊断指标，能够快速反映总体轮廓特征。

THE PRIMARY purpose of this study was to investigate the credibility of a stream salinity index based on a small set of easily obtained landscape indicators, by comparing the index with independent measures of stream salinity. The study was also designed to look at the time needed to compile a data set from readily available data, and whether meaningful results could be obtained from averaged data for third-order catchments.

Why use a set of landscape metrics to rate relative salinity risk across a group of catchments when the measurement of salt concentrations in streams is relatively simple? The answer is that there is a major dilemma with salt measurements from streams. The problem is illustrated by Figure 1, in which stream salinity — electrical conductivity (EC) in microSiemens per cm — is plotted against

sample time. Figure 1 shows that EC is extremely variable and is related to stream flows: high flows tend to have low salt concentrations and vice versa. The range in salt concentrations can be important; for example, for stream biota and for livestock drinking the water. Given that most streams lack sample points, establishing catchment stream salinity status would require regular sampling over years or even decades.

An alternative measure of salinity risk is salt loads in streams (concentration × volume). In Australian streams, water volumes can vary quickly following rainfall, often in a timespan of hours; stream volume is therefore much more difficult to measure than EC. Sampling across a region can take several days, so it is difficult to sample similar parts of the stream hydrograph (plot of volume against time).

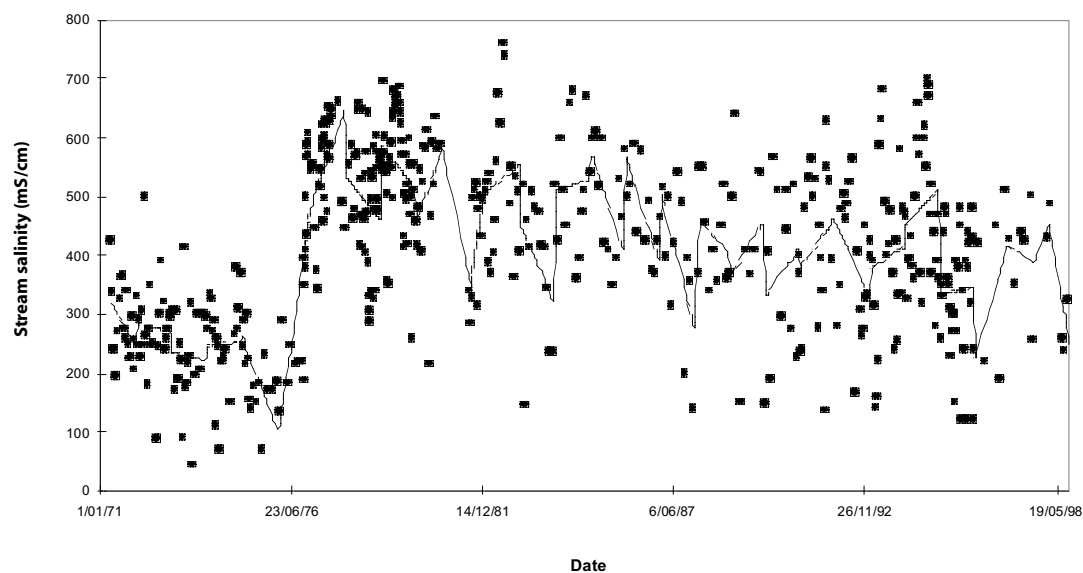


Figure 1. Stream salinity (electrical conductivity, EC) plotted with time for a stream in the Gininderra catchment, Australian Capital Territory (data from Environment ACT).

Accurate measuring of stream EC and volume requires permanent sampling stations and frequent (at least every hour) sampling. Such stations occur primarily on research sites or at the outlets of very large catchments, providing sparse but high-quality data. Dividing a large catchment into contributions from subcatchments can be a problem in the absence of sampling sites in the subcatchments.

We believe that stream salinity status can be assessed with appropriate landscape indicators. In this way, sparse, high-quality data can be complemented by poorer-quality, dense sampling. If the measures selected are the main drivers of the systems, the values obtained can act as benchmarks for further monitoring.

Study Area, Data Collection and Indicators

Figure 2 of the Overview shows the location of the Upper Murrumbidgee catchment. The catchment has a total area of approximately 12,000 km² and includes the national capital, Canberra (population 300,000), and the rural centres of Yass and Cooma,

each with a population of less than 10,000. Land uses include cropping, extensive livestock grazing, forestry, viticulture, water catchments for the supply of town drinking water, national parks and many small hobby farms. Many areas have been cleared of native forest and woodland vegetation, and this contrasts with other areas that are in pristine condition. Issues identified by local Landcare groups and the Upper Murrumbidgee Catchment Committee include weeds, feral animals, waterlogging, salinity, stream turbidity, soil erosion and water quality.

Walker et al. (2001) and Jones et al. (1997) have suggested a series of steps in developing an indicator approach to resource assessment. These are:

- first identify *societal values*;
- then identify the *specific issue* to examine;
- frame an *assessment question* to address the issue; and
- select *indicators* that address the assessment question.

In this study of the Upper Murrumbidgee catchment, the societal value was good-quality water; the issue was the risk of increasing stream salinity; and the assessment question was ‘What is the relative salinity status of catchments in the Upper Murrumbidgee?’

In order to gain an indication of how long it would take to complete a national assessment, a time limit for the study was set at 10 days. Another aim of the study was to determine whether a catchment size of about 500 km² could be used to assess catchment condition. The size is typical of catchments used by Landcare groups and as management units for regional planning and management. At an Australia-wide scale, catchments approximately 500–1000 km² in area are often third-order catchments and can be explicitly defined from appropriate digital elevation models (DEMs).

The strategy adopted to address the assessment question was as follows:

- identify and collate readily available spatial environmental attributes for the region;
- select indicators from the available attributes according to the criteria (reliability, interpretability, data availability, known thresholds and links to biophysical processes);
- use a simple additive model to calculate an index of salinity status for each catchment (a relative ranking from best to worst (good to bad)); and
- collect independent data on stream salinity and examine the relationship with the catchment condition values (the expectation is that a relationship should exist).

Figure 2 shows the subcatchments used in the study. The Upper Murrumbidgee region was divided into 13 third-order stream catchments defined by the New South Wales Department of Land and Water Conservation from previous and current gauging stations. Catchment No. 8 was larger than the others and subdivision would be desirable. However, only 13 catchments were gauged.

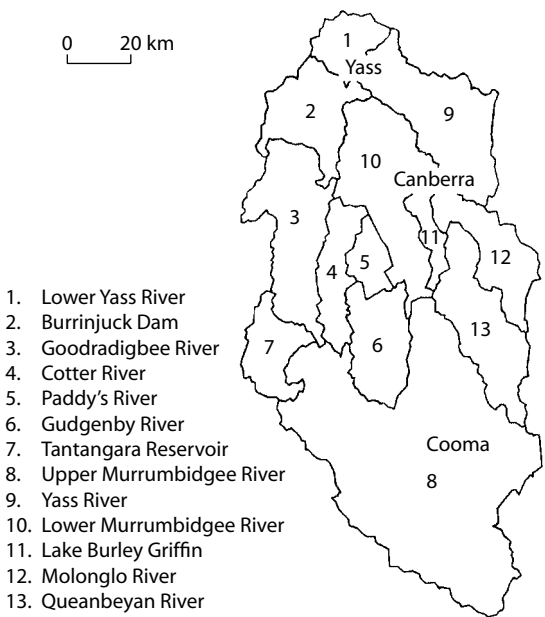


Figure 2. Subcatchments in the Upper Murrumbidgee Region of New South Wales.

Indicators of Catchment Condition

The processes driving salinisation in this region are well understood; they include urban development, tree removal for agriculture, destruction of the riparian buffer and shallow, salty groundwaters. We selected indicators that were linked with these processes and were readily available. The data sources were Thematic mapper satellite imagery,¹ a DEM at 250 m resolution (AUSLIG 1994), and cadastral and land-use information (AUSLIG 1996). The imagery enabled us to identify the major vegetation/land-use types—treed areas (woodland and forest with a projected cover of more than 20%), improved pastures, cropping areas and urban areas. The DEM allowed slope classes and catchment areas to be derived. From the DEM data we calculated two landscape indexes—catchment area and a hypsometric integral. Strahler (1952) defined a hypsometric integral as an area–altitude curve that relates horizontal cross-sectional area of

¹ Provided by Dr Tim McVicar and Lingtao Li, CSIRO Land and Water. See Chapter 16 for specifications of Landsat Thematic mapper.

a drainage basin to relative elevation about the basin mouth. The measure was considered to be related to several catchment processes, including hydrological regime, soil erosion, landscape age and sedimentation. It has seldom been applied or used to interpret catchment processes.

Six indicators collected were used in the analysis. Indicators used were per cent forest cover, per cent forested areas of more than 50 ha, road density per unit area, per cent agriculture on steep slopes (slopes of more than 5%), number of roads crossing streams per unit area and the hypsometric integral. Table 1 shows values for the biophysical indicators.

Classification

The individual indicator values were placed into three classes (thresholds), representing poor, medium and good (red, yellow and green), as illustrated in the example shown in Table 2. For four of the six indicators, the range in values was

simply divided into three equal parts. For per cent forest cover, evidence from other studies suggested that classes at < 20%, 20–60% and > 60% were correlated with stream salinity (high to low). The three classes for the hypsometric integral were determined as equal areas under the frequency/value curve obtained from a more extensive study in the region. This classification gave approximately equal numbers of catchments in each class for each indicator (more by chance than design). Maps of classes for individual indicators were drawn using individual indicator values but are not presented here.

Class weightings

Weightings can be carried out in several different ways; similarly, the means to recognise class boundaries and to develop an index can have several variants. Weightings were applied to each of the classes as 1, 2 or 3 (poor, medium or good) and summed for each catchment to give an aggregated

Table 1. Biophysical attributes (indicators) for the catchments.

Catchment number	Road density per unit area	% Forest cover	% Forested > 50 ha	Roads crossing streams	% Agriculture on steep slopes	Hypsometric integral	Biophysical index
1	0.0165	2.99	0.00	0.3181	38.07	0.3787	7
2	0.0136	21.51	1.53	0.1443	46.64	0.2393	9
3	0.0137	72.41	32.20	0.1890	23.46	0.3995	14
4	0.0174	81.75	46.16	0.2695	16.05	0.4312	14
5	0.0169	54.79	17.68	0.1793	37.18	0.3836	12
6	0.0100	61.55	20.58	0.1780	33.41	0.4495	16
7	0.0108	60.99	8.12	0.2059	21.57	0.2916	12
8	0.0156	46.15	14.26	0.1449	28.81	0.3200	12
9	0.0152	13.63	0.17	0.0442	37.13	0.3578	8
10	0.0210	14.91	0.39	0.0598	46.02	0.3028	8
11	0.0282	17.89	0.26	0.0514	34.87	0.2195	9
12	0.0157	35.35	7.45	0.1130	27.96	0.3342	11
13	0.0144	48.57	15.04	0.1618	34.47	0.3853	13

value for its condition, as illustrated in Table 2. Thus, values for catchment biophysical condition ranged from 6 (all indicators poor) to 18 (all indicators good). These catchment ratings were then compared with independent field measures of stream salinity.

Table 1 shows the biophysical index values for the catchments using these threshold values and weightings.

Field Sampling for Stream Salinity and the Biotic Response

We selected four independent measures (termed field indicators) to reflect changes in stream salinity:

- salt concentration (measured as EC at base flow/discharge);
- salt load (salt concentration × stream base flow); and
- two measures of macroinvertebrate group richness (number of families of

macroinvertebrates, and observed over expected number of families).

The measures were for an autumn sample and were taken at the exits of the 13 catchments during a period of base flow some 10 days after a rainfall event. The assessment team collected the data for EC. The Co-operative Research Centre for Freshwater Ecology (University of Canberra) and Environment ACT supplied the data for macroinvertebrates. These data are part of a national study that defined expected values and determined methods for sampling and analysis. One field site was omitted from the analyses (site 2 was sampled at the outlet rather than the inlet of Lake Burley Griffin), because the lake acted as a salt buffer.

The field sampling had to be deferred several times because of variable stream base flows across the catchments, and the need to coincide with the macroinvertebrate sampling. Sampling for EC required two field days, so we had to wait for the right conditions. Table 3 gives the values for the field measures and the field index.

Table 2. Classification of indicators using threshold values. Green indicates good; yellow indicates medium; and red indicates poor. Classes are weighted 1, 2 and 3, respectively (good to poor) and the weightings added to give an index score. The minimum score is 6 (all poor); the maximum is 18 (all good). Three examples are shown to introduce the working.

Threshold values for the 13 site analysis						
Weighting	Forest cover (%)	% Forested areas > 50 ha	Road density per unit area	% Agriculture on steep slopes	No. of roads crossing streams per unit area	Hypso-metric integral
1 (poor) (red)	< 20	< 5	> 0.015	> 36.0	> 0.2	< 0.31
2 (medium) (yellow)	20–60	5–10	0.015–0.010	22.0–36.0	0.1–0.2	0.31–0.4
3 (good) (green)	> 60	> 10	< 0.010	< 22.0	< 0.1	> 0.4

Catchment no.							Field index
1	2.9	0.00	0.0165	38.1	0.318	0.3787	7
2	21.5	1.5	0.0136	46.6	0.146	0.2393	9
3	72.4	32.2	0.0137	23.5	0.189	0.3995	14

Relationships Between Catchment Condition and Field Measures

The four field data sets and the field index were plotted against the catchment biophysical index. Figure 3 shows the plots that had a significant linear relationship (note that some points are plotted on top of each other, giving apparently different numbers of catchments). The relationship between stream salinity (measured as EC) and the biophysical index (Fig. 3a) was negative and the correlation strong ($r^2 = 0.75$, $P < 0.001$). This suggests that the index is predicting the salinity status of the streams very well.

The relationship between the biophysical index (based on indicators) and the field index (which includes biological and stream salt measures) (Fig. 3b) was likewise strong and positive ($r^2 = 0.74$, $P < 0.001$). The relationship between the macroinvertebrate data (observed number of

macroinvertebrate families over expected number) and the biophysical index (Fig. 3c) was positive but weak ($r^2 = 0.34$ $P < 0.05$). This suggests that at the scale of catchments used in the study (500–1000 km²), the influence of landscapes and changes in land use is reflected in the stream fauna. Although weak, this relationship is encouraging, given the limited nature of the field data and the potential for large variability. The relationship between salt load and the biophysical index (not shown) was very weak ($r^2 = 0.04$). An examination of the biophysical data set suggested that the measure dominating the results is per cent tree cover remaining in the catchment.

Discussion and Conclusion

This study set out to compare readily available landscape biophysical data, which can be collected quickly, with stream measurements, which take much longer to collect and also require specialist

Table 3. Field measurements of salinity and biota in the catchments.

Catchment Number	Conductivity (EC)	Salt load (concentration × flow)	Macro-invertebrates (observed mean)	Macro-invertebrates O/E	Field index
1	974	1.412	8.50	0.86	7
2	406	0.128	2.00	0.21	7
3	102	2.239	14.00	1.11	10
4	64	0.077	10.50	0.83	11
5	99	0.072	12.20	1.08	12
6	140	0.057	11.20	0.97	12
7	30	0.777	13.00	0.89	11
8	494	0.401	11.00	0.97	11
9	1081	0.954	8.00	0.79	6
10	970	0.085	5.15	0.57	6
11	456	0.133	5.33	0.55	7
12	505	0.504	8.20	0.88	9
13	314	0.412	7.80	0.78	9

O/E = number of families of macroinvertebrates observed compared to the number expected

expertise. The strong correlation between the biophysical landscape data and the field data suggests that, at least for the area examined, the index performed very well.

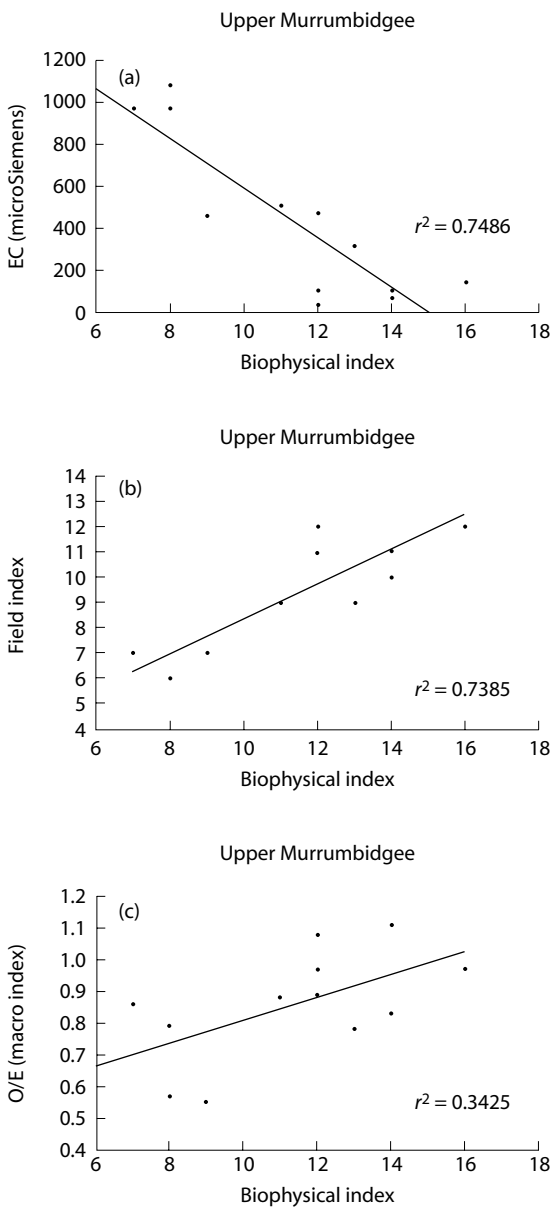


Figure 3. Relationships between catchment condition and stream measurements: (a) plot of stream salinity versus the catchment condition biophysical index; (b) plot of the biophysical versus field catchment condition indexes; and (c) plot of observed/expected macroinvertebrate groups versus the biophysical index of catchment condition.

The mechanisms controlling salinity in the study area were reasonably well known and the question arises as to whether the same indicators can be used in other areas to rate salinity status. Sufficient research has been carried out across Australia to suggest that different mechanisms are at work in different regions (e.g. seasonality of rainfall, magnitude and mobility of salt stores and different kinds of groundwater flow systems contributing to dryland salinity). Recent groundwater mapping as part of the National Land and Water Resources Audit (Coram et al. 2000) shows the areas with local, intermediate and regional groundwater flow systems. Inspection of the maps suggests that the indicator set could apply to the southeast temperate areas of Australia on the western side of the Great Dividing Range, mapped as local or intermediate groundwater flow systems.

The catchment size used approximated third-order catchments, with the majority ranging in size from 500 to 1000 km². Subsequent studies over smaller and larger areas suggest that size does influence the results, particularly threshold values, and the indicators that are appropriate (Walker et al. 2001). There could be many different reasons for this effect, but the most obvious with respect to stream salinity are that:

- as size increases, varying inputs of high-quality versus salty water along the length of the river will affect the relationships, and
- at smaller scales, the impacts of good management practices can reduce salt inputs from the land (e.g. repairs to the riparian zone can reduce overland flows).

Data for these parameters are generally not available at the broader scales. Therefore, it is advisable to use sizes of around 500 km². Nevertheless, the indicator approach described can be useful as context information at the more detailed scale, and detailed data can be added when available.

The collation of the data sets was carried out within a week, suggesting that application at a national level is possible within a realistic timeframe. Regional differences are important in such an exercise, and it would be advisable to identify the local mechanisms controlling salinity inputs.

Because the study was confined to 13 catchments it has statistical limitations. The next stage, before a national study, involved collecting data from 169 subcatchments in the Upper Murrumbidgee and more intensive field sampling. Some results of this work are reported in Chapter 26.

The results raise an interesting question about the use of coarse-scale data as opposed to detailed measurements to carry out 'big-picture' assessments. It may well be that detailed measurements will not perform any better, and past experience suggests that spatial density is a major consideration. Perhaps continental-scale data have

been undervalued and a top-down approach will suffice for most applications relevant to planning or policy development.

References

- AUSLIG (Australian Land Information Group) 1994. Topo 250k Series 1, 1:250,000 Digital Topographic map data of Australia. AUSLIG, Canberra (digital data).
- AUSLIG 1996. Geodata 9 second DEM, Total Relief in 9 seconds, A national digital elevation model of Australia with a grid spacing of 9 seconds in latitude and longitude. AUSLIG, Canberra (digital data).
- Jones, K.B., Ritters, K.H., Wickham, J.D., Tankersley Jr, R.D., O'Neill, R.V., Chaloud, D.J., Smith, E.R. and Neale, A.C. 1997. An ecological assessment of the United States mid Atlantic region: a landscape atlas. United States Environmental Protection Agency, EPA/600/R-97/130.
- Strahler, A.N. 1952. Hypsometric analysis of erosional topography, Bulletin of the Geological Society of America, 63, 1117–1142.
- Walker, J., Veitch, S., Braaten, R., Dowling, T., Guppy, L. and Herron, N. 2001. Catchment Condition in Australia: Final Report to the National Land and Water Resources Audit, November 2001.

26 Using Indicators to Assess Environmental Condition and Agricultural Sustainability at Farm to Regional Scales

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Abstract

In this chapter we review recent experiences in using soil, terrain, landscape and catchment indicators to assess the condition of the resource base underpinning agricultural activities. We describe the use of indicators in three case studies, and suggest potential indicators for assessing and monitoring system sustainability in the northern grains region of Australia.

本文回顾了近些年来使用诊断指标对土地和流域健康状况进行评价的经验，介绍了三个具体的研究实例，并提出了可评估和监测澳大利亚北部产粮区生态系统持续能力的一套指标。

IT IS IMPORTANT to choose indicators that match predetermined regional needs and priorities, be they for farm production or environmental issues. In choosing indicators, current knowledge about

their strengths and weaknesses needs to be consolidated (see Chapter 24). For example, publications such as SOILpak (Daniells et al. 1994) or Soil Matters (Dalglish and Foale 1998) deal with

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the management of soils in the northern grain belt. In southern Australia, PADDOCKCARE (McCord et al. 2000) consolidates information on 51 farm indicators. PADDOCKCARE, which is available as a CD-ROM, allows farmers to record and graph indicator data over time and to progressively rank and integrate the status of a range of issues assessed by indicators. Dalal et al. (1999) provide an example of selecting indicators for the central Queensland grain region.

Whilst industry and regional benchmarks for assessing economic indicators are available, our focus is on the sustainability of the resource base. The following case studies show how data sets can be integrated and visualised at catchment to regional scale, using biophysical indicators. In each study, we used geographic information systems (GIS) to produce interpolated surfaces of risk. In the Upper Murrumbidgee region, we used surrogate indicators (indirect measures) to assess catchment conditions. In the Mount Lofty Ranges of South Australia, we determined risks for soil salinity, sodicity and acidity by extrapolating from a subcatchment to a subregion using detailed point source data and knowledge of landscape processes. In the Young area of southern New South Wales, we assessed several catchments using report cards based on easily measured indicators. At a regional scale, we developed indicators to assess the sustainability of the northern grains industry. The Overview provides background information about these areas and shows their location (Figure 2 of the Overview).

Case Study 1: The Upper Murrumbidgee Catchment

To construct maps of catchment condition, we focused on readily available rather than high quality data, as the latter are often not available for the whole region. We identified key regional issues, then refined the assessment questions and sampling strategy for a small group of indicators, generally surrogates, relevant at the catchment scale. The

study area was the Upper Murrumbidgee catchment (Canberra–Yass–Cooma), comprising 169 subcatchments in an area of approximately 12,000 km². The main environmental issues were salinity and sediment movement. The preliminary study of 13 large catchments in this area is described in Chapter 25.

We used seven readily available biophysical indicators (all surrogate indicators):

- percentage of forest cover (surrogate for estimating departures from the original condition and also related to stream salinity);
- percentage forest cover greater than 50 hectares (habitat);
- agriculture on steep slopes (potential erosion);
- road density (human impact);
- roads crossing streams (correlated with sediment input to streams); and
- intact forest along streams (a riparian zone/ habitat and sediment filter).

The data were obtained from satellite imagery, AUSLIG¹ road information and digital elevation model (DEM) information, all of which is readily available and can be assembled within one week. We estimated each indicator for a total of 169 catchments and placed the value in one of three classes: (1) good, (2) intermediate and (3) poor.² Catchment condition scores were obtained by summing the weightings for each indicator per catchment to get an aggregate catchment condition value. These values ranged from 8 to 16 and were divided into three catchment classes: 8–10 (good),

¹ Australian Surveying and Land Information Group.

² The use of good and poor raises semantic issues, and some prefer to use best to worst when the analysis gives a relative ranking. However, in this case we had a reasonable idea of the threshold values and used good to poor ranking. See Chapter 24 for details on weightings and aggregation.

11–13 (intermediate) and more than 13 (poor). Figure 1 shows the distribution of these classes in the Upper Murrumbidgee catchment.

This condition map is best considered a risk map. Catchments in poor condition are most likely to contain areas with evident or likely future environmental degradation, those in intermediate condition are likely to have some problems or to develop problems in the future, and those in good condition are likely to have few biophysical condition problems.



Figure 1. A preliminary catchment condition assessment for the Upper Murrumbidgee basin.

Case Study 2: Mount Lofty Ranges

We integrated soil, vegetation and terrain indicators using a GIS framework and assessed variability in drainage/waterlogging, salinity and acidity/alkalinity using remotely sensed data. Based on the

results we developed an index of catchment health and a field manual. The purpose of the manual is to enable landholders and regional advisers to identify problems on properties and plan remedial action.

Study site

The regional study area in the Mount Lofty Ranges of South Australia covers approximately 80 km², including the town of Mount Torrens and an area to the east of the town (Fitzpatrick et al. 1999). The climate is Mediterranean and representative of the eastern part of the Mount Lofty Ranges, with a mean annual rainfall of 650–700 mm. A northeast to southwest topographic high east of Mount Torrens bisects the area: small catchments to the west drain into the Onkaparinga and Torrens catchment systems; catchments to the east form part of the Murray–Darling Basin system. Based on morphological, chemical and physical soil data (Fritsch and Fitzpatrick 1994), landscape DEM data (Davies et al. 1998), and water quality and remote sensing data (e.g. AIRSAR/TOPSAR; Bruce 1996), four focus areas were selected:

- a toposequence (~400 m in length) from the Herrmann area;
- the Herrmann area (~0.20 km²);
- the Herrmann focus catchment (~2.0 km²); and
- the Mount Torrens regional area (~80 km²), comprising 55 smaller catchments.

Soil degradation index

We constructed a best-estimate map for each type of soil degradation data and used the maps to develop a soil degradation index (SDI), which itself is part of the broader catchment health indicator (see below).

In the Herrmann focus catchment, the processes by which drainage/waterlogging, salinisation and acidification/alkalisation occur are well understood (Fritsch and Fitzpatrick 1994; Fitzpatrick et al. 1996). We extrapolated spatial patterns of soil

degradation processes at toposequence scale (400 m within a 0.2 km² key area) to catchment (2 km²) and regional (80 km²) scales (Fitzpatrick et al. 1999). By integrating data obtained on the ground with remotely sensed, DEM and vector GIS data, we created best-estimate maps for soil salinity (Fitzpatrick et al. 2000; see Figure 2), waterlogging/drainage (Davies et al. 2000) and acidity/alkalinity (Merry et al. 2000) for the 80 km² regional area. A prediction that 3% of the soils of the region would be extremely saline or very saline and that 10% would be slightly saline was validated by data from 50 randomly selected sites and other observations across the 80 km² region (see Chapter 21).

Index of catchment health

The United States Environmental Protection Authority (Jones et al. 1977) ranked catchments at large regional scales to obtain an index of relative condition. Our approach is similar in that we

ranked attribute values from best to worst for soil salinity, waterlogging/drainage and acidity/alkalinity, and then summed rankings across all three categories to give an aggregated score. Thus, the method differs from the aggregation approach used in the Upper Murrumbidgee study. This method has also been applied to smaller catchments and fewer categories of indicators (Bruce et al. 2000; Fitzpatrick et al. 1999).

Most of the 55 small catchments or watersheds lie totally within the rectangular regional boundary. Catchment subdivisions were based on general surface water flows interpreted from topographic shapes and stream flow patterns (Bruce et al. 2000).

We constructed an SDI by ranking each of the 55 catchments according to the area of degradation due to soil salinity, waterlogging/drainage and acidity/alkalinity and then summed the rankings for each catchment to derive new SDIs (Bruce et al.

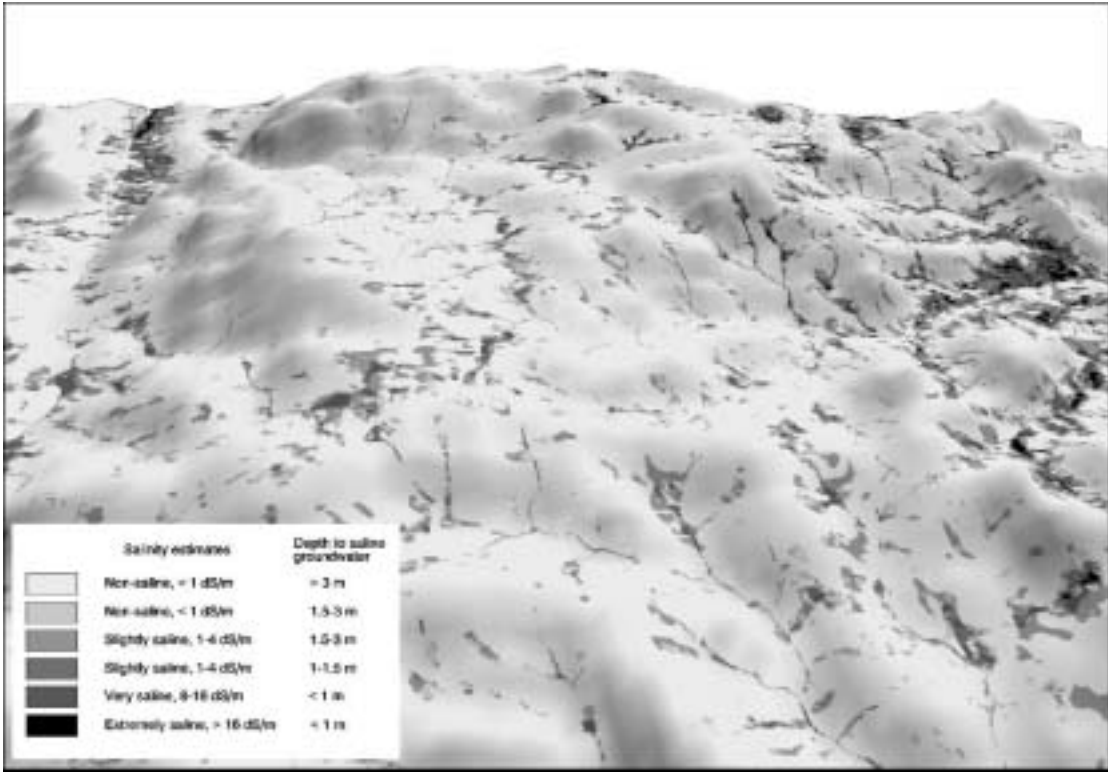


Figure 2. Three-dimensional representation showing six classes of salinity for part of the 80 km² study area (from Fitzpatrick et al. 2000).

2000). We used regional maps for best estimates of these three categories to produce a composite, regional-scale assessment of soil degradation.

As illustrated in Figure 3, we used the following indexes to rank the 55 catchments in terms of landscape processes and subsequent environmental effects such as stream water quality:

- SDI—developed from the best estimates of salinisation, drainage/waterlogging and acidity/alkalinity;
- land cover index (LI)—developed from land cover and DEMs;

- riparian land cover index (RLI)—developed from the intersection of buffered streams and land cover; and
- road index (RI)—developed from a summation of the weighted lengths of roads.

Using these indexes, catchments were ranked based on the zonal summation of raster GIS attributes per vector subcatchment polygon. To normalise for different catchment areas, the index value was divided by the area of the catchment.

We combined the rankings by summing each ranking for all catchment characteristics. The final

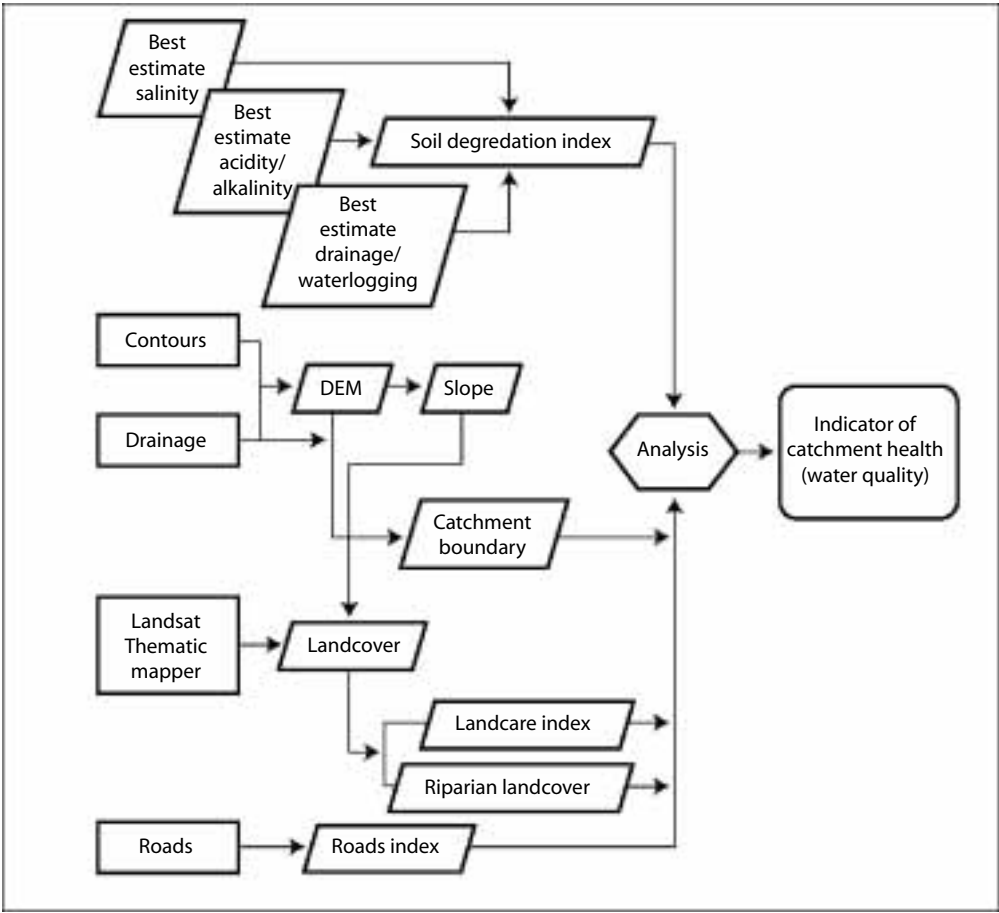


Figure 3. Data model used for the generation of catchment indices (from Fitzpatrick et al. 1999). DEM is digital elevation model.

catchment indicator (CI) of health was calculated using the following model:

$$CI = SDI + RI + LI + RLI$$

We then grouped catchments into quintiles, and rated soil and surface water quality.

To give land managers graphic tools on which to base management decisions, we produced maps such as the final CI map, which used different colours to indicate differences in quality (e.g. catchments with red tones were considered to have poor quality soil and water). The Herrmann focus catchment in the Mount Torrens region fell in the poorest category. Our knowledge of the area suggested that other catchment rankings were valid, but they require validation on the ground.

In the ‘Catchment Condition’ project of the National Land and Water Audit, Walker et al. (2001) developed a decision system called CatCon that enables indicator aggregations and spatial scenarios to be produced easily.³

Availability of data

Most data sets that are needed to aggregate from point measurements in focus catchments to regions are readily available throughout Australia; for example, there are regional data sets for most Australian agricultural regions. Although radar data (used here to refine the drainage/waterlogging and salinity maps) are not readily available for the whole country, the data sets that are readily available still allow for very robust analysis. The key data sets used in this case study need to be combined with knowledge from a representative key study area (‘training area’). A hydrologically correct DEM (obtained by editing contour and stream data for the terrain analysis of the region) is needed, as is expert knowledge of the soil hydrological processes for a small key area.

³ <http://www.brs.gov.au/mapserv/catchment/>

Application of the approach to other areas

Information gained through use of indicators has been used to help landholders better assess problem sites and develop property management plans. The approach can help Landcare groups, government agencies and others to make resource management decisions and assess the social and economic viability of a region.

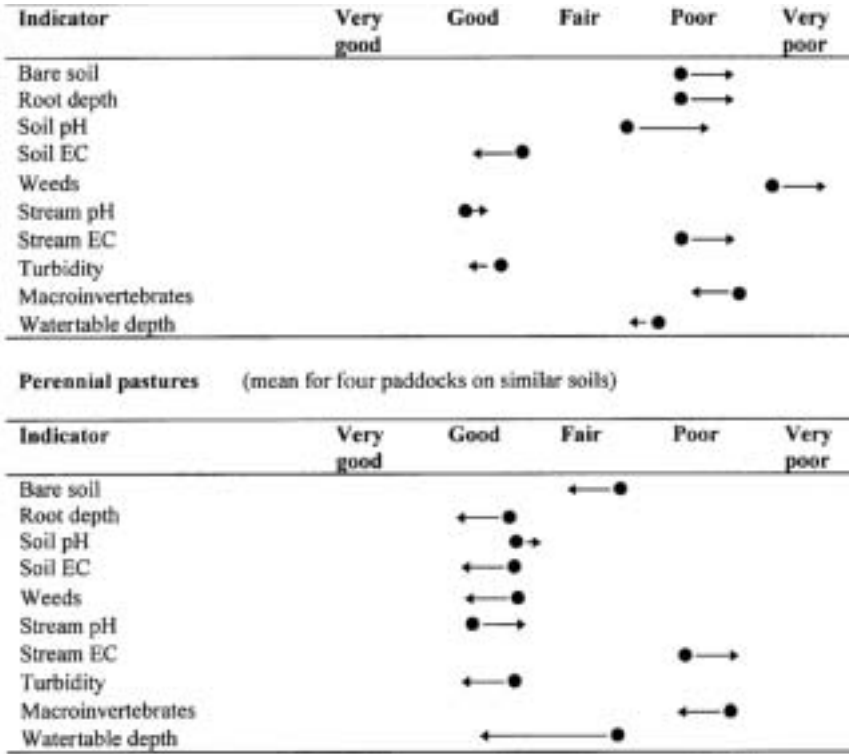
Case Study 3: Catchment Condition Report Card for the Young Area

A great strength of an indicator approach is that it can identify individual activities that are causing specific problems, which is useful in planning and implementing remedial actions. Walker et al. (1996) applied landscape indicators to a mixed farming area around Young in the Upper Murrumbidgee catchment. The outputs were presented in a report card that summarised the indicator values, classes and trends (see Table 1 for an example of a report card).

Table 1 shows a report card for two groups of paddocks—one with annual pastures (low capital input), the other with improved perennial pastures (lucerne established after lime and phosphate fertiliser application)—with each indicator giving a measure of some aspect of system health. Standards to rank each indicator from very good to very poor were established using locally collected data. The table shows that the condition of annual pastures was generally poor and deteriorating: weeds and bare soil were high, plant rooting depth was shallow and the saline watertable had stayed at a constant level.

For perennial pastures, the trends were generally good and improving. Depth to the watertable had increased (the watertable was saline and needed to be well below rooting depth). The rooting depth was greater than in the annual pastures and was expected to improve water use efficiency (WUE); the higher percentage yield implied that the pastures were making better use of the available

Table 1. A trend report card for paddocks with annual pastures and perennial pastures.



EC = electrical conductivity

rainfall; and stream water quality, especially turbidity, was satisfactory for most indicators.

There were some negative signs for the perennial pasture system. The trend in pH indicated that liming was necessary to maintain production, and the low macroinvertebrate biodiversity counts in nearby streams implied a higher than acceptable level of salinity in water moving from paddocks. An increase in stream electrical conductivity (EC) could indicate that more areas might be affected by salinisation in the future; therefore, a more detailed examination, such as mapping EC with appropriate equipment, could be warranted.

Overall, the health of the landscape had slowly degenerated. The following actions were suggested to reverse the downward trend:

- changes in crop rotations (generally wheat in this area) towards longer periods of permanent

pasture to improve soil and water health (these improvements at the farm scale would have flow-on effects in improving the general health of the landscape);

- possibly tree planting across the contours and above evident discharge areas (salinity levels have been partially stabilised under the perennial pasture system but are still of some concern); and
- closer monitoring of streams, because their poor biological condition implies that pollution other than salinity is a problem.

The report card approach gives landholders sufficient information to decide on positive actions. Decisions about what to do in any specific example will depend on commodity prices versus continuing slow declines in the health of the landscape.

Application to the Northern Grains Region

The northern grains region lies on the subtropical slopes and plains of eastern Australia (SCARM 1998) between latitudes of 21°30' (north of Clermont, Queensland) and 33° (south of Dubbo, New South Wales). It comprises three agroecological zones: western, eastern and central Queensland (Fig. 4). The region is bounded on the east by the Great Dividing Range (152°E at its eastern extremity) and on the west by rainfall isohyets suitable for dryland cropping (146°E at its western extremity). Agriculture is the dominant land use. In 1997–98, 25% of the region was cropped and 25% was sown to pastures (ABARE 1999). The remaining land was used for extensive grazing or nonagricultural uses such as state forests, national parks and mining. Between 1995 and 1999, 17.5% of the Australian grain crop was harvested from this region, of which 65% was produced in the eastern zone (Knopke et al. 2000).

Land use

The region incorporates a variety of farm enterprises; the ratio of cropped land to pasture land ranges from 0 to 1. The cropping–pasture mix tends to ebb and flow according to commodity prices and farmers’ aspirations, but the following



Figure 4. The northern grains region of Australia consists of three subregions: western, eastern and central Queensland.

general types of farms can be identified in the region:

- *Mixed farming.* Livestock and cropping enterprises are integrated and use the same land. This form of land use is usually practised more in the older, eastern areas of the region.
- *Cropping only.* Intensive, continuous cropping is mostly undertaken on the more fertile lands of the region and where there are small areas of irrigation. Few, if any, livestock graze these areas.
- *Separate cropping and livestock industries on the same farm.* Cropping and livestock enterprises are undertaken on the same farm, but each is located in a separate area, often determined by factors such as soil type and slope. On the fertile Darling Downs of Queensland and the Liverpool Plains of New South Wales, cropping is practised on flat to undulating alluvial plains, while livestock graze the steep nonarable slopes. In the western part of the region, traditional livestock farms are gradually changing into mixed, but nonintegrated, farming enterprises.
- *Livestock only.* Much of the region is used only for cattle and sheep grazing, as the land is unsuitable for cropping or the landowner does not wish to produce crops.

Areas of dryland and irrigated cotton growing fall into the first three categories. Dryland grain cropping in the region is dominated by winter and summer production of cereals (chiefly wheat, sorghum, barley and corn). The dominant soil types for cropping are Vertosols (black, grey and brown cracking clays), Sodosols (solodised solonetz and solodic), Chromosols (red-brown earths) and Ferrosols (Krasnozems and Euchrozems) (Webb et al. 1997). The moderate to high water-holding capacity of the Vertosols is important for the production of winter crops because most rain falls in the summer, particularly in the north. Webb et al. (1997) provide more information about the region, its soils and the characteristics of its climate.

Sustainability issues for the northern grains region at various scales

The first step in using indicators is to identify the key sustainability issues facing the region. These vary at paddock, farm, catchment and regional level, as shown in Tables 2–4.

At the paddock and farm scale, soil health is a key issue. Soil erosion causes loss of surface structure, decreased storage of plant available water, and loss of soil nutrients in eroded sediments. Other issues include increased risk of salinisation, sodicity, soil acidification and structural damage, crop pests and weeds and diseases; and reduced diversity and abundance of soil fauna. These issues are related to site-specific factors such as soil type, climate, agronomic management and farm history. In some cases, the problems may not be recognised by land managers because they are relatively insidious or

not well understood (e.g. subsoil compaction, deep drainage, vertical and lateral leakage of solutes, and the conservation of beneficial soil organisms).

Most catchment-scale issues relate to water quality. Catchment-scale issues tend to have downstream and offsite impacts on whole communities, affecting towns, cities, forests, national parks, beaches, estuaries and coral reefs as well as agriculture. For example, widespread soil erosion in the Fitzroy River catchment, which drains much of the central Queensland agricultural area, has led to high levels of suspended sediments, nutrients and pesticides in streams and groundwater (Noble et al. 1997). For many local towns, this in turn impacts upon their sole water supply. In the Liverpool Plains in northern New South Wales, six key natural resource management issues pertinent to the sustainability of the catchment have been identified: dryland salinity (and groundwater recharge),

Table 2. Performance indicator levels in Queensland showing the number of businesses in each category.

Farm indicators	Performance targets				Queensland sample (% of farms in each category)			
	Weak	Medium	Strong	Dynamic	Weak	Medium	Strong	Dynamic
Disposable income Per family (\$'000)	< 30	30–60	60–100	> 100	33	29	24	14
Farm input costs Operating costs/farm income (%)	> 60	60–50	50–45	< 45	65	21	10	4
Land productivity Operating surplus/land value (%)	< 8	8–15	15–20	> 20	31	43	16	10
Farm size Land value per family (\$'000)	< 400	400–800	800–1200	> 1200	6	55	18	21
Debt servicing Financing costs/total income (%)	> 15	15–7	7–3	< 3	29	37	16	18
Machinery Machinery market value/farm income (ratio)	> 1.2	1.2–0.8	0.8–0.6	< 0.6	53	21	18	8
Nonfarm income Net nonfarm income per family (\$'000)	< 5	5–15	15–30	> 30	63	16	17	4

flooding, soil erosion, water quality and quantity, biodiversity and riparian zone degradation (Dames and Moore 2000).

At the regional level, most sustainability issues relate to soil nutrient depletion, soil structural degradation, soil erosion, diseases, pests, weeds and chemical contamination of food and the environment (Clarke and Bridge 1997). Until recently, cropping in the region was often characterised by nutrient ‘mining’, as nutrients (particularly nitrogen) removed through harvested

grain, stubble removal (either hay-baling or burning) and soil erosion were not replaced (Dalal and Probert 1997). Although many farmers now replace ‘harvested’ nutrients with fertiliser inputs, the regional balance is still negative (Knopke et al. 2000). SCARM (1998) found phosphorus and potassium balances for broadacre industries in the subtropical slopes and plains to be consistently negative during the period 1986–95, with no indication of improvement. Another regional issue is stream eutrophication and turbidity (Knopke et al. 2000).

Table 3. Business health indicators.

Indicators	Performance targets				Qld median
	Weak	Medium	Strong	Dynamic	
Business health					
<i>Disposable income/family</i> (\$'000)	< 30	30–60	60–100	> 100	46
<i>Net worth</i> —Net assets/family (\$'000)	< 500	500–1000	1000–1500	> 1,500	971
Income drivers					
<i>Production system</i> Farm income per hectare per 100 mm annual rainfall (\$/ha/100 mm rain)					
• Intensive cropping	< 60	60–70	70–80	> 80	51
• Mixed farms	< 40	40–50	50–60	> 60	51
<i>Farm input cost</i> —Operating costs/farm income (%)	> 60	60–50	50–45	< 45	62
<i>Farm size</i> —Land value/family (\$'000)	< 400	400–800	800–1200	> 1200	656
<i>Debt servicing</i> —Financing costs/total income (%)	> 15	15–7	7–3	< 3	11
<i>Machinery</i> —Machinery market value/farm income (ratio)	> 1.2	1.2–0.8	0.8–0.6	< 0.6	1.2
Nonfarm income					
Net nonfarm income/family(\$'000)	< 5	5–15	15–30	> 30	2
Resource use					
<i>Land productivity</i> —Operating surplus/land value (%)	< 8	8–15	15–20	> 20	10
<i>Labour</i> —Income per labour unit (\$'000)	< 100	100–150	150–200	> 200	115
<i>Return on capital</i> —Return on farm capital (%)	< 2	2–7	7–12	> 12	3

Table 4. Associating farm productivity issues in the northern grains region with commonly advocated indicators.

Sustainability issue / component	Scale	Suggested sustainability indicators	Possible action to take	Investor (who pays?)	Likely time to achieve benefit
Declining productivity					
Poor WUE by crops (declining crop yields)	P, F	• % of potential yield • WUE	• Adopt improved agronomy • Identify yield limiting constraints including subsoil factors • Use water balance / push probe to better target yields	• Farmer • Farmer / advisory companies / research funds • Farmer / adviser	• Within season • Few years • Within season
Declining profitability	P, F	• \$WUE • Disposable income per family • Net profit per hectare	• Optimise inputs and rotation sequence (opportunity cropping) • Be aware of commodity price shifts	• Farmer / adviser / researchers • Farmer / cooperatives / commodity markets	• Few years • Within season
Declining product quality					
Declining protein in cereals	P, F	• % protein of crop	• Attend N budgeting workshop • Increase N applications • Rotate annual cereal crops with legumes	• Farmer / agriculture departments / cooperatives / grain boards / grain companies	• Within season
	R	• % protein at local silo	• As above	• As above	• Few years
	P, F, R	• Nonlegume:legume ratio in rotations	• Grow pulses or legume-based pastures	• Farmer	• Season after pulse crop
	P, F, R	• % legume in pasture	• Increase pasture legume composition	• Farmer	• Season after pasture removal (effect may last several seasons)

F = farm; N = nitrogen; P = paddock; R = region; WUE = water use efficiency

Suggested indicators for the northern grains region

Tables 4 and 5 list potential sustainability indicators at paddock to farm scale; Table 4 shows those more relevant at the catchment to regional scales. Some indicators are common to different scales. The tables also describe actions that could be taken in order to solve problems, suggest who is likely to invest in solving either farm or environmental problems, and provide estimates of how long after remedial treatment benefits are likely to accrue. Clearly, not all indicators will be used simultaneously. Individual farmers or rural communities need to determine the most pressing issues.

A popular and effective means for creating a greater knowledge base for targeting local issues are programs such as ‘Farming for the Future’, where farmers learn together in facilitated action-learning groups. A recent survey by Lobry de Bruyn (1999) found that farmers across northwestern New South Wales monitored soil health through soil tests, crop performance (yield and protein), visual observation of plants and soil, and the structure and workability of soil (by a soil ‘feel’ test).

Where more than one problem is identified, combined corrective measures often produce a synergistic response. For example, some 16% (195,000 ha) of the Liverpool Plains catchment is considered to be at risk from salinisation, with 50,000 ha currently exhibiting symptoms of dryland salinity (LPLMC 2000). This is a significant local issue and one worth monitoring and addressing, because farm profit and environmental outcomes are linked. Soil tests (EC), piezometer monitoring (watertable height and EC), observations of salt scalds, dominance of pastures by salt-tolerant plant species and permanently waterlogged areas within paddocks are all useful indicators for identifying salinity. Where salinisation is identified or where the risk of salinisation is high, farmers may fence off salt-affected land, plant deep-rooted perennials, use

salt-tolerant species, or use reverse interceptor banks (especially on sloping duplex soils) to divert lateral subsoil water. Landowners usually pay for these actions, but Landcare funding is sometimes available. It is important to realise that where changes to groundwater hydrology are sought, the results of these actions may not be manifest for several years or even decades.

The above example of salinity deals with farm and paddock-scale remedial actions. Broader-scale solutions are typically required to prevent salinity in the first place. At a catchment scale, indicators of salinity include soil, groundwater and streamwater EC, electromagnetic surveys (mapping of EC within the landscape), and DEM (inferring and mapping likely areas of salinity hazard based on landscape position). Catchment management strategies are typically funded by federal or State governments. An example at a State level is the New South Wales Salinity Strategy (August 2000), which set interim end-of-valley salinity targets for salt load and EC to be achieved by 2010. An example of a catchment-scale response is the Liverpool Plains Catchment Investment Strategy, which proposes an environmental management system to be used as a tool for sharing the cost of implementing solutions to problems such as dryland salinity (LPLMC 2000). One recommended action is to cease cropping in designated land management units where deep drainage is most likely, and instead establish and maintain tree cover (farm forestry).

Future directions

Farming and rural communities will adopt sustainability indicators only if they believe they will improve the short-term benefits and long-term viability of their enterprises. It is worth remembering that the farming community has always used broad indicators in farming practice and management. This is often thought of as ‘experience’ and it extends to reading the likely weather, knowing when to fertilise, examining trends in commodity prices and exchange rates and

Table 5. Associating soil health issues in the northern grains region with commonly advocated indicators).

Sustainability issue / component	Scale	Suggested sustainability indicators	Possible action to take	Investor (who pays?)	Likely time to achieve benefit
Soil health					
Poor surface structure / reduced water infiltration	P, T	• Dispersion / slaking tests • Exchangeable sodium percentage • Soil organic carbon • Soil consistency • Water intake rate • Surface crusting / sealing / pugging	• Grow pastures • Apply gypsum • Reduce tillage • Increase organic matter	• Farmer	Few years up to a decade
Subsurface compaction	P, T	• Effective rooting depth • Soil consistency • Visual assessment • Push probe measurement	• Avoid trafficking (machinery or grazing animals) on wet soils • Practise controlled traffic	• Farmer	Few years up to a decade
Soil erosion	P, T, C	• % bare soil • Slope class • Exchangeable sodium percentage • Presence of rill/gully erosion • Soil movement under fences	• Maintain groundcover • Reduce tillage • Stubble retention • Grassed waterways • Contour banks	• Farmer • Landcare groups • Catchment management committees	Straight after introduction of most actions
Sodicity	P, F, C?	• Dispersion tests • Exchangeable sodium percentage • Sodicity meter	• Apply gypsum • Use low sodium irrigation water • Plant pastures instead of crops	• Farmer	Within first season after application

Table 5. (cont'd) Associating soil health issues in the northern grains region with commonly advocated indicators).

Sustainability issue / component	Scale	Suggested sustainability indicators	Possible action to take	Investor (who pays?)	Likely time to achieve benefit
Soil health					
Salinisation	P, F, C, R	• Electrical conductivity • Electromagnetic surveys • Digital elevation modelling • Salt scalds observed • Areas dominated by salt-tolerant species • Permanently waterlogged areas within paddocks	• Fence off salt-affected land • Plant deep-rooted perennials • Use salt-tolerant species • Use reverse interceptor banks (especially on sloping duplex soils) to divert lateral subsoil water	• Farmer • Landcare	Years to decades
Nutrient deficiencies	P, F	• Soil and plant tests • Nutrient balance sheet (inputs x efficiency / outputs)	• Match projected and actual nutrient exports with fertiliser application • Use regular soil/plant testing	• Farmer • Fertiliser industry	Within first season after action (effects may last for several years)
Acidification	P, F, C	• Trends in soil pH	• Adopt liming practices • Use less acidifying practices	• Farmer • Agribusiness	Several years
Crop diseases	P, F, C	• Crop rotation index • Plant diagnosis • Soil DNA probes • Climate prediction model	• Identify disease problem • Alter tillage practices • Adopt better crop rotations • Use disease-resistant varieties	• Farmer • Plant breeders • Plant pathologists	Within season or within new rotation

C = catchment; DNA = deoxyribonucleic acid; F = farm; P = paddock; R = region; T = toposequence

so on. Making the effort to collect relevant environmental data beyond soil tests should not be a major shift in attitude, provided the tests can be interpreted in a way that is meaningful to the productivity of the farm or region. The adoption of environmental measures in Farm 500 (a group of 500 Australian farmers collecting environmental and production indicators) and the collection of information in 'precision farming' demonstrate that many farmers believe that benefits can be obtained.

If farmers are to adopt the indicators, they must first be shown how to collect, store and interpret the data. After that, the greatest success is likely to come from self-help groups.

Conclusions

Several packages to help land managers to address sustainability issues at the paddock, farm and catchment scale have now been developed and implemented in some of Australia's southern farming regions. A common feature of the cases discussed in this chapter is the incorporation of knowledge about the soil and landscape characteristics with various direct and indirect (surrogate) indicators, and the conversion of this information to a regional scale using technologies such as DEM, GIS and remote sensing. This level of complexity is not always necessary; the message here is to encourage farmers to clearly identify the issues to be assessed, to ask assessment questions likely to provide the information they need, to identify the best indicators, and then to record the indicators consistently and accurately.

Australia's northern grains region, where soil and catchment degradation are recognised as significant issues, would benefit from the kind of knowledge and decision-support packages that we have described for southern Australia. We have assembled a suite of sustainability indicators to help identify paddock, farm and catchment health issues and to monitor the situation after remedial action. We hope these may form the beginning of wider

recognition of soil and catchment sustainability issues in the north.

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References

- ABARE 1999. Performance indicators for the grains industry. In: Australian Grains Industry Performance by Grains Research and Development Corporation Agroecological Zones. 15–21.
- Bruce, D.A., Fitzpatrick, R.W., Davies, P.G., Spouncer, L., Merry, R.H. and Phillips, J. 2000. Catchment indicators: the use of remote sensing, vector and raster GIS in sub-catchment assessment. Proceedings of the 10th Australasian and Remote Sensing Conference, Adelaide, August.
- Bruce, D.A. 1996. Soil moisture from multi-spectral, multi-polarising SAR. In: Proceedings of 8th Australasian Remote Sensing Conference. Canberra, March.
- Clarke, A.L. and Bridge, B.J. 1997. Constraints in perspective. Clarke, A.L. and Wylie, P.B., eds, Sustainable Crop production in the Sub-Tropics: and Australian Perspective. Queensland Department of primary Industries, 170–178.
- Dalal, R.C., Lawrence, P., Walker, J., Shaw, R.J., Lawrence, G., Yule, D., Doughton, J.A., Bourne, A., Duivenvoorden, L., Choy, S., Moloney, D., Turner, L., King, C. and Dale, A. 1999. A framework to monitor sustainability in the grains industry. Australian Journal of Experimental Agriculture, 39, 605–702.
- Dalal, R.C. and Probert, M.E. 1997. Soil nutrient depletion. In: Clarke, A.L. and Wylie, P.B., eds, Sustainable Crop Production in the Sub-Tropics: and Australian Perspective. Queensland, Department of Primary Industries, 42–63.
- Dalgliesh, N. and Foale, M. 1998. Soil matters: monitoring soil water and nutrients in dryland farming. Toowoomba, Queensland, Agricultural Production Systems Research Unit.
- Dames and Moore 2000. Natural resource management report to Liverpool Plains Land Management Committee.

- Daniells, I., Brown, R. and Deegan, L. 1994. Northern wheat-belt SOILpak: a soil management package for dryland farming in the summer rainfall zone. Tamworth, New South Wales Agriculture.
- Davies, P.J., Bruce, D., Fitzpatrick, R.W., Cox, J.W., Maschmedt, D. and Bishop, L. 1998. A GIS using remotely sensed data for identification of soil drainage/waterlogging in southern Australia. In: Proceedings of the International Soil Science Society Congress. 20–26 August, Symposium No. 17. France, Montpellier, 8.
- Davies, P.J., Fitzpatrick, R.W., Bruce, D.A., Spouncer, L.R. and Merry, R.H. 2000. Use of spatial analysis techniques to assess potential waterlogging in soil landscapes. In: Adams, J.A. and Metherell, A.K., eds, Soil 2000: New Horizons for a New Century. Australian and New Zealand Second Joint Soils Conference, Volume 3: Poster papers. 3–8 December 2000, Lincoln University. New Zealand Society of Soil Science. 49–50.
- Fitzpatrick, R.W., Davies, P.J., Merry, R.H., Cox, J.W., Spouncer, L.R. and Bruce, D.A. 2000. Using soil-landscape models to assess and manage salinity in the Mt Lofty Ranges. In: Adams, J.A. and Metherell, A.K., eds, Soil 2000: new horizons for a new century. Australian and New Zealand Second Joint Soils Conference Volume 2: Oral papers. 3–8 December 2000, Lincoln University. New Zealand Society of Soil Science, 107–108.
- Fitzpatrick, R.W., Fritsch, E. and Self, P.G. 1996. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: V. Development of saline sulfidic features in non-tidal seepage areas. *Geoderma*, 69, 1–29.
- Fitzpatrick, R.W., Bruce, D.A., Davies, P.J., Spouncer, L.R., Merry, R.H., Fritsch, E. and Maschmedt, D. 1999. Soil Landscape Quality Assessment at Catchment and Regional Scale. Mount Lofty Ranges Pilot Project: National Land & Water Resources Audit. CSIRO Land & Water Technical Report, 28/99, 69. www.clw.csiro.au/publications/technical99/tr28-99.pdf
- Fritsch, E. and Fitzpatrick, R.W. 1994. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: I. A new method for constructing conceptual soil-water-landscape models. *Australian Journal of Soil Research*, 32, 889–907. (colour figs. 880–885).
- Knopke, P., O'Donnell, V. and Shepherd, A. 2000. Productivity growth in Australian grains industry. ABARE Research report 2000.1, Canberra, ABARE.
- LPLMC (Liverpool Plains Land Management Committee) 2000. Liverpool Plains Catchment Investment Strategy.
- Lobry de Bruyn, L.A. 1999. Farmers' perspective on soil health: capturing and adapting intuitive understanding of soil health to monitor land condition. In: Proceedings of 'Country Matters', 20–21 May Canberra 1999. Canberra, Bureau of Rural Science.
- McCord, A., Reuter, D.J., van Gaans, G., Davies, K. and Fisher, F. 2000. PaddockCARE: a software tool to identify and rank key sustainability issues. (A CD-ROM product).
- Merry, R.H., Spouncer, L.R., Fitzpatrick, R.W., Davies, P.J. and Bruce, D. 2000. Prediction of soil profile acidity and alkalinity—from point to region. In: Adams, J.A. and Metherell, A.K., eds, Soil 2000: new horizons for a new century. Australian and New Zealand Second Joint Soils Conference Volume 3: Poster papers. 3–8 December 2000, Lincoln University. New Zealand Society of Soil Science. 145–146.
- Noble, R.M., Duivenvoorden, L.J., Rummenie, S.K., Long, P.E. and Fabbro, L.D. 1997. Downstream Effects of Land Use in the Fitzroy Catchment. A Summary Report. Biloela, Queensland Department of Natural Resources.
- SCARM (Standing Committee on Agricultural Resource Management) 1998. Sustainable Agriculture: Assessing Australia's Recent Performance. Melbourne, CSIRO Publishing.
- Walker, J., Richardson, P.B. and Gardiner, T. 1996. The report card: a case study. In: Walker, J. and Reuter, D.J., eds, Indicators of Catchment Health: A Technical Perspective. Melbourne, CSIRO Publishing.
- Walker, J., Veitch, S., Braaten, R., Dowling, T., Guppy, L. and Herron, N. 2001. Catchment Condition in Australia: Final Report to NLWRA, November 2001.
- Webb, A.A., Grundy, M.J., Powell, B. and Littleboy, M. 1997. The Australian sub-tropical cereal belt: soils, climate and agriculture. In: Clarke, A.A. and Wylie, P.B., eds, Sustainable Crop Production in the Sub-Tropics. Brisbane, Queensland Department of Primary Industries, 8–23.

27 Ecosystem Rehabilitation on the Loess Plateau

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Abstract

The Loess Plateau is well known for its deep loess deposits and serious soil erosion. The region covers five provinces and 0.62 million km²; 45% of the area is eroded and there is an average soil loss of 3720 tonnes/km²/year. Since 1985, the comprehensive reclamation of the Loess Plateau has been listed as a key science and technology project in China. Eleven small catchments have been selected as experimental and demonstration areas for ecosystem rehabilitation in different regions of the plateau. After 15 years, each of the 11 catchments has formed a good model for local areas. A set of technologies to control land degradation has been developed. The average yield of farmland has increased by 100–300%, the area under crops has decreased by 30–70%, perennial vegetation cover has increased by 70–150% and soil erosion has decreased by 60–80%. The economic structure of the region has undergone major changes, with income from grain down from 80% to 30%. Other sources indicate that farmers' incomes are 5–10 times greater than previous levels.

The key task in the region is to improve land use. In the loess hill region, cultivated land occupies more than 40% of the total area, most of which is on steep slopes (more than 15°) and about 20–30% of which is on slopes of more than 25°. Only 12% of the region is forested, and only half of that forested area effectively controls soil erosion. Only 30.5% is grassland, of which almost 69% has deteriorated from overgrazing. Land use should consist of flat area cropping for subsistence; forestry in gullies to protect the local ecology; and fruit growing and animal husbandry on sloping land for income.

Results from the 11 trial areas indicate that small catchments can be ecologically rehabilitated, but that they must pass through three stages—restoration, stabilisation and sustainable development—taking 15–20 years. The prospects for the Loess Plateau are bright, but there is a long way to go.

黄土高原以其深厚的黄土沉积和严重的水土流失著称于世。黄土高原地区涉及 5 个省（区），62 万平方公里。其中水土流失面积占 45%，每平方公里平均每年有 3720 吨的土壤流失掉。从 1985 年开始，国家把黄土高原的水土保持综合治理列为重点科技攻关项目，在不同类型区选择了 11 个小流域作为国家生态恢复重建试验示范区。经过 15 年连续治理，这 11 个小流域均成为当地的先进样板。研究开发了一套防治土地退化的技术。农田的单位面积

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产量提高了 1-3 倍，林草植被覆盖度增加了 70-150%。土壤侵蚀减少了 60-80%，农民收入提高了 5-10 倍。土地利用和经济结构发生了根本变化，农耕地面积减少了 30-70%，种植业的收入在总收入的比例由过去的 80%以上变为 30%左右。

15 年的研究结果表明：调整土地利用结构是首要而关键的任务。黄土丘陵区农耕地面积占总面积的 40%，大部分是 15 度以上的坡耕地，20-30%的耕地的坡度大于 25 度。有林地面积只占总面积的 12%，其中能起到控制水土流失作用的林地只有 6.5%。草地面积只占总面积的 30.5%，其中 68.8%的草地由于超载放牧严重退化。根据 11 个试验示范区的研究结果，黄土高原的土地利用和产业调整的基本原则为平地为农耕地，实现粮食基本自给；沟壑坡地宜发展生态保护型林业；在坡地上发展草业和果，这将是该区商品经济潜力所在。

11 个试验示范区的实践表明，一个退化的小流域生态系统是可以通过有序治理达到恢复重建的，但要经过 3 个阶段，即恢复阶段、稳定发展阶段和良性循环阶段。一般需要 15-20 年时间。所以，黄土高原的治理前景是美好的，但需要付出时间和投入。

THE Loess Plateau, located in the middle reaches of the Yellow River, is the cradle of Chinese civilisation. Cultivation in this region started 6000 years ago. The national economy relies on the energy base of the Loess Plateau for its heavy and chemical industries. The plateau is rich in sunlight and heat energy, the soil layer is thick, and there are vast areas of land suitable for forestry, fruit trees and grass. However, predatory exploitation, wanton deforestation, overgrazing and other forms of malpractice caused by a population explosion have caused degeneration of the ecosystems on the plateau. As a result, local economies are underdeveloped. The Overview provides background information about the region; Figure 1 of the Overview shows its location.

People in the Loess Plateau region have struggled long and hard against soil and water loss. The

government has increasingly paid attention to the region, especially in the past 50 years, and has made great efforts to improve conditions. Since 1985, state authorities have listed the control of water and soil losses on the Loess Plateau as key research topics.

The Study Areas

Eleven experimental and demonstration areas (EDAs) were set up on the Loess Plateau on the basis of natural and social differences. Figure 1 shows the location of the experimental and demonstration areas; Table 1 shows the main environmental characteristics of the sites.

All EDAs represent seriously depleted ecosystems on the Loess Plateau. We have developed a set of technologies to control land degradation, as a result of which each EDA is expected to develop as a

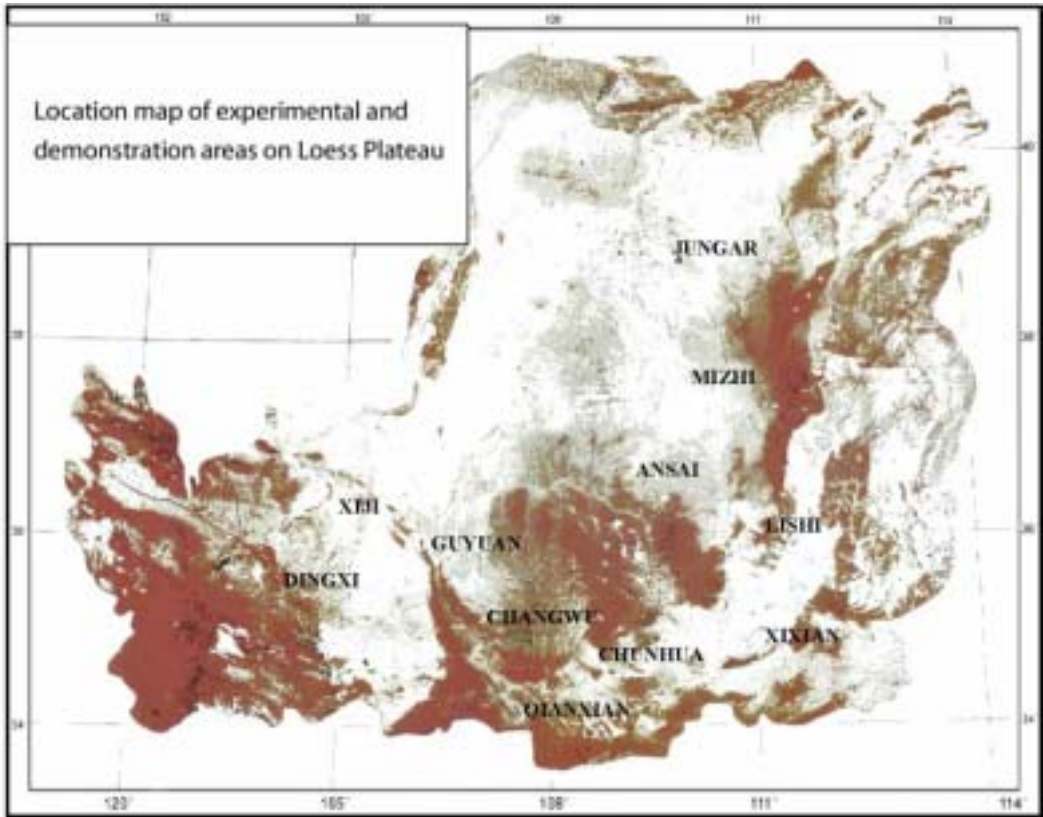


Figure 1. Location of experimental and demonstration areas on the Loess Plateau.

Table 1. Main environmental characteristics of experimental and demonstration areas (EDAs) on the Loess Plateau.

Type of region	Name of EDA	Area (km ²)	Annual rainfall (mm)	Annual average temperature (°C)	Population (persons)	Density of gully (km/km ²)
Windy and sandy	Jungar	7.7	344.2	5.3	330	2.37
Loess hill	Mizhi	5.6	422.0	8.4	586	3.00
	Ansai	8.3	497.6	8.8	407	3.06
	Lishi	9.1	484.7	9.0	1235	3.81
	Guyuan	15.1	472.0	7.0	785	2.16
	Xiji	5.7	402.0	5.3	491	3.32
	Dingxi	9.2	415.0	6.3	1564	1.57
Loess tableland	Changwu	8.3	584.0	9.7	1815	2.76
	Chunhua	9.2	600.0	9.8	2708	2.13
	Qianxian	8.5	590.0	10.8	1806	1.89
	Xixian	10.9	510.6	8.8	1211	1.46

Source: Database of the office of EDA project, Bureau of Resources and Environment, Chinese Academy of Sciences

sustainable farming zone on a large scale. Each EDA has formed a good model for the local region.

Main Achievements of the Program

During the past 15 years, the 11 EDAs have undergone great change. The average yield of farmland has increased by 100–300%. Grain yield has increased from 5737.5 kilograms per hectare (kg/ha) to 8196 kg/ha; average personal income has risen from 218 yuan/year to more than 2000 yuan/year (US\$1 = 8.0 yuan). The amount of reclaimed land has increased from 46.1% to 80.2%. Research achievements have been applied to up to 10 million hectares of farmland, with some 5.55 billion yuan in increased crop value.

The project has not only improved the regional economy and farming practice on the Loess Plateau, but also promoted rehabilitation of the regional ecosystem. Some 150,000 km² of eroded land has been controlled by various conservation measures. The flow of sediments into the Yellow River has been reduced by about 300 million tonnes/year. By the end of 1995, reclamation had already led to an increase of 53.9 million tonnes in the aggregate grain yield over the previous 10 years. Increases in crop yield through the prevention of soil erosion and flood containment have resulted in economic returns of 180 billion yuan according to 1995 prices. Statistics from more than 2000 small watersheds showed that in each of the past 20 years, more than 4% of the eroded area has been controlled by soil and water conservation engineering on the Loess Plateau (before the 1980s, the figure was less than 1%) (Li Yushan 1996; Yang Wenzhi et al. 1992).

Land Use

Improving the land-use structure

The Loess Plateau has a long history of cultivation but natural and social factors have resulted in severe land-use problems, in particular a low proportion

of vegetation cover and severe soil erosion and desertification.

Proportion of cultivation and vegetation cover

In loess hill areas, cultivated land occupies more than 40%, most of which is on steep slopes, with about 20–30% on slopes of more than 25°. There is little vegetation cover and the grassland is severely degraded, with less than 50% grass cover in most areas. For example, in south Nixia, grass yield is less than 500 kg/ha. Recent investigations have suggested that forested areas account for 12% of the whole region, of which only 6.5% can effectively control soil erosion. Most regions have only 30.5% grassland, of which 68.8% has deteriorated to some extent from overgrazing (Yang Wenzhi et al. 1992; Li Rui et al. 1992).

Soil erosion and desertification

The Loess Plateau suffers severe soil erosion and desertification. The long-term average sediment load of the Yellow River is about 1.6 billion tonnes per year, most of which comes from the plateau. Table 2 shows the main types of soil erosion on the Loess Plateau; Table 3 shows the intensity of the erosion.

Principles of rational land use

Experience, environmental characteristics and the nature of the land-use problems on the Loess Plateau suggest that the following principles should be considered for land-use planning in this region.

Table 2. Types of soil erosion on the Loess Plateau.

Soil erosion type	Area (km ²)	Proportion of total area (%)
Water erosion	289,300	46.36
Wind erosion	156,500	25.08
Water and wind erosion	178,200	28.56

Source: Tang Keli (unpublished lecture notes on soil erosion and conservation in China for the 2nd International Training Course on Soil and Water Conservation, September 1993).

Consider the economic benefits and ecological effects together

Human impact on the environment is continually increasing as the population increases and more demands are placed on land resources. If ecological effects are neglected during cultivation, land degradation and environmental deterioration will be more severe. Considering the economic benefits and ecological effects together will bring land reclamation and cultivation into ecological balance. On the other hand, soil conservation measures are unlikely to be followed by farmers if economic benefits are neglected.

Look at the integrated structure of land use

We must look at the overall regional economic arrangements as well as comprehensive land use. As mentioned above, semiarid regions have a variety of land-use types, which tend to be distributed in regular patterns. For example, in the hilly area, land types are in the following order: hilltop; land with a gentle slope (< 8°); steeply sloping land (15–35°); gully slope land (< 30°); gully terrace land (< 5°); and gully bed. Land-use arrangements must match the structure of the land type.

Remember that the overall function is bigger than the sum of the parts

This is one of the principles of systems engineering. Land use must match local conditions and there are mutual benefits between different land uses. For example, imagine that there are three hills to be used for planting crops, grass and trees. There are at least two ways to proceed. One is to plant crops on one hill, grasses on another and trees on another; the other is to plant grasses on the top, crops on the middle part (with gently sloping terraces), and trees on the lower part (the gully slope) of each hill. The first method means that one hill will produce grain, another forage and another wood. The results are the sum of the parts: 1 + 1 + 1 = 3. In the second method, the three kinds of uses can provide mutual benefits: the grassland on the top can protect cropland from water and soil erosion; trees on the lower part can control gully erosion. The results are more than the sum of the parts: 1 + 1 + 1 > 3. The second method is known as the integrated (or ‘inlaid’) method (Ju Ren et al. 1992; Song Guiqing and Quan Zhijie 1996). The key to realising this principle is to correctly handle the relationships between the subsystems and to establish a coordinated environment.

Table 3. Intensity of soil erosion on the Loess Plateau.

Grade of erosion	Amount of soil lost through erosion (t/km ² /year)	Area (km ²)	Proportion of total (%)
Very slight	< 1,000 (500) ^a	99,434	15.94
Slight	1,000 (500)–2,500	192,348	30.83
Moderate	2,500–5,000	40,622	6.51
Severe	5,000–10,000	111,384	17.85
Very severe	10,000–15,000	94,162	15.00
Extreme	> 15,000	86,049	13.79

^a The figure in brackets refers to rocky mountain regions, not the loess region
Source: Tang Keli (unpublished lecture notes on soil erosion and conservation in China for the 2nd International Training Course on Soil and Water Conservation, September 1993).

Combine land use with land construction

Land degradation — soil erosion, desertification, salinity, soil deterioration and so on — occurs easily on the Loess Plateau. The situation is exacerbated because the poor economic situation means that there is little input to the land. We recommend the following techniques to reduce soil degradation.

- *To transform steeply sloping land into level land.* Steeply sloping lands are widespread in the Loess Plateau. They are known as ‘three losses land’ because they tend to lose water, soil and fertiliser. Terracing and dam lands¹ are effective in improving conditions. Some problems can be solved by conservation measures such as reduced ploughing.
- *To enrich the soil.* Loess soil is a young soil with low fertility, so it must be enriched in order to get higher yields. We recommend rotation cropping (for example, grass–crop–grass–crop or grain–beans–grain–beans, etc.) and increasing the amount of farm manure and chemical fertiliser.
- *To develop limited irrigation.* In arid and semiarid areas, water is an important limiting factor for agricultural development. Water conservation and optimal water use are key measures for increased agricultural production.

Techniques for Maximising Land Productivity

Grain is essential for people’s survival. In the past, people have resorted to every possible means to provide farmland to obtain grain, including deforestation. Deforestation has led to the destruction of ecosystems, causing chronic and increasing impoverishment. To change this scenario, we must increase grain output per unit area, and transform the primitive practice of

extensive cultivation — and its concomitant notorious low productivity — into intensive cultivation. Yields will increase and the environment will be rehabilitated if all land resources on the plateau are used rationally in the balanced development of various farming undertakings, including crop plantation, fruit production, forestry and animal husbandry. Increasing grain yield is the main objective of our work on the plateau, in order to eliminate poverty among the local inhabitants and boost the rural economy. The grain production target on the Loess Plateau is 400–500 kg per capita, at which level the local people will have a slight surplus of grain. Our experiences in the experimental zones prove that such a target may be reached within five years if input is increased sufficiently and if key agronomic instructions are available at the right time (Li Yushan 1996).

Any increase in grain yield depends on the planted crop strain, the amount of good basic farmland, agronomic measures taken for crop cultivation, etc. In order to cope with natural conditions and the current grain-planting situation on the Loess Plateau, the key to increasing grain yield lies in an improved water supply for farmland irrigation and in fertiliser application.

Increasing the amount of applied fertiliser and farmyard manure is especially important. The level of fertiliser application on the plateau is about 32% of the national average. Initially, chemical fertiliser was used to increase yields from medium (0.75 t/ha) to high (1.5–2.25 t/ha) levels. In the experimental areas, yields doubled or tripled when chemical fertiliser and farmyard manure were applied together. At a demonstration point in Dingxi Prefecture, for example, yield increased by 79.9% when the amount of chemical fertiliser was increased by 166%. Similarly, when the amount of chemical fertiliser at a demonstration point in Changwu County was increased by 144%, a yield of 5.25 t/ha was achieved, an increase of 99.5%. On average, the application of 1 kg of impurity-free

¹ Dam land is a kind of flat land at the bottom of a gully, formed by the deposited soils eroded from the slope.

fertiliser to Loess Plateau farmland will increase grain yield by 6–10 kg (Li Yushan 1996).

For nonirrigated farmland, yields are increased primarily by collecting water from seasonal rainfall. When there is sufficient water, fertiliser plays a key role in increasing yield up to a certain point, but above this point water is again the decisive factor for further increases in yield. Over many years, our work has shown that it would be impossible to break the ceiling of 3 t/ha for dryland wheat yield by simply increasing the amount of fertiliser applied. It is also necessary to increase the water supply; for example, by collecting runoff from seasonal rainfall, using plastic film to suppress evaporation from the ground surface and making more effective use of available water. Farmland tests in the demonstration zones in Luochuan, Guyuan and Changwu counties showed that these measures could be both feasible and effective. For example, in Guyuan County, when 40 m³ of water (one-quarter to one-third of the amount of water required for the whole crop) was applied to spring wheat just before the tillering stage, the yield increased from 2.175 to 3.915 t/ha, three-quarters of the yield in fully irrigated crops. In this case, the water use efficiency is about 42 kg/ha using 1 m³ irrigation water. On the other hand, there is considerable potential to make better use of local precipitation. In semiarid areas of the plateau, 25–30% of natural precipitation is absorbed by individual crops in transpiration, 10–20% becomes runoff on the ground surface and flows away, and the remaining 55–65% evaporates. Rainwater can be used more effectively by collecting runoff and reducing surface evaporation with plastic film.

Stages of Ecosystem Rehabilitation of Catchments

In Ansai County in northern Shaanxi Province, we restored a tiny watershed to its original state by mending and rebuilding the depleted ecosystem and ensuring that any further development would be sustainable. The watershed was a barren and depopulated gully in Zhi Fanggou in the hilly

heartland of the plateau that had been plagued by serious water loss and soil erosion. From the 1940s to the 1990s Zhi Fanggou underwent 40 years of land degradation followed by 20 years of restoration. Before the drive, farming was a primitive kind of extensive cultivation; the grain yield was 0.6 t/ha and income as pitifully low as 222.1 yuan (about \$27.80) per person per year. After the reclamation drive, the proportion of uncultivated land went down from 51.5% to 18%. The proportion of forest and meadow increased to 41.2%. By 1995, there was 0.18 ha/person of farmland, 0.47 ha/person of woodland, and 0.14 ha/person of artificially created pastureland; the average per capita income was 1658 yuan. Almost all peasant households now have their own television sets; 40% own colour television sets. Every village has its own ground-based equipment for receiving satellite-relayed television signals. Hence the countryside has undergone a radical change in appearance (Lu Zongfan et al. 1997). The experimental zones have become high-level models for comprehensive reclamation of the plateau; they also provide a base for theoretical exploration and an exemplary agrotechnological system for water and soil preservation.

The Loess Plateau is a backwater of the Chinese hinterland, plagued by poverty, underdevelopment, and serious water loss and soil erosion. Our work in Zhi Fanggou for the past 20 years suggests that in order to ensure that the Loess Plateau has a bright future it is best to focus efforts on sustainable ecological development rather than just on economic return. In line with this approach, in the context of stability and progress in the local farming system, we recommend the following three stages to develop ecoagriculture on the plateau while maximising water and soil preservation (Lu Zongfan et al. 1997).

Restoring the ecosystem

The main task of restoration is to increase vegetation cover by returning some cultivated land

to forest. The ecological benefits are likely to be seen earlier than economic benefits, although the gap between the two is decreasing and the effectiveness of the investment increases as the original vegetation is gradually restored. At present, restoration is hampered by the difficulty of communicating the complex technological information that forms the basis of any restoration to the local people who carry it out.

Making sure the ecosystem is stable

The newly restored ecosystem is weak and relative unstable. It may revert to its previous state unless care is taken. It is therefore very important to maintain a balance between ecological benefits and economic return. A timeframe of 5–10 years is usually practical for both ecological and economical benefits.

Making sure the ecosystem is sustainable

As the ecosystem becomes sustainable, people’s natural and social attributes reach harmony. Both family planning and the rational exploitation of natural resources become conscious actions, with well-defined goals among the local inhabitants. The ecoagricultural system will be more complicated but will function more efficiently. Farming practice and business management are based on scientific and technological data and information resources. Our studies at Zhi Fanggou suggest that the following parameters should be regarded as standardised targets for appraising the three stages in developing an ecosystem rehabilitation in a small catchment: the area of controlled land, the basic amount of farmland and cropland per capita, and the yield (see Table 4).

Table 4. Stages and targets of ecosystem rehabilitation of a small catchment.

Stages	Time (years)	Area controlled (%)	Basic farmland (ha/person)	Cropland (ha/person)	Yield (t/ha)
Restoration	10–15	40	0.07–0.1	0.5–0.8	0.6–0.975
Stabilisation	5–10	60	0.1–0.13	0.4–0.53	0.96–1.35
Sustainable development		80	> 0.17	0.27–0.4	1.875–2.25

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References

Ju Ren, Song Guiqing and Li Rui. 1992. Land resources and the principles of rational use in the Loess Plateau. Memoir of the Northwestern Institute of Soil and Water Conservation, 16.

Li Yushan 1996. The new position of the Loess Plateau in the development of the national economy. Chinese Academy of Sciences Bulletin, 11(2), 118–121.
Li Rui, Zhao Yongan, Song Guiqing et al. 1992. Land resources information system of Shanghuang in Guyuan County. Memoir of the Northwestern Institute of Soil and Water Conservation, 16.
Lu Zongfan et al. 1997. Research on Eco-agriculture on China’s Loess Plateau. Xi’an, Shaanxi Science and Technology Press.
Song Guiqing and Quan Zhijie. 1996. Theory and Practice on the Land Resources of the Loess Plateau. Beijing, China Hydro-power Press.
Yang Wenzhi et al. 1992. The Regional Reclamation and Appraisal of the Loess Plateau. Beijing, The Science Press.

28 Reclaiming the Saline Soils of Nanpi County: Turning Knowledge into Practice

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Abstract

Through studies over five years the authors assessed the health of a catchment in a saline region of Nanpi County in Hebei Province, China using a set of key indicators. The indicators chosen included groundwater table level, electrical conductivity in groundwater, soil colour, pH and consistency. From this assessment they constructed a knowledge transfer network involving the Nanpi Eco-Agricultural Experimental Station, local government, a technical extension station, scientists, technicians and key users.

根据区域农业发展存在的环境问题，利用环境质量评价指标体系，建立了南皮县盐碱地环境质量评价体系。体系的构成包括地下水水位、水质、土壤颜色、土壤 pH 值、土壤紧持度等一系列指标。在指标建立的同时，建立了指标的推广体系。这一体系包括中国科学院南皮生态农业试验站、南皮县政府、南皮县技术推广站、直至农民用户。通过努力，一个持续健康发展的农业体系必将在盐碱地环境下建立。

NANPI County is located in the east of Hebei Province, which is near Beijing and Tianjin on the North China Plain (NCP). The county is 70 km west of the Bohai Sea, at an elevation of 6–13 m. It covers 690 km² and has a population of 320,000. Annual

mean temperature is 11.3°C and mean precipitation is 500–600 mm. Over 70% of annual rainfall occurs in July, August and September. The shallow groundwater table is about 5–8 m below the

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surface; about two-thirds of the shallow groundwater is saline. The deep groundwater table is 60 m below the surface and is declining. Wheat, corn, cotton and Chinese dates are the main cultivated crops of the region. The Overview provides further details about the NCP region; Figure 1 of the Overview shows its location.

The lower reaches of many rivers are located in Nanpi County, so it is a region of salt deposit and accumulation, with a history of problems due to saline soils. Chapter 13 describes the chemical properties of some of the soils in the region. It has been said that in wet seasons the region has only frogs, in dry seasons only locusts and in normal seasons only salt. Until the 1960s, about 30% of the land area was saline. With water shortages, better water engineering and better reclamation of saline soils, the area affected by salinity is rapidly decreasing and now accounts for less than 5% of the land area.

Problems for sustainable agriculture in saline areas of Nanpi County

Although the area of saline soil in Nanpi County has been reduced, the remaining saline area will be more difficult to reclaim because of water deficit and secondary salinity (because the salt in the reclaimed soils has not moved out of the region). In 1995, the Dalangdian reservoir was constructed to provide water from the Yellow River for domestic

and industry use in Cangzhou city. This development will affect the groundwater table and may lead to further soil salinisation. Thus, drought, water deficiency and soil salinity are major problems for the development of sustainable agriculture in Nanpi County. Methods to assess catchment health are needed in order to achieve sustainable agriculture.

Long-term studies on the reclamation of saline soil have provided much knowledge, which should be shared not only with scientists but also with end users such as landholders and local officers. To do this, the knowledge must be converted into simple, transferable environmental indicators. This approach will benefit Nanpi County and adjoining regions such as Huanghai and Haixing, where there are about 100,000 ha of saline soil (Liu and Tian 2000).

Selection of Key Indicators and Saline Soil Reclamation

Table 1 shows the key indicators selected for assessing soil salinity in Nanpi County based on the criteria developed by Walker and Reuter (1996) and on the theory and experience of saline soil reclamation (Mao and Liu 2000).

In Nanpi County, soil salinity and soil formation are controlled mainly by groundwater and water quality. The groundwater table itself is affected by

Table 1. Threshold guideline for soil salinity indicators in Nanpi County.

Indicator	Very good	Good	Fair	Poor	Very poor
Groundwater table (m)	4.5–6	3.5–4.5	2.5–3.5	1.5–2.5	< 1.5
Electrical conductivity in groundwater (dS/m)	<0.5	0.5–1	1–1.5	1.5–3	> 3
Soil colour	–	–	Grey brown	White	Grey black brown
Soil pH	7–7.5	7.5–8	8–8.5	8.5–9	> 9
Soil consistency	Loose	Soft	Firm	Very firm	Rigid

dS/m (deciSiemens per metre) = mS/cm (milliSiemens per centimetre)

climate, topography, irrigation and drainage, and is thus an important indicator of trends in water and salt balance. Based on a study at the Nanpi Eco-Agricultural Experimental Station (NPEES) of the Chinese Academy of Sciences, the groundwater table is declining by about 2–3 m each year (NPEES 1996,1997,1998,1999). The reduction in the depth of the groundwater table helps to remove salt from the soil, but if it is too extensive it will result in seawater entering the watertable, increasing salinity.

Groundwater electrical conductivity (EC) is an indicator for irrigation water quality and soil alkalinisation during soil desalination. Soil colour is an important attribute for assessing soil quality, and in Nanpi County, soil colour can easily be used as an indicator of soil salinity. For example, saline soil containing chloride is grey, black or brown; saline soil containing sulfate is white. The pH value of soil can easily be measured with pH paper; the consistency of the soil can be tested by hand.

We used the indicators and methods of saline soil reclamation to construct a diagram for guiding saline soil reclamation (Fig. 1). The model indicates that controlling the groundwater table is the most important aspect of saline soil reclamation. Rainwater, irrigation and the construction of

drainage systems are important in the adjustment of the groundwater table. Fertilisers and biological methods can also be used in soil reclamation (e.g. to supply N to raise the bioproductivity and grow salt-tolerant plans such as lucerne for fodder production).

Knowledge Transfer

In order to turn this knowledge into practice, we developed a knowledge transfer network and built several testing plots (Fig. 2). The network included NPEES, local government, a technical extension station, scientists, technicians and key users.

- *NPEES*. The station is a centre for knowledge creation and transfer, where scientists study indicators of salinity, assess trends in soil

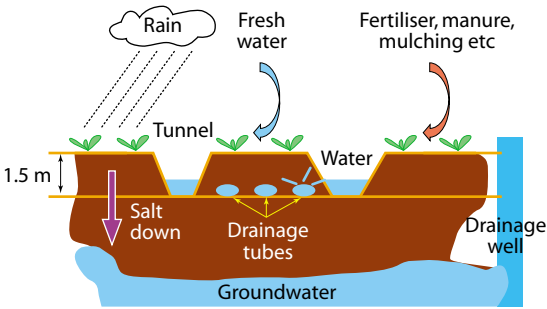


Figure 1. Diagram of saline soil reclamation in Nanpi County.

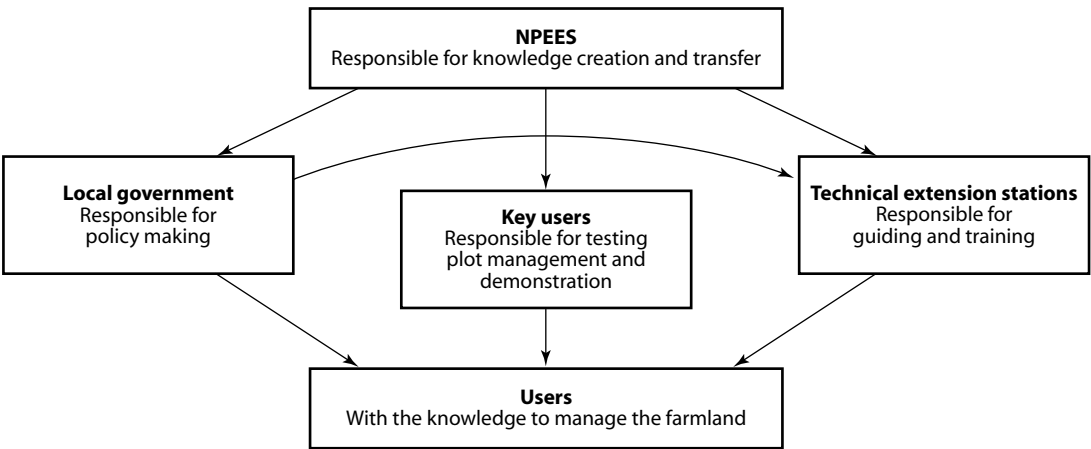


Figure 2. Knowledge transfer network in Nanpi County. NPEES is the Nanpi Eco-Agricultural Experimental Station.

salinity and monitor changes in the groundwater table. Twice a month, technicians from NPEES measure the groundwater table and electrical conductivity, and take water samples. In alternate months, starting in January, soil samples are also taken, to measure salt content and electrical conductivity. Scientists use the results to write proposals for local government and provide technical support for technical extension stations and users. NPEES has built five trial plots to demonstrate research results directly to end users. For example, in a trial plot close to the Dalangdian reservoir, vegetables are grown in greenhouses in winter. Groundwater is recharged mainly between November and January, when the introduction of fresh water improves the quality of the shallow groundwater and raises its level. Farmers can pump irrigation water and obtain a good income while improving groundwater use and controlling soil salinisation. Other trial plots demonstrate the irrigation of winter wheat and the use of cotton fields to grow pasture in winter.

- *Local government.* At least twice each year the local government in Nanpi County formulates policies based on technical reports and proposals from NPEES for managing regional agriculture. Local government asks extension stations and technical departments to use the research results, and it assists with knowledge transfer by providing some funding for publishing technical reports and holding meetings.
- *Technical extension stations.* Nanpi County has several technical extension stations, including an agricultural technical service and a soil and fertiliser technical station. Technicians at these stations are familiar with the needs and practices of the end users and are well placed to transfer knowledge to them. Therefore, NPEES asks the local government to send five technicians from different technical extension stations to NPEES, to act as a bridge between the institution and

end users during the growing seasons. Funds are available from local or higher levels of government for technology transfer.

- *Key users.* Key users are the landholders who use the indicators first and then demonstrate the results to other users. In China, landholders are often poorly educated; in order to be successful in implementing new practices, they need a good understanding of the changes they are being asked to make. Key users play an important role in knowledge transfer. Several well-educated users are taught how to use indicators to assess plot health and make rational decisions about plot management. Once these key users have obtained acceptable results, several site meetings are held on their plots, with other landholders invited to attend. Generally, these meetings are jointly organised by NPEES, local government and technical extension stations. In a meeting, a key user tells other landholders about the results he has obtained and how he has achieved them. Through this process, knowledge is transferred easily and quickly.
- *Users.* In a family unit in China, each landholder has only a small area of land: in Nanpi County this is about 0.8 ha/family. To see an effect of the indicators on catchment health, all the landholders in a village must be involved, which is difficult to achieve. Administrative measures and site meetings can be useful in organising landholders.

Results and Discussion

Over the past five years, we have made progress in using indicators to assess health in a saline environment. The area of saline soil in Nanpi County has continually decreased and there is no secondary salinity around Dalangdian reservoir. The mean income of landholders increased from 1100 yuan/person in 1996 to 2400 yuan/person in 2000 (US\$1 = 8.0 yuan). In certain areas where trial plots were located, such as Dalangdian, the net

income per hectare increased from 6000 yuan to 30,000 yuan. The groundwater table has been maintained at around 5 m and water quality is improving. The local government has formulated three policies for catchment health:

- building greenhouses around the Dalangdian reservoir;
- irrigation of winter wheat in spring; and
- using cotton fields in winter to grow pasture.

More than 3500 indicator report cards have been sent out. Eight site meetings have been held and more than 1000 landholders attended.

Although much has been achieved in assessing catchment health using indicators of salinity, much

remains to be done because this is a new technique for China. Indicator research on a regional scale with remote sense techniques and a computer-based transfer network is needed.

References

Liu, X. and Tian, K. 2000. Preliminary discussion on the distribution of agricultural resources and sustainable agriculture development patterns in saline region of Huan Bohai Sea. *Chinese Journal of Eco-Agriculture Research*, 8(4), 67–70.

Mao, R. and Liu, X. 2000. Study on the indicators for assessment of agro-ecoenviromental quality in saline region of Lower Haihe Plain. *Chinese Journal of Eco-Agriculture Research*, 8(3), 59–62.

Nanpi Eco-Agricultural Experimental Station Annual Report. 1996, 1997, 1998, 1999.

Walker, J. and Reuter, D.J. 1996. Key indicators to assess farm and catchment health. In: Walker, J. and Reuter, D.J., eds, *Indicators of Catchment Health: A Technical Perspective*. Melbourne, CSIRO Publishing, 21–33.

29 Transferring Scientific Knowledge to Farmers

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Abstract

This study describes the development of a systematic approach to identifying important soil morphological and vegetation field indicators. The objective was to use the indicators to target land management in degraded landscapes in a specific region. The authors linked soil–landscape features to the main soil and water processes operating within the landscape. In Australia, they used this information to develop a set of field indicators (e.g. soil colour) within a user-friendly soil classification key that was linked to land-use options to form the basis of a manual. Information written in this format helped farmers and regional advisers to identify options for remediation of waterlogged and saline areas and to improve planning at property and catchment scales. The authors identified a series of steps to be taken in producing the manual. Steps 1 to 5 describe the soil layers and construct them in toposequences, which are then used to map soil types in key surrounding areas. Steps 6 to 9 involve the local community in developing the manual.

This chapter describes how manuals were produced for two badly degraded areas in southern Australia (the Mount Lofty Ranges in South Australia and an area in western Victoria) and suggests how they can be applied elsewhere. Descriptive soil information and pictures taken along toposequences are used to identify key soil features. The use of coloured cross-sectional diagrams and photographs of soil and vegetation helps local groups to understand complex scientific processes and terminology, and see how best management practices can be used to advantage. A similar approach using indicators such as soil colour and morphology was developed in Luancheng County on the North China Plain. Scientists in this region linked their data to farmers' observations to provide a set of indicators to help farmers manage their land more effectively.

本章介绍了确定重要的野外土地形态和植被诊断指标的系统方法，目的在于应用这些指标对特定区域退化的土地进行治疗。作者将土地景观与其上面的主要土壤与水文过程结合为一体，形成一套野外诊断指标（如土壤颜色），置于一个简单易懂的、与土地利用方式相联系的土壤类别比照图内，制作成应用指南。此种形式的信息可帮助农民与有关人员选择渍涝与盐碱地

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的改良措施，改进农场和区域的利用规划。作者总结了制作此应用指南的一系列步骤，包括土层及其在坡面的构成，土壤类型图的生成等，也涉及当地社区在此过程中所起的作用。

文章具体讲解了南澳两个土地严重退化地区应用指南的制作以及如何将该指南用于其它区域。描述性的土壤信息和沿坡面拍摄的照片用来辨明土壤的主要特点。彩色的截面土壤和植被照片及图表可以最大程度地帮助当地居民和团体了解复杂的科学知识和专业术语，了解可以采取的措施。太行脚下的栾城县也采用了一种相似的、以土壤颜色或地貌特征作为指标的方法。该地区的科学家将他们的数据跟农民的观察结合起来，提供了一套指标系统来帮助农民更有效的管理他们的土地。

MUCH has been published on the general application of soil indicators and tests, and on the causes and remediation of land degradation in Australia (e.g. Hunt and Gilkes 1992; Charman and Murphy 1991; Dalglish and Foale 1998; Moore 1998; NSW DLWC 2000). Most of these publications provide a good general overview of the major issues but are not designed to address land-use and degradation issues for a specific region, although there are exceptions like SoilPak (McKenzie 1998), which is specific for irrigated cotton in New South Wales. The objective of the studies described in this paper was to develop some tools to communicate scientific knowledge to farmers and regional advisers in order to help them to identify land degradation in specific regions. In Australia, the approach was to produce a manual to help landholders to identify and remedy degradation. The study focused initially on two regions in southern Australia where dryland salinity and waterlogging cause major land degradation — the Mount Lofty Ranges of South Australia and an area in southwestern Victoria. In Luancheng County on the North China Plain, the approach was to show farmers how they could better manage their lands using easily observable soil indicators.

Field indicators linked to landform elements help landholders and regional advisers to identify areas of soil degradation. Indicators used for characterising ‘soil quality’ can be descriptive or analytical (Fitzpatrick et al. 1999). Standard descriptive soil indicators such as visual indicators (e.g. colour) and consistency are often used by farmers, regional advisers and scientists in the field to identify and report attributes of soil quality (Fitzpatrick 1996). For example, soil colour can provide a simple means to recognise or predict salt-affected, waterlogged wetlands caused by poor drainage (Fitzpatrick et al. 1996), providing an alternative to the difficult and expensive process of documenting watertable depths to estimate water duration in soils (Cox et al. 1996). Visual indicators may be obvious (e.g. white salt accumulations on soil surfaces) or subtle (e.g. subsoil mottling patterns). Analytical indicators include electrical conductivity (salinity) and dispersion (sodicity). Combining descriptive and analytical indicators can provide vital information about soil–water processes to improve land management and remediation of degraded land (Fitzpatrick et al. 1994). The challenge is to communicate this information to landholders and agricultural advisers.

Fitzpatrick et al. (1994, 1998) have previously shown that complex scientific processes and terminology can be effectively communicated to local groups using coloured cross-sectional diagrams and photographs of soil and vegetation. By combining this approach with community advice, the authors developed easy-to-follow manuals that incorporated soil–landscape and vegetation keys. The manuals could be used as a simple decision-making tool for land management based on recommendations in the scientific literature.

Developing a Manual: a Systematic Approach Used in Australia

Topography strongly affects the physical and chemical characteristics of soils, because landform influences the flow of water both through and over the soil surface. For example, excessive runoff on sloping ground reduces plant growth by decreasing the availability of soil water, increasing erosion (leading to reduced soil depth) and causing loss of nutrients. On flat land at the bottom of slopes, severe waterlogging can have a pronounced effect on plant production. A specific type of landscape or catchment is generally characterised by a particular succession of soils down the slope of the topossequence, associated with changes in soil moisture (Milne 1934; Sommer and Schlichting 1997).

To understand the lateral linkages and relationships between soil profiles down landscape slopes, we developed a systematic approach for studying the morphological (e.g. colour and textural patterns), chemical and mineralogical characteristics of soils and their underlying weathered bedrock or saprolite (Fritsch and Fitzpatrick 1994; Fitzpatrick et al. 1996). We linked these soil–landscape features to the main soil and water processes operating within the landscape and developed a set of field indicators, described in easy-to-follow practical manuals. The manuals help farmers and regional advisers to identify options for remediation of waterlogged and saline catchments and to improve planning at the property and catchment level.

Box 1 shows the sequence of steps used to develop the manuals. Steps 1 to 5 describe the soil layers and construct them in toposequences, which are then used to map soil types in key surrounding areas. Steps 6 to 9 involve the local community in developing the manual. Figure 1 summarises the steps involved.

The steps were identified and evaluated during work at a study site in the Mount Lofty Ranges of South Australia (Fitzpatrick et al. 1997) and in western Victoria (Cox et al. 1999). Both regions have 500–600 mm annual rainfall; in both, the problem of land degradation is worsening and farmers are concerned about the rapid increase in saline scalds. Figure 2 shows the location and some characteristics of the Mount Lofty Ranges. Figures 3–5 show some of the tools used in developing and applying the manual: Figure 3 shows an example of a key; Figure 4 shows how major soil types are linked to on-farm management options; Figure 5

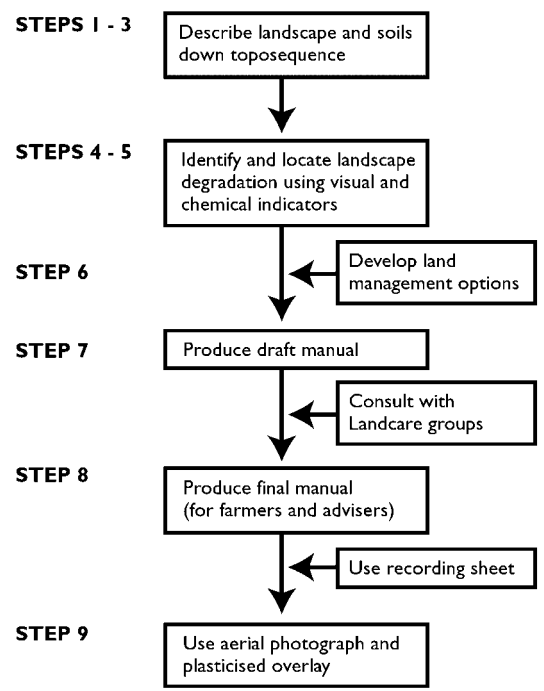


Figure 1. Flow diagram showing the main steps involved in developing a pictorial manual to aid property and catchment planning.

Box 1. Steps in developing an Australian manual

This box summarises the main steps involved in developing a pictorial manual to aid property and catchment planning. These steps are described in detail below and summarised in Figure 1.

Step 1. Select representative focus catchments and landscape sequences

Two tasks are required for this step:

- *Collate soil, geological and climatic information.* Using published broad-scale (e.g. regional) soil, geological and climatic maps such as the one shown in Figure 2a; the first task is to select a representative focus catchment such as the one shown in Figure 2b (Fitzpatrick et al. 1997).
- *Reconnaissance survey soil in the focus catchment.* Establish the most common succession of soil types within the representative catchment, using aerial photographs, road cuttings (if available), random soil augering and soil pits along toposesquences. Then select a suite of the most commonly found soils along an idealised toposequence (X–Y shown in Figure 2b).

Step 2. Describe in detail soils along the selected toposequence

This step requires two tasks:

- *Describe soil layers in detail.* This step involves three stages:
 - identify and photograph the complete sequence of soil profiles down the toposequence (X–Y, Figures 2b and c);
 - identify and describe, by depth interval only, all similar soil features (i.e. soil components with similar consistency, colour, textural and structural patterns, and chemical and mineralogical properties) using conventional soil description handbooks (e.g. McDonald et al. 1990; Soil Survey Division Staff 1993); and
 - draw boundaries around the similar soil features within the soil profiles and record them (Boulet et al. 1982; Fritsch et al. 1992, Fritsch and Fitzpatrick 1994).

- *Describe soil horizons and classify soil profiles.* Identify standard soil horizons in order to classify the soils according to soil taxonomy (Soil Survey Division Staff 1998) or the Australian Soil Classification System (Isbell 1996).

Step 3. Group and map similar soil features in the toposequence

This step requires two tasks:

- *Group similar soil features into fewer soil layers using structural analysis.* Structural analysis of the soil involves three stages:
 - use nested or concordant relationships to group soil features, and discordant relationships to separate them;
 - draw boundaries around similar features between the soil profiles to link them down the toposequence, and map them at toposequence scale in cross-sections (Boulet et al. 1982) (Note: soil horizons are not used to demarcate these boundaries because the features used to define soil horizons are too strictly grouped to allow accurate lateral linking between profiles along toposesquences); and
 - group similar soil features into a smaller number of soil layers based on concordant and discordant relationships.
- *Display the combined soil layers of the toposequence graphically in cross-section.* Using computer software, display the soil layers graphically in cross sections down toposesquences (Rinder et al. 1994). The colour patterns down the X–Y toposequence in Figure 2c display the soil layers.

Step 4. Match soil layers to hydrological processes

- *Field monitoring and laboratory analyses.* Monitor rainfall, watertable fluctuations (in piezometers and dipwells), soil water content, soil redox (Eh electrodes) and chemical changes (e.g. electrical conductivity, cations and anions) (Cox et al. 1999; Fitzpatrick et al. 1996). To select representative sites and determine soil depths where field instrumentation should be placed, monitoring

Box 1. (cont'd)

must focus on identifying changes in soil layers along the entire length of the toposequence.

- *Link soil and hydrological processes to soil layers.* Link soil and hydrological processes (e.g. water flow paths and salinity) to each soil layer displayed in cross-sections. In Figure 2c hatching represents soil salinity and arrows indicate water flow.

Step 5. Develop vegetation and soil–landscape keys

- *Develop easy-to-follow vegetation keys.* Photograph and list groups of plants that identify high, moderate and low levels of salting (e.g. Matters and Bozon 1995). Also record features such as plant density, vigour, health and abundance for each category of plant.
- *Develop simple soil–landscape keys.* Identify up to 10 soil types that best represent the soils in the study region (which could contain 100 or more soil series), based on topography, simple morphological features and chemical tests. Construct a taxonomic key to enable the reader to easily identify these soil types. The key comprises a colour photograph of the typical soil type, an indication of where the soil is usually found (e.g. crest, mid-slope, lower slope, footslope) and drainage characteristics (well drained, poorly drained). Each soil layer (e.g. top, bottom layer 1, bottom layer 2) is clearly demarcated using a thick black dotted line. Alongside each layer, easily observable (e.g. colour, white salt crystals, vegetation) or measurable (e.g. soil consistency and dispersion) features can be recorded. The key is ordered so that the reader moves systematically through the identification of the soils in a stepwise progression, answering ‘yes’ or ‘no’ to the question of whether the features shown for each soil are present. Selected portions from a key are shown in Figure 3.

Step 6. Link major soil types to on-farm management options

For each soil type, identify appropriate management options based on input from a wide range of

technical experts, including pasture agronomists, salt land agronomists, livestock advisers, specialists in woody perennial revegetation, soils and drainage specialists, and key community members. Summarise management options in a box above a colour photograph of the soil type located along the generalised toposequence. This process is illustrated in Figure 4.

Step 7. Draft the manual

- *Develop a framework.* Set up a framework for the spiral-bound manual, including:
 - soil keys based on colour photographs of soils and plants;
 - an idealised cross-section of a toposequence sketched in colour compiled from the features found in most of the major toposequences of the region (Figs. 2 and 4); and
 - recording sheets for use in the field.

Figure 5 illustrates a recording sheet.

- *Consult with community groups.* Work with potential users of the manual to obtain feedback.

Step 8. Produce the final manual

Revise the manual in the light of feedback from potential users. Recommendations following the field trials described above included expanding the number of photographs of indicator plants, using high-grade graphics for production of all photographs and constructing a water-resistant summary sheet or insert. The quality of the diagnostic photographs was improved so that they could be more easily recognised by landholders, and the text was revised with input from both the Northern Hills Soil Conservation Board and local officers of Primary Industries and Resources South Australia.

Step 9. Obtain aerial photographs

Obtain aerial photographs for the paddocks (fields) and overlay with clear plastic, on which field observations and management options can be marked. Figure 6 illustrates aerial photographs for the selected catchment.

shows one of the recording sheets used in the field. At present, salinity affects only about 1500 ha in the Mount Lofty Ranges but it has a serious impact on Adelaide's water resource and the expanding wine grape industry. A similar approach was subsequently used in Luancheng County, on the North China Plain. The Overview provides some background information about the study areas in

China and Australia; Figures 1 and 2 of the Overview show their location.

The Northern Hills Soil Conservation Board, in South Australia's Mount Lofty Ranges, expressed an interest in developing a manual based on recommendations in the scientific literature and incorporating a soil-landscape and vegetation key

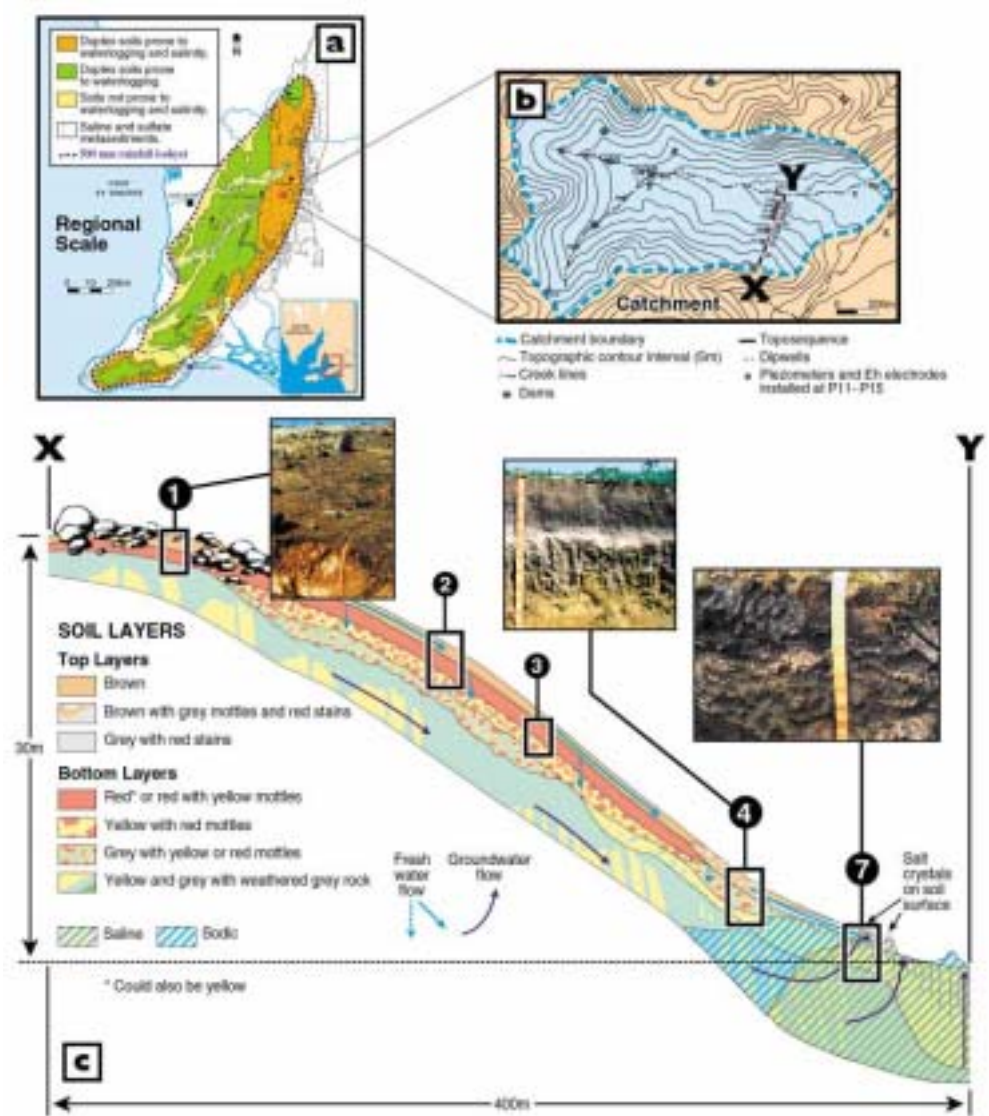


Figure 2. Diagram showing (a) a regional map of the Mount Lofty Ranges with generalised rainfall, geology, and soil pattern, (b) selected focus catchment, (c) toposquence with soil features and water flow paths and three selected soil profiles (modified from Fitzpatrick et al. 1997).

(Fitzpatrick et al. 1994). The board thought that the key described in this work used too much scientific terminology and could be improved if it were made more practical and written in a language and style that would engage landholders. Although the board accepted the need for a simple decision-making tool, it wanted to avoid the approach of ‘glossy’ booklets that are seldom used because they are written in obscure language, involve impractical tests or advocate unrealistic options. The board also required the manual to be ‘road tested’ to demonstrate that it would provide accurate interpretation and lead to realistic management options.

Applying the manual to a farm

To use the manual on a particular property, a landholder selects several transects across a

paddock (usually down a slope) likely to have waterlogging or salinity problems, and marks them on a plastic overlay on an aerial photograph of the property. Starting at the top of the hillslope (observation point a1, Fig. 5), observations are made on the recording sheet at several points down the slope (observation points a2 – a7, Fig. 5). Where needed, soil samples are collected for measuring dispersion and pH in the field, using methods described in the manuals.

From the information on the recording sheet, the boundaries between soil types and the soil type number (1 – 7) are marked (Fig. 6a), making use of the landholder’s personal knowledge of the paddock, contours and vegetation differences to improve the accuracy of the boundaries. Finally,



Figure 3. Examples of two pages from the taxonomic key for identifying soil features that indicate degrees of waterlogged and saline conditions, and management options (modified from Cox et al. 1999). Magnified areas appear in bold text to give an indication of the nature of the key.

management options associated with each of the soil types listed in the key are selected and recorded using a set of symbols (Fig. 6b).

Evaluating the manual in the field

Members of the Woorndoo Landcare Group in western Victoria tested the key developed for their area. Some profiles were found to lie between one

standard profile in the key and the next, a situation that has implications for determining appropriate management options. The group had a pre-conception about the sequence of soils they would find in the landscape, based on surface features such as slope, but discovered that their estimate of the location of profiles was often inaccurate.

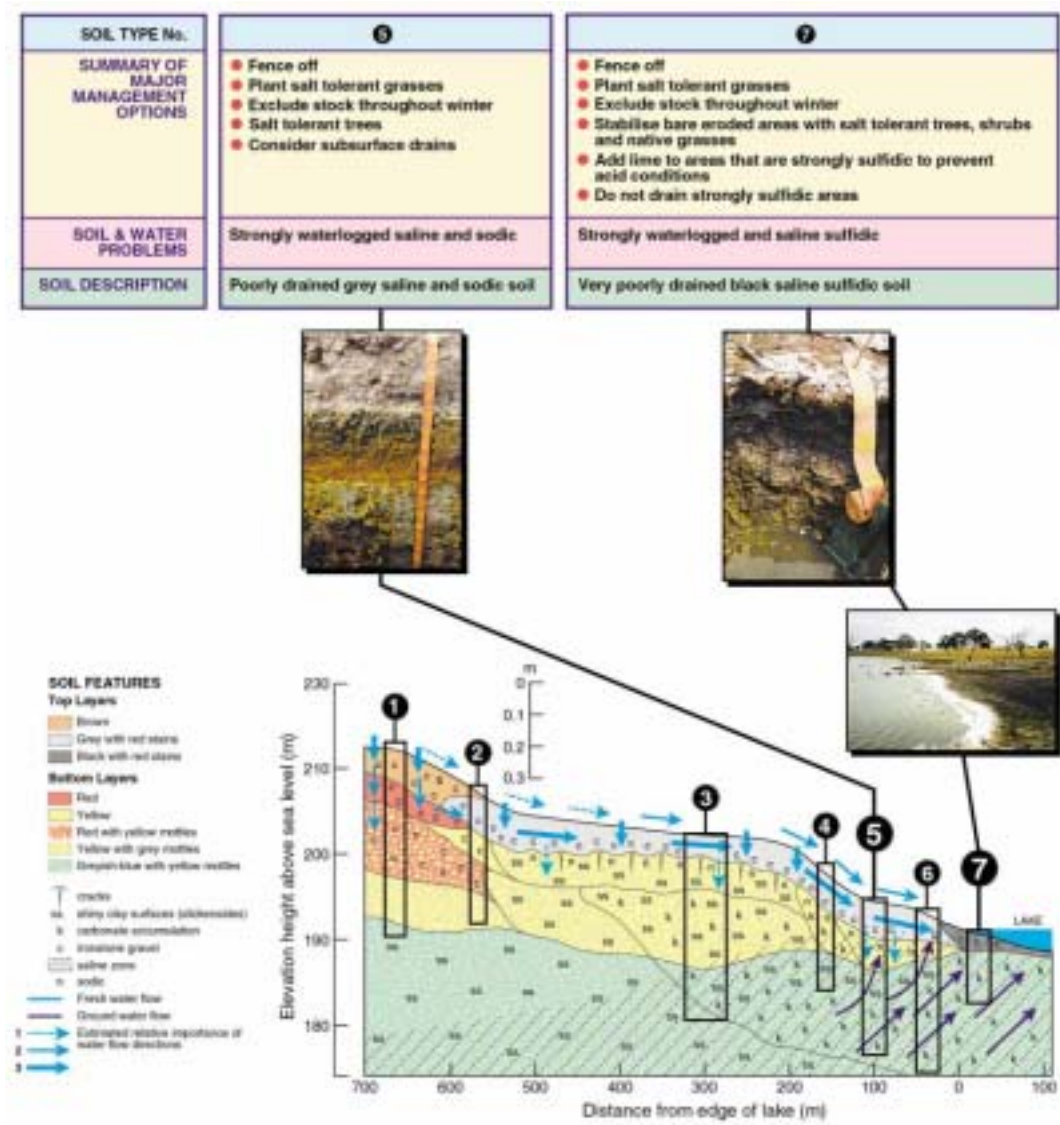


Figure 4. Sequence of soils down a slope to a lake (two of the seven soils are illustrated) with brief summaries of management options associated with each of the soil types (modified from Cox et al. 1999).

Observation point	a1	a2	a3	a4	a5	a6	a7
Plants indicating low level salting (Class 1)	✓	✓					
Plants indicating moderate level salting (Class 2)				✓	✓		
Bottom layer 1		✓					
- red with ironstone gravel		✓					
- yellow			✓		✓		
- yellow with grey mottles, nodules, cracks and shiny clay surfaces				✓			
- dark grey with yellow mottles						✓	✓
Bottom layer 2							
d. Soil tests - bottom layers							
Salinity (1:5 soil in water suspension)			✓	✓			✓
Partly cloudy (not sodic)			✓	✓			✓
Cloudy (medium)						✓	
Very cloudy (highly sodic)				✓	✓		
Salinity			✓	✓	✓		
Not saline		✓	✓	✓	✓		
EC of top layer is above 0.7 dS/m						✓	✓
Acidity (pH in water)							
pH less than 5.5 (highly acidic)							
pH between 5.5 and 8.5		✓	✓	✓	✓	✓	✓
pH greater than 8.5 (highly alkaline)							
e. Soil type number (1-8) from soil key. Could be transitional between 2 soil type numbers			1	2	3	4	5

Figure 5. Three sections from the field recording sheet, which consists of three A4 pages (modified from Cox et al. 1999).

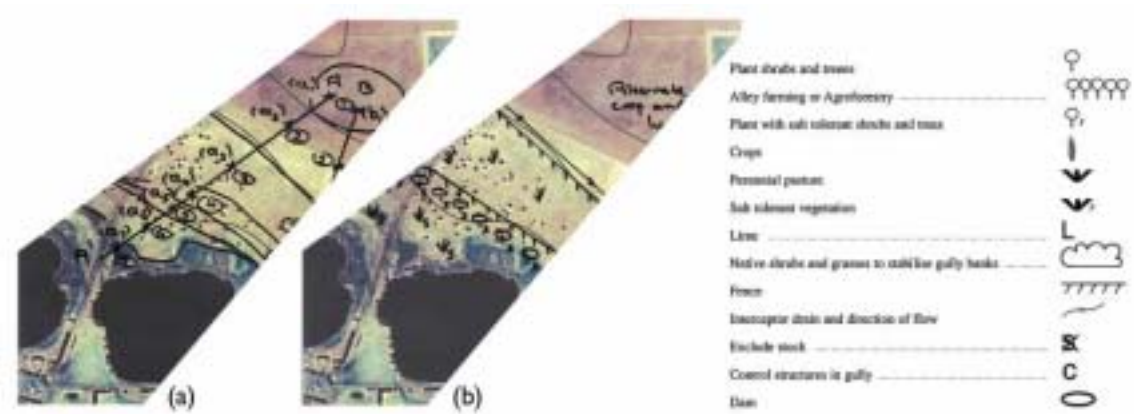


Figure 6. (a) Soil type number marked and boundaries demarcated along a single transect on a portion of an aerial photograph, (b) management decisions marked on the aerial photograph showing perennial pastures, fencelines and areas to plant with salt-tolerant shrubs and trees (modified from Cox et al. 1999).

Developing Indicators at an Appropriate Scale: the Chinese Approach

Indicators are measurable attributes of the environment that can be monitored via field observation, field sampling, remote sensing or the compilation of existing data. Each indicator describes a particular function of the environment and can signal desirable or undesirable changes that have occurred or that may occur in the future (Walker and Reuter 1996). Different users have different concerns and objectives, and different indicators may be required for different scales of land use (farmland, county, region). For example, soil colour, soil texture and leaf colour are suitable indicators for farmers but measured data may be more useful for people working on a county scale. Figure 7 shows how soil colour and texture are suitable soil health indicators for farmers. Chinese scientists have developed a set of indicators at farm scale based on measurements of soil properties (Hu Chunsheng and Wang Zhiping 1999; Hu

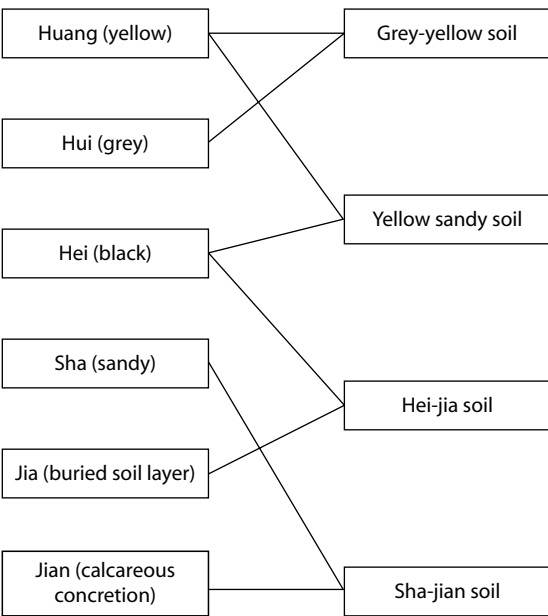


Figure 7. Example of soil classification used by Chinese soil scientists (right) and equivalent categories recognised by farmers (left).

Chunsheng 1999). Box 2 shows how indicators were selected and verified to assess soil health on the NCP.

Discussion

The key was a crucial component of the Australian manual. Local advisory officers from Primary Industries and Resources South Australia (PIRSA) and members of the community-based Northern Hills District Soil Conservation Board tested the key developed for the case study area in the Mount Lofty Ranges. A typical subcatchment on a local property was selected at random, and groups of advisory officers each completed separate transects down a toposequence. Surface observation down one transect suggested saline conditions because saline-tolerant plant species dominated much of the area. By exposing the soil profile at a number of points along the transect (Fig. 6a) and comparing it to the standard profiles outlined in the key, it became clear that waterlogging was the major problem, with salinity present only in the lowest part of the subcatchment. Along a second transect there were no plant indicators of saline conditions, and the area was not saline. The group was surprised to find that the profile at the top of the transect was waterlogged rather than well drained, meaning that the pasture species being grown at this location was not ideal.

Trialling the manual in the case study areas confirmed the value of the key. It also emphasised the need to look beyond surface soil and plant factors, and to consider additional soil observations and measurements to better understand and manage local situations. Combining the manual with observations of subsurface soil features can improve management decisions. For example, the pasture species most appropriate for well-drained areas on upper and mid-slopes would be different from those selected for areas that are periodically waterlogged, but it would be difficult to distinguish well-drained areas from waterlogged areas by surface observation alone. Similarly, surface

Box 2. Selecting key indicators to assess soil health on the North China Plain

At the farmland scale, the main soil indicators should include soil colour, texture, bulk density, field capacity, wilting point, total organic material, total nitrogen, available phosphorus and available potassium. Morphological properties such as soil colour, soil texture and the structure of soil profiles are very useful indicators for farmers to assess the health of the land.

In Luancheng County on the piedmont plain of Mount Taihang, farmers can identify six categories of soil that can be used to indicate the degree of soil fertility, the soil tilth index, the degree of porosity and the degree of conservation of soil water and nutrients. These categories are:

- Huang (yellow soil colour), which is associated with good water drainage and good tilth;
- Hei (black soil colour), associated with a high organic matter content;
- Hui (grey soil colour), associated with an even higher soil organic matter content than Hei;
- Sha (sand), associated with good drainage capacity but a low nutrient content and a poor ability to conserve soil water and nutrients;
- Jia, which is soil with a 'buried' soil layer, indicating clay, with poor-quality tilth restricting

the growth of seedlings but suitable for older shoots; and

- Jian, which is soil with calcareous concretion or a calcium horizon, which restricts root growth.

These categories are the easiest and most practical way for farmers to assess soil health.

Soil in Luancheng County is typical cinnamon soil with a thin humus layer and middle or thick solum. The buried layer, clay course, calcareous concretion layer, sand soil layer and ploughed layer are the standard diagnostic horizons for soil species classification. Soils can be divided into 17 soil types. The boxes on the right side of Figure 7 show four examples of the soil classification used by soil scientists; those on the left indicate the equivalent categories recognised by farmers.

Case study: grey–yellow soil

From the name of the soil, farmers can judge that this kind of soil has good soil structure, tillage properties and moisture capacity, but that there is a plough pan with high bulk density where the soil becomes lighter in colour (Tables 1 and 2). Measurement of root density, consistency and texture confirms farmer perceptions based on soil colour.

Table 1. Morphology and root density of grey–yellow soil in Luancheng County.

Layer	Thickness (cm)	Consistency	Colour	Texture	Root density (cm/cm ³)	
					Corn	Wheat
A ₁	0–17	Soft	Grey brown	Sandy loam	3.49	1.12
A ₁ B	17–30	Very hard	Light brown	Sandy loam	1.63	0.48
B ₁	30–65	Firm	Dark brown	Loam	0.51	0.26
B ₂	65–90	Firm	Dark brown	Loam	0.34	0.25
BK	90–145	Very hard	Light yellow	Light clay	0.16	0.12
B ₃	145–170	Very hard	Gray yellow	Light clay	0.18	–
BC	170–190	Very hard	Light yellow	Medium clay	–	–

Box 2 (cont'd)

Table 2. Physical indicators of grey–yellow soil in Luancheng County.

Layer	Thickness (cm)	Field capacity (%)	Wilting point (%)	Plant available water (%)	Bulk density (g/cm ³)	Total porosity (%)	Air-filled porosity (%)
A ₁	0–17	36.35	9.63	26.73	1.41	46.42	10.07
A ₁ B	17–30	34.86	11.37	23.49	1.51	42.62	7.76
B ₁	30–65	33.25	13.92	19.33	1.47	44.14	10.89
B ₂	65–90	34.28	13.91	20.37	1.51	42.62	8.34
BK	90–145	34.36	12.95	21.41	1.54	41.48	7.12
B ₃	145–170	38.98	13.87	25.11	1.64	37.68	1.42
BC	170–190	38.05	16.44	21.61	1.59	39.58	1.53

(reverse interceptor) drains are sometimes installed to remove water to improve pasture establishment (e.g. Cox and McFarlane 1995); in sodic subsoils they are likely to fail due to dispersion of soil particles, but this condition is difficult to determine simply from surface soil observations.

The manual helps users to make good decisions, improves their understanding of the processes of dryland salinity and waterlogging, and offers solutions to improve the quality of their properties. Where the manual has been applied in the Mount Lofty Ranges area, degraded saline wet areas have been rehabilitated and erosion has been halted through measures such as realigning fencelines and revegetation.

The manual developed for the Mount Lofty Ranges has been used as a standard text in the small farms land management course that is run four times a year by the local soil board. Bruce Munday, a farmer near Mount Torrens, during an interview with Pyper and Davidson (2001), stated:

The publication of the CRC–CSIRO manual on waterlogged, saline and acid sulfate soils in the Mount Lofty Ranges has also made land management that much easier for farmers ... The manual is very much a do-it-yourself kit that has enabled us to manage these things properly, rather than by trial and error ... Trial and error has always been a great standby for farmers, but it sometimes has dire consequences.

Conclusions

We have summarised a set of procedures for identifying the best set of soil–landscape and vegetation field indicators for a region. Farmers, catchment groups and natural resource management agencies can use the approach to achieve the following outcomes.

- Knowledge of soil and hydrological processes and production systems can be brought together and used as the basis for recommendations for appropriate management options.

- Viable land-use options and management systems (including mosaic farming) that are more resource efficient than current ‘trial and error’ practices can be adopted.
- Significant impetus for land-use change based on sound scientific knowledge and community involvement and an understanding of community needs.
- Effective extension mechanisms that can be used to transcend institutional boundaries (e.g. the Commonwealth Scientific and Industrial Research Organisation (CSIRO); PIRSA; catchment boards; Landcare groups). The mechanisms provide a model for other multiagency interdisciplinary research.

The following procedures are used to identify the best set of soil–landscape and vegetation field indicators:

- identifying easily recognised landform elements and soil morphological features, such as soil colour and consistency, down an idealised slope sequence (toposequence);
- using an idealised toposequence to encompass a compilation of the main features present within most of the major toposequences of a specific region;
- linking the soil and vegetation indicators to a pictorial soil–landscape and vegetation key and thereby matching to locally practised on-farm management options;
- using, where needed, simple tests for soil electrical conductivity (salinity), dispersion (sodicity) and pH (acidity); and
- packaging information in an easy-to-follow pictorial manual with input from Landcare groups.

The approach has generic application.

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References

- Boulet, R., Humbel, F.X. and Lucas, Y. 1982. Analyse structural et cartographie en pédologie: II Une méthode d'analyse prenant en compte l'organisation tridimensionnelle des couvertures pédologiques. Cahiers ORSTOM, série Pédologie 19, 323–339.
- Charman, P.E.V. and Murphy, B.W. (eds). 1991. Soils: their properties and management—a soil conservation handbook for New South Wales. Sydney University Press and Oxford University Press.
- Cox, J.W., Fritsch, E. and Fitzpatrick, R.W. 1996. Interpretation of soil features produced by ancient and modern processes in degraded landscapes: VII. Water duration. Australian Journal of Soil Research, 34, 803–824.
- Cox, J.W. and McFarlane, D.J. 1995. The causes of waterlogging in shallow soils and their drainage in southwestern Australia. Journal of Hydrology, 167, 175–94.
- Cox, J.W., Fitzpatrick, R.W., Minter, L., Bourne, J. and Whipp, G. 1999. Managing waterlogged and saline catchments in south-west Victoria: a soil–landscape and vegetation key with on-farm management options. Woorndoo Land Protection Group Area Case Study. Melbourne, CSIRO Publishing, Catchment Management Series No. 2.
- Dalgliesh, N. and Foale, M. 1998. Soil matters: monitoring soil water and nutrients in dryland farming. Toowoomba, Queensland, Agricultural Production Systems Research Unit.
- Fitzpatrick, R.W. 1996. Morphological indicators of soil health. In: Indicators of Catchment Health: a technical perspective, eds J. Walker and D.J. Reuter. Melbourne, CSIRO Publishing, 75–88.
- Fitzpatrick, R.W., Cox, J.W. and Bourne, J. 1997. Managing waterlogged and saline catchments in the Mt. Lofty Ranges, South Australia: a soil–landscape and vegetation key with on-farm management options. Melbourne, CSIRO Publishing, Catchment Management Series No. 1.
- Fitzpatrick, R.W., Cox, J.W. and Bourne, J. 1998. Soil indicators of catchment health: tools for property planning. In: Proceedings of the International Soil Science Society Congress, Montpellier, France. Montpellier, International Soil Science Society, Symposium No. 37, CD-ROM, 8.

- Fitzpatrick, R.W., Cox, J.W., Fritsch, E. and Hollingsworth, I.D. 1994. A soil-diagnostic key for managing waterlogging and dryland salinity in catchments in the Mt Lofty Ranges, South Australia. *Soil Use and Management*, 10, 145–152.
- Fitzpatrick, R.W., Fritsch, E. and Self, P.G. 1996. Interpretation of soil features produced by ancient and modern processes in degraded landscapes. V. Development of saline sulfidic features in non-tidal seepage areas. *Geoderma*, 69, 1–29.
- Fitzpatrick, R.W., McKenzie, N.J. and Maschmedt, D. 1999. Soil morphological indicators and their importance to soil fertility. In: *Soil Analysis: an interpretation manual*, eds K. Peverell, L.A. Sparrow and D.J. Reuter. Melbourne, CSIRO Publishing, 55–69.
- Fritsch, E. and Fitzpatrick, R.W. 1994. Interpretation of soil features produced by ancient and modern processes in degraded landscapes. I. A new method for constructing conceptual soil–water–landscape models. *Australian Journal of Soil Research*, 32, 889–907 (colour figures 880–885).
- Fritsch, E., Peterschmitt, E. and Herbillon, A.J. 1992. A structural approach to the regolith: identification of structures, analysis of structural relationships and interpretations. *Sciences Géologiques*, 45(2), 77–97.
- Hunt, N. and Gilkes, R. 1992. *Farm monitoring handbook*. Perth, University of Western Australia.
- Hu Chunsheng. 1999. Physical and chemical indicators of soil health diagnostics and its application. *Eco-Agriculture Research (in Chinese)*, 1.7(3).
- Hu Chunsheng and Wang Zhiping. 1999. The soil nutrient balance and fertilizer use efficiency in farmland ecosystems in Taihang Mountain Piedmont. *Progress in Geography*, 17 (supp.), 131–138.
- Isbell, R.F. 1996. *The Australian soil classification system*. Melbourne, CSIRO Publishing.
- Matters, J. and Bozon, J. 1995. *Spotting Soil Salting: a Victorian field guide to salt indicator plants*. Victoria, Department of Natural Resources and Environment.
- McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. 1990. *Australian Soil and Land Survey Field Handbook*, 2nd edn. Melbourne, Inkata Press, 87–183.
- McKenzie, D. 1998. *SOILpak for cotton growers*, 3rd edn. Orange, New South Wales Agriculture.
- Milne, G. 1934. Some suggested units of classification and mapping particularly for east African soils. *Soil Research*, 4(2), 183–198.
- Moore, G (ed). 1998. *Soil Guide: A handbook for understanding and managing soils*. Perth, Agriculture Western Australia, Bulletin No. 4343.
- NSW DLWC (New South Wales Department of Land and Water Conservation). 2000. *Soil and Landscape Issues in Environmental Impact Assessment*, 2nd edn. Sydney, NSW Department of Land and Water Conservation, Technical Report No. 34.
- Pyper, W., Davidson, S. 2001. Bubble bubble—Uncovering the true nature and severity of acid sulfate soil in inland Australia. *Ecos*, 106, 28–31.
- Rinder, G., Fritsch, E., Fitzpatrick, R.W. 1994. Computing procedures for mapping soil features at sub-catchment scale. *Australian Journal of Soil Research*, 32, 909–913 (colour figures 886–887).
- Soil Survey Division Staff. 1993. *Soil Survey Manual*. United States Department of Agriculture Handbook No. 18. Washington DC, US Government Printing Office.
- Soil Survey Division Staff. 1998. *Keys to Soil Taxonomy*, 8th edn. Washington DC, US Government Printing Office.
- Sommer, M. and Schlichting, E. 1997. Archetypes of catenas in respect to matter—a concept for structuring and grouping catenas. *Geoderma*, 76, 1–33.
- Walker, J. and D.J. Reuter (eds). 1996. *Indicators of catchment health—A technical perspective*. Melbourne, CSIRO Publishing.