Precision farming for intensive rice systems in Asia

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Rice demand is expected to increase by approximately 4 million t year^{-1} over the next 30 years, equivalent to adding around 1 million ha of new land per year at the present world average yield levels. Such land is not available, and so we must increase the efficiency of present production systems.

Increasing yields and input use efficiency will require new farming concepts that focus on fine-tuning of seed, nutrient, water, pesticide, energy, and labor inputs for smaller management units. *Precision farming, prescription farming,* or *site-specific crop management* (SSCM) are frequently used new terms to describe such emerging technologies (Robert et al 1995b). They originated as a response to the increasing awareness of the large variability between and within production fields. However, the premise underlying site-specific management, namely that heterogeneity (particularly that of soil) influences the productive potential of agricultural land, is not a new concept (McBratney and Whelan 1995). First attempts to continuously manipulate farming operations date back to 1925 or even earlier, when Haynes and Keen used a dynamometer to draw maps of plow resistance (Haynes and Keen 1925).

During the past 20 years, research has provided many examples of detailed investigations of magnitudes and sources of spatial and temporal variation of climate (Hubbard 1994, McBratney 1985), topography (Huang and Bradford 1992), soil properties (Beckett and Webster 1971, Burgess and Webster 1980, Burrough 1993, Webster 1985), weeds (Chancellor and Goronea 1994, Dessaint and Caussanel 1994, Donald 1994), diseases (Lannou and Savary 1991, Larkin et al 1995), nematodes (Webster and Boag 1992), and other production factors at scales that are relevant for producers. Due to the evolution of computers and electronic, pneumatic, and hydraulic devices, the technologies for managing this variability have now become available (Robert et al 1995a).

In this paper, we tried to assess opportunities, realities, and requirements for "precision" farming in rice-based cropping systems of Asia. We restricted the discussion to intensive, mostly irrigated rice systems as the concepts and technologies proposed are currently mainly of interest to those farmers; however, certain concepts will be applicable to other ecosystems. Many irrigated farmers have achieved tremendous yield gains during the past 30 years, often approaching economically attainable yields. However, average yields of irrigated rice have to increase from 4.9 t ha^{-1} in 1991 to about 8 t ha^{-1} in 2025 (Cassman and Pingali 1995). Thus, irrigated rice farmers will have the greatest need to fine-tune their farm management to produce the bulk of the future increase in rice supply. At the same time, positive awareness of environmental aspects of farming means that farmers have to ensure sustainability and environmental compatibility of their systems. They will have to move from simple general decisions and recommendations to much more knowledge-intensive, site-specific crop management (Fig. 1).

The questions we tried to answer were:

1. What are the principles of site-specific crop management?
2. What are the current realities and major limitations of site-specific crop management in developed countries?
3. What are the opportunities for site-specific crop management in irrigated rice?

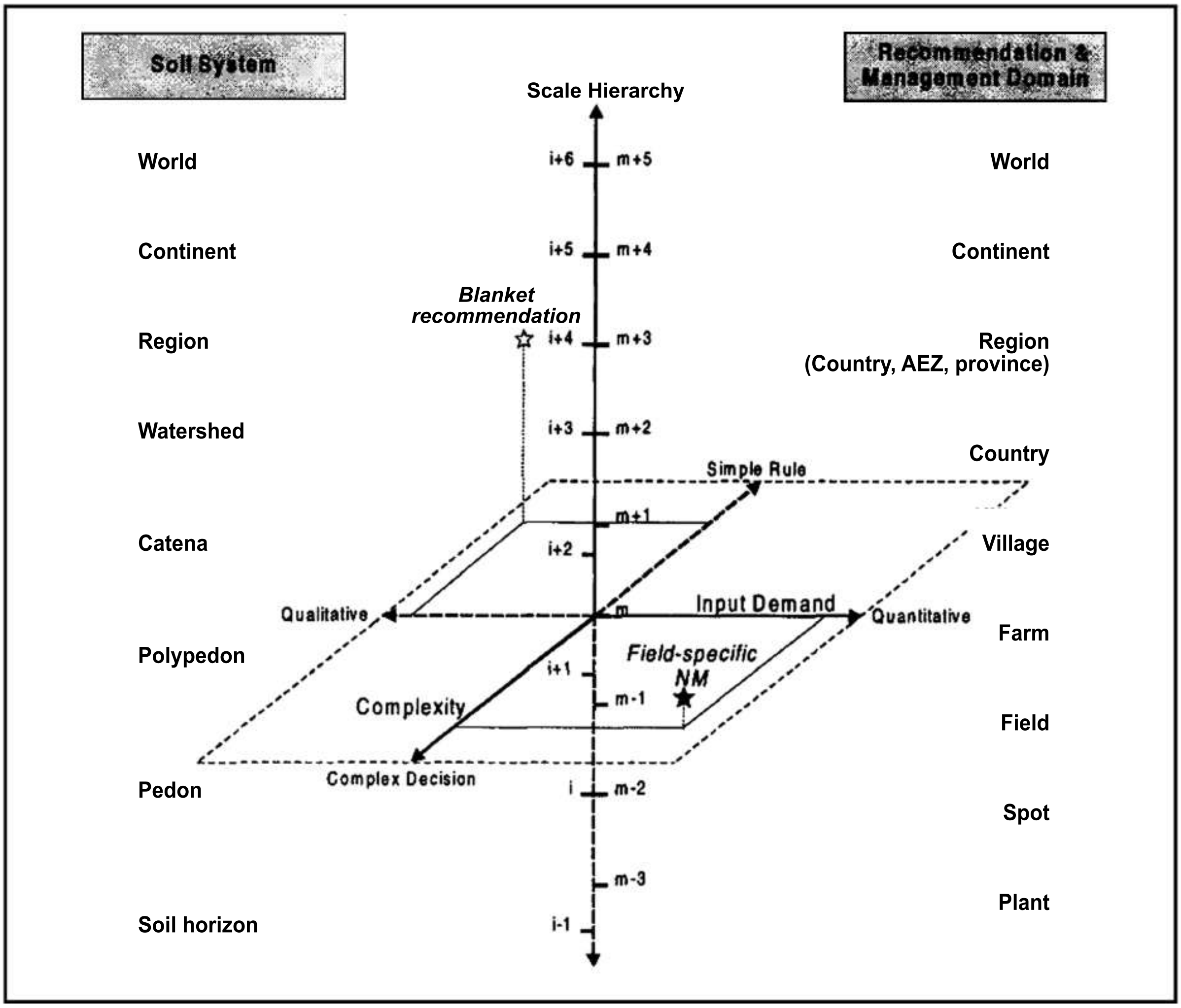


Fig. 1. Classification of crop management operations according to spatial scale (y), input demand (x), and complexity of information processing (z). The approximate positions of blanket and field-specific fertilizer application are drawn as examples. Modified from Hoosbeek and Bryant (1992).

Definition of farm and site-specific crop management

Most of the terms previously proposed are limited in scope to managing spatial variability and/or variability within a single field using specialized machinery (Appendix 1). However, certain operations in a precision or site-specific farming approach can be uniform for several fields or even farms and one should also consider the relationships between different farms and between different commodities within a farm.

We consider precision farming as a scientific concept that is applicable to farms and fields of all sizes, including those found in Asia. Therefore, we propose three terms for characterizing modem farming operations: (1) total farm management, (2) site-specific crop management, and (3) technology application domain (Fig. 2).

Total farm management (TFM) is an information-based agricultural management system that provides an optimum balance between profitability, food production, and sustainability within a single farm by

- maximizing output and utilization efficiency of all production inputs,
- optimizing flows of nutrients, water, energy, machinery, and labor,
- adding value to production,

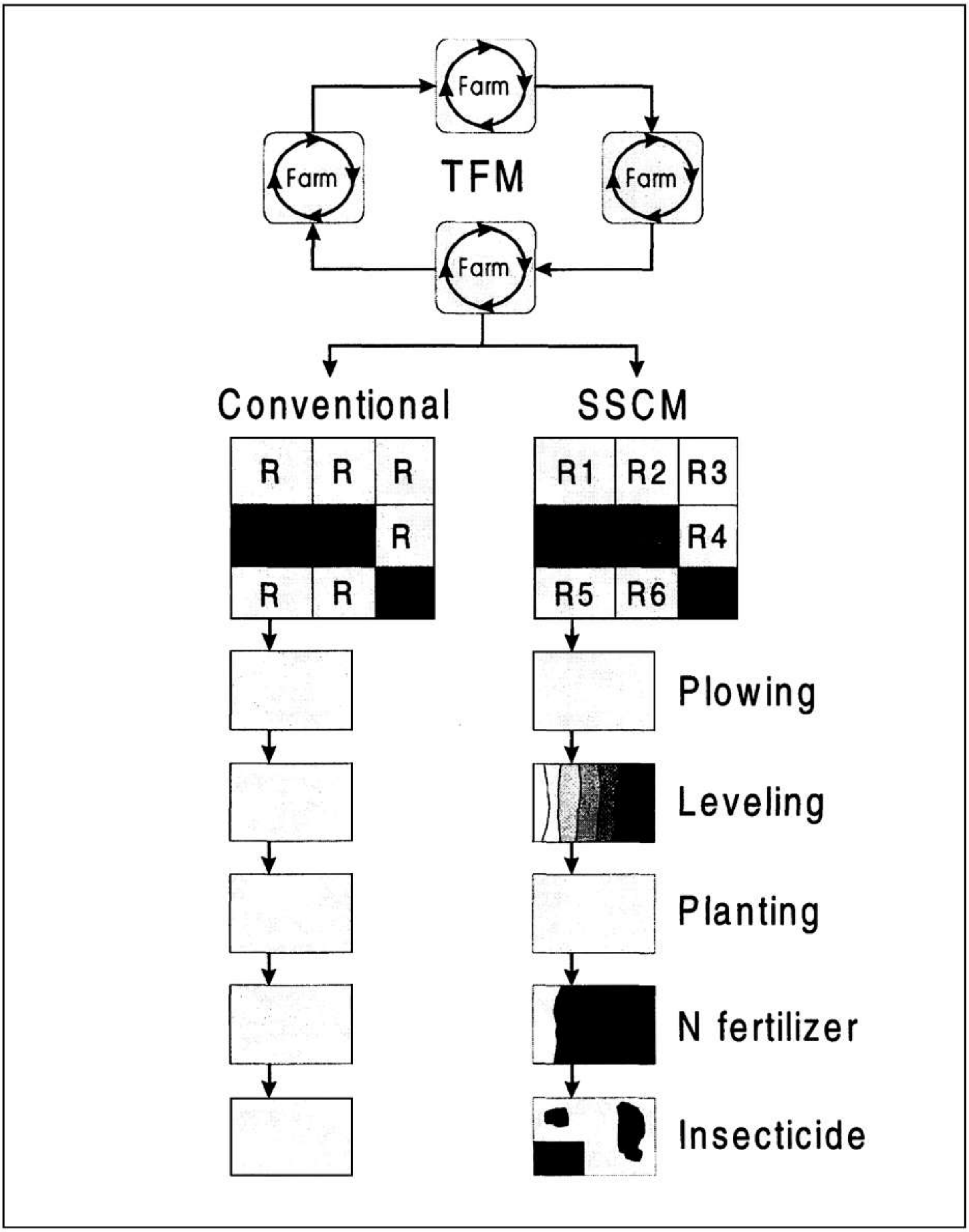


Fig. 2. Site-specific crop management (SSCM) operations vs. conventional farm management. At the whole farm level, relationships within and between farms are directed by total farm management (TFM). At the field level, in the conventional approach all fields planted to the same crop (e.g., rice/R or wheat/W) are managed similarly and applications do not vary much between and within fields (left side). In the SSCM approach, each field planted to the same crop may be treated specifically (e.g., R1 is different from R5). Depending on the technology available, some operations vary between and within fields (right side), i.e., technology application domains range from small patches to the whole farm.

For each farm size a precision management approach can be designed with technologies differing according to biophysical and socioeconomic conditions.

- minimizing off-farm effects on soil, water, and air quality across different production systems within the farm and between farms.

This definition emphasizes optimization of management of a whole farm, including various cropping systems and, if applicable, other types of agricultural production. At this level, a farmer has to make decisions about the allocation of major inputs and any optimization attempts should also consider relationships with other farms in a neighborhood of varying sizes. The latter include buy-and-sell operations, rental of machinery and labor, credits, distribution of manure, and postharvest activities. Considering the differences in population distribution, a village is probably the most appropriate scale for such between-farm operations in Asia, whereas in North America such operations may have much less weight (and perhaps would be defined for an environmental unit such as a watershed). TFM mainly requires the right intellectual concepts and tools (software) for collecting, analyzing, and interpreting relevant information.

Site-specific crop management is the crop-specific use of local soil, crop, and climatic parameters to make precise applications of production inputs to technology application domains with different characteristics. Typical components that form the SSCM of a particular crop are varying the depth of soil tillage based on topography, changing varieties or sowing rates according to soil types, adjusting the fertilizer application rate according to variation in soil test values, selective liming of certain fields or field parts only, or varying the pesticide spray rate based on actual crop stress.

This definition emphasizes management of a single crop according to site characteristics.

Technology application domains (TAD) are, for a specific technology, the smallest uniform spatial units that can be treated differently. Within an SSCM approach, the size of TADs can be different for different crop management operations and depends on

- site characteristics with the greatest influence on growth of the specific crop,
- relationship between additional net return from differentiated treatment (value/cost ratio) and size of TAD, and
- technical feasibility for collecting information and applying inputs at different spatial scales.

Therefore, SSCM decisions and operations may include continuous on-the-go adjustment, applications specific to patches within a single field, uniform applications to single fields, or uniform applications to groups of several fields with similar properties. This definition of TAD emphasizes a specific technological solution for implementing a certain crop management operation according to site characteristics.

General practice of site-specific crop management

A typical SSCM application includes the following steps (Fig. 3):

1. Knowledge capture: Identify and quantify (map) the variability of key input parameters at the scale needed to make a decision about the specific SSCM operation.
   - What is the information to monitor?
   - What are the suitable tools to quantify the variation in the key information?

2. Knowledge interpretation: Translate the information into decisions about management (application) by understanding the sources of variability and its impact on yield.
   - What tools are available/needed for this information to be interpreted?
   - What does the collected information mean for crop management?
   - What are the appropriate crop management options?

3. Application: Identify the available application technology and the optimal size of

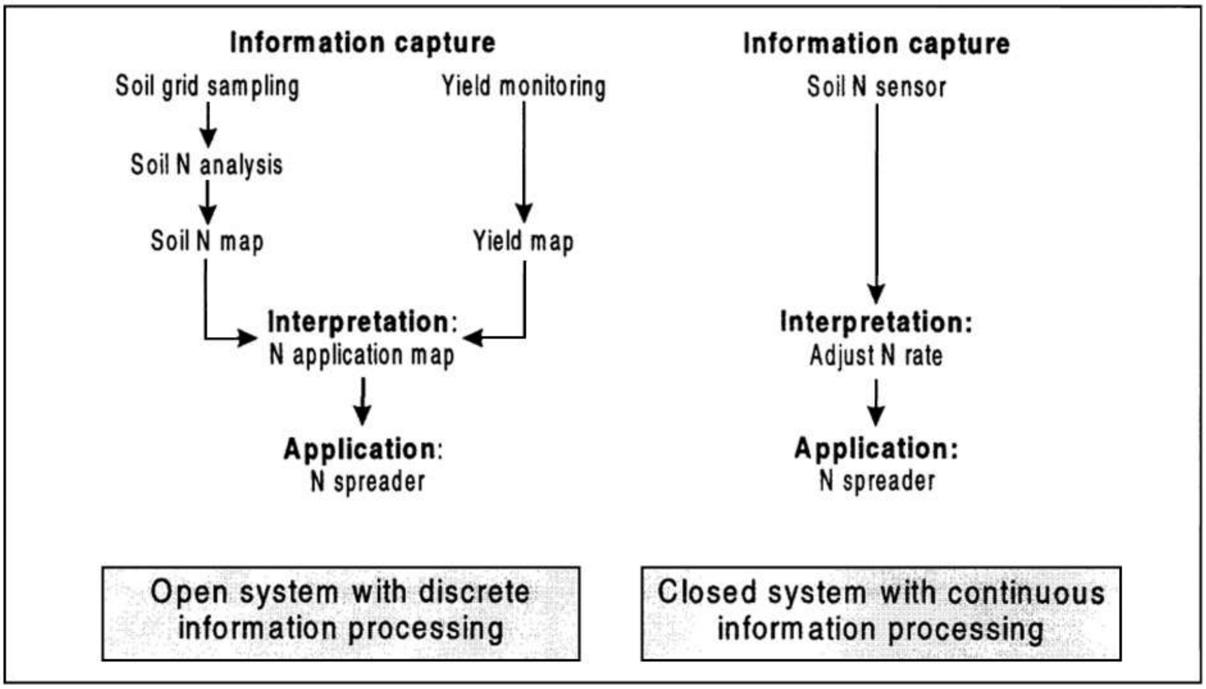


Fig. 3. SSCM technologies for managing variability within fields differ in their information flow. Fertilizer N application is shown as an example.

the technology application domain. Apply differential amounts of inputs to the TADs.

- What technologies are available/needed to apply the treatment?
- How can the whole approach be communicated and implemented?

Based on the kind of information processed we can classify SSCM approaches into (1) univariate (single measurement and action), (2) multivariate (multiple measurements and actions), and (3) historical (use of multiple crop years). For information flow, we can further distinguish two types of SSCM applications for managing variability within a field (Fig. 3), namely (1) systems with discrete steps on information processing, and (2) systems with continuous information processing. More discussion of information processing in SSCM is found elsewhere (Schueller 1992, 1997).

Systems with discrete steps of information processing

In a discrete system, information is captured in one or more temporally separate steps (e.g., soil sampling and analysis or yield monitoring). Interpretation of information is done in a second step by combining new with already existing data to produce an application decision. In a third step, the application is carried out. Important features of this technology include:

- A real-time positioning system is required for geo-referenced collection of information and for variable rate application.
- A minimum lag time of several days or weeks occurs from sampling to application.
- Much of the information processing is done off-farm.
- Each discrete step is subject to error.

Systems with continuous information processing

In a continuous system, information is captured automatically in real time using on-the-go sensors, immediately processed in a computer on board (including combining it with previous information), and the applicator is immediately adjusted (McBratney and Whelan 1995). Thus, as the machine drives over the field, information is gathered and tillage depth, fertilizer rate, sowing rate, etc., are adjusted accordingly. Important features of this technology include:

- A real-time positioning system may not be required for operations that only require measuring one or a few variables on the go.
- Accurate and robust on-the-go sensors are needed.
- Lag time from sampling to application is only a few seconds or less.
- Information processing is done on board.
- Steps such as sampling error, interpolation error, or positioning error are either significantly reduced or eliminated.
- Precise variable-rate technology (VRT) and a high degree of synchronicity between speed, information processing, and adjustment of the applicator are needed.

Obviously, equipment like this would eliminate many of the difficulties and uncertainties associated with the current discrete approach. The major bottleneck in developing complete continuous application solutions is the availability of suitable on-the-go sensors and adequate production functions for identifying correct treatment for given characteristics at a given location.

Potential benefits of SSCM

The basis of SSCM is that fields are highly variable (both between and within) and new technologies are available that can characterize that variability and delineate meaningful management zones to optimize supply and demand of nutrients, water, energy, and other resources according to their variation in time and space (Fig. 3). Where there is less supply (e.g., certain fields or certain locations within a field), application has to be greater than in physical land units with higher supply and vice versa. At the farm level, expected benefits are:

- increase in total production by higher yields
- improved use efficiency of nutrients, water, pesticides, and other key farm inputs (greater yield per unit input)
- greater profitability
- enhancement and maintenance of soil fertility
- reduced negative impact on the environment by greater crop use of inputs and so less loss to the environment
- rural communities benefit: increased cash flows and creation of additional jobs
- increased farmers' knowledge and awareness about soil and crop management

The latter is difficult to measure, but very important. For the first time, many farmers have hard data about variability in growth in their fields. Even though interpretation of a yield map or maps of soil test values is a difficult task, the map alone is a real eye-opener and farmers have become very interested in fine-tuning soil and crop management in their fields.

Cost-return analysis on specific practices is important so that their individual contribution to profitability can be determined (Reetz Jr. and Fixen 1995). But there is still a substantial lack of good quality research on costs and benefits of SSCM. Potential net benefits for the farmer and for the environment (Fig. 3) depend on

- additional equipment and operational costs required,
- quality of capturing and processing the right information into the right decision, and
- precision of application (VRT).

Current SSCM realities

Important tools include positioning systems, sampling and mapping procedures, sensors for continuous measurement of crop yield (yield mapping), on-the-go sensors for continuous measurement of some soil properties, real-time weed and pest damage recognition systems, software and hardware for data storage and decision making, and VRT for precise continuous adjustment of application rates (McBratney and Whelan 1995, Robert et a1 1995b). Appendix 2 summarizes the state-of-the-art for specific components of SSCM.

The degree of variability, the quality of the input information, the approaches used to translate it into application decisions, and the costs associated with differentially managing a field determine the benefits obtained from SSCM. The more variable the environment, the greater the economic and environmental benefit from SSCM will be.

Fertilization is the dominant SSCM application. Fertilizer spreaders or liquid applicators for variable application are readily available in different sizes. Compared to conventional (uniform) fertilizer application, differential application increases the cost by approximately 10-15% (Reetz Jr. and Fixen 1995, Wollenhaupt and Buchholz 1993). Whether gains in net return can be achieved depends on the degree of variability in soil nutrients, the quality of measuring and translating it into an application map (i.e., understanding of the production function), and the precision of application. Increase in net returns is usually lowest in field parts with already high nutrient status. Average increase in profit is highest in fields with a generally low nutrient level.

Weeds tend to be spatially aggregated, making them easier to sense. Decisions about spraying or not spraying or continuous variation of the rate are options for site-specific weed management. Intermittent herbicide applications based on actual infestation can reduce herbicide use substantially (Mortensen et al 1995). The VRT for this is available, but the field sampling required to describe weed seedling populations is a significant limiting factor in implementing this technology. Presumably, variable rate application of pesticides will always require continuous, real-time data acquisition systems (Fig. 3, right) to be fully efficient. Recent developments in sensor or real-time weed recognition technology (Felton et a1 1991, Woebbecke et a1 1995) are promising and we may expect similar solutions for managing insect and disease pests on-the-go. So far, integrated pest management (IPM) in SSCM has not received enough attention.

Other developments include VRT for site-specific soil tillage, anhydrous ammonia application, liming, drill seeding, or sprinkler (pivot) irrigation (Robert et al 1993, 1995b).

Despite all the excitement about new farming technologies such as SSCM, we must be aware of the problems that are associated with them. Schueller and Wang (1 994) present a good summary of some of the considerations for fertilizer and pesticide application. Many of the new tools are impressive, but the currently dominant "discrete" SSCM approach (Fig. 3, left side) has many shortcomings. What if the variability is miscalculated and the application maps fed into the controller are not accurate? What if the applicator cannot react sensitively enough to the variation in soil nutrients? For example, in the variable application of nutrients, the following problems may occur:

1. Error associated with information capture: The current SSCM solutions for fertilizer application are all based on soil grid sampling. Success depends directly on whether the sampling procedures used can actually resolve the spatial variation at a level that allows useful interpolation.

- The largest proportion of the overall variation in available soil nutrients usually occurs over short distances (Beckett and Webster 1971, Burrough 1993). Up to half of the variance within a field may already be

Sophisticated VRT is available, but if used in combination with application maps that are obtained from rather simple procedures with limited accuracy, use of VRT creates pseudo-accuracy. Agronomists must distinguish deterministic sources of yield variability from those that are stochastic.

There are situations where the investment in sampling, sample processing, computing, and variable application will not pay off simply because theoretical assumptions do not hold. This applies to any SSCM technology, whether it is a high-tech one applied to large fields or a low-tech one used in small fields.

Many of the shortcomings associated with the discrete information collection and processing concept (Fig. 3, left) can only be overcome by developing continuous, real-time information collection, processing, and application equipment (Fig. 3, right).

present in any square meter in it (Beckett and Webster 1971).

- Within a single field, magnitudes, scales, and sources of variation are different for different soil properties (Dobermann et a1 1997a, Webster and McBratney 1987). Any “optimal” sampling scheme is only a compromise to obtain information about different soil properties simultaneously. Reliance on soil grid sampling is perhaps the greatest source of error in current variable fertilizer application technologies.
- The soil test chosen may not accurately reflect potential soil nutrient supply.
- The laboratory error may be too large.
- All interpolation techniques will give a map, but the quality of a map is often not known (Burrough 1993). Any map is only a rough model of the reality. Most interpolation techniques smooth the data so that extreme large and small values are made invisible. These extremes may be important. When the sampling distance used does not allow clarification of the most important scales of variation in soil nutrients, interpolation is meaningless and the best estimator of the field nutrient status (and hence crop response to applied nutrient) would be the mean of all samples collected, not an interpolated map representing a pseudo reality.

2. Error associated with interpretation of information: The method used to calculate the application map(s) may be inaccurate.

- Currently, most calculations are based on simple empirical models (fertilizer response curve or nutrient balance/nutrient replenishment concept). Those empirical relationships were often developed over a much wider range of soil types. Are they compatible with site-specific management? Crop response to interactions of nutrients is often neglected and more sophisticated crop models are hardly used because of lack of input data.
- Processing time may be too long. Temporal variability of soil nutrient status may equal or even exceed spatial variability (Beckett 1987, Dobermann et al 1994). If information processing is too slow, the application map is not fully relevant anymore. In the most developed SSCM regions of North America, the minimum time from soil sampling to generation of application map is about 3 days, but is often much more.

3. Application error: The minimum application area (TAD) may exceed the scale at which most of the variability occurs.

- Cruising over the field at speeds of at least 30-40 km h^{-1} with a spread of 21 m within 1 sec, the Terra Gator (see Appendix 2) applies fertilizer in an area of 175-235 m^2. The actual feasible response time for smooth adjustment of the applicator is probably even larger than 1 sec so that any soil variability occurring within 200-300 m^2 is already neglected.

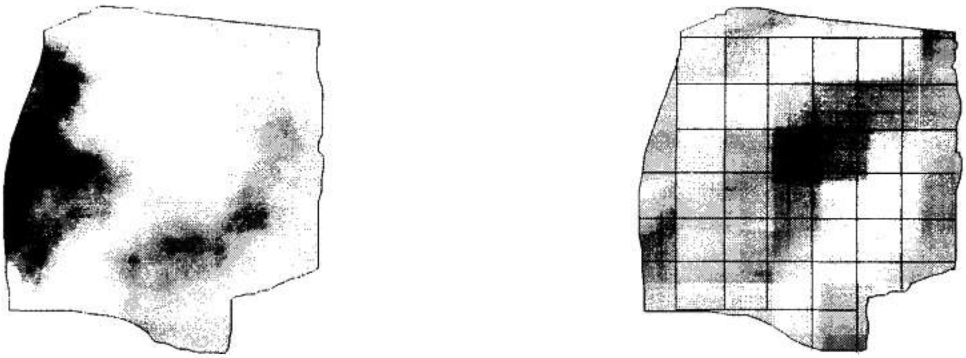
Thus, although new tools are promising, we have to know where we can use them to justify acquisition and operational costs. There is an eminent lack of research on quantitative error assessment in SSCM to (1) distinguish the different sources of errors in all major steps (information capture, processing, application), (2) identify how errors propagate throughout the whole operation, and (3) quantify the precision that is always claimed. The statistical techniques for doing this are available (Heuvelink 1993, Leenhardt 1995), but no such attempt to assess quantitative errors is known to us. These techniques would certainly help to refine SSCM.

Opportunities for SSCM in intensive rice systems of Asia

Is SSCM necessary?

Crop management recommendations over the past four decades in Asia were driven by the increasing use of externally provided inputs and the so-called “package approach’ based on blanket recommendations over wide areas (Byerlee 1996). Should and can we apply the principles of SSCM to manage irrigated rice fields in Asia? We believe that yes we can because recent research in lowland rice areas has demonstrated that

Generally, SSCM in Asia can be built around much less sophisticated technology than implementing SSCM in large fields, where global positioning systems (GPS), mapping systems, computer technology, and VRT are minimum requirements (Fig. 4).



Heterogeneous treatment of a large field according to variation of soil P supply and crop P demand within a single field

1. Create digital maps of soil P supply and maps of past yields [1]
   - Conduct soil grid sampling.
   - Conduct soil P analysis on all grid samples.
   - Translate soil P test values into estimates of soil P supply (kg ha^{-1}).
   - Interpolate soil P supply map from grid values.
   - Measure past yields with high resolution using a yield monitor mounted on a combine and equipped with a global positioning system (directly creates yield map with high resolution, no interpolation).
2. Create digital application map showing the different amount of P to be applied to different parts of the field
   - Estimate amount of P to be applied for each pixel on the map (based on estimates of soil P supply and crop P removal; overlay soil maps and yield maps by using empirical models of fertilizer response for a specific yield target).
3. Apply P using variable rate technology and geo-referencing system (GPS)
   - Feed application map into the computer.
   - Apply varying rates of P according to the position in the field.

Homogeneous treatment of a single small field based on average, field-specific soil P supply and crop P demand (Dobermann 1996)

1. Estimate average soil P supply
   - Conduct soil sampling to obtain one composite sample per field. [2]
   - Conduct soil P analysis on one sample.
   - Estimate potential soil P supply (kg ha^{-1}).
2. Predict amount of P to be applied to the field
   - Estimate amount of P to be applied to the whole field (based on a nutrient supply - nutrient uptake - grain yield model that accounts for interactions between N, P, and K).
3. Apply P using conventional technology

[1] If desired, determinations of other soil properties could also be done to improve the prediction of soil P supply.

[2] If tools for *in situ* measurement of soil P supply are available (resin capsule or P omission plot), no soil sampling is required.

Fig. 4. Managing variability within (large) fields requires different SSCM technology than managing (small) fields on a field-specific basis in which less attention is paid to variability within the field. The detailed steps in application of P fertilizer are shown as an example.

- there is large variability in stable soil properties, soil nutrient supply, nutrient use efficiency, other production factors, grain yield, and economic performance between rice farms or between single rice fields (Angus et al 1990, Cassman et a1 1996, Dobermann et a1 1997a, Dobemann and Oberthuer 1997b, Oberthuer et a1 1996, Olk et a1 1996, Pinnschmidt et a1 1994, Ueno et al 1988), and
- even within very small rice fields, tremendous variation in yields and yield components exists that is caused by microvariation in soil nutrients, land

leveling, crop emergence, weeds, and other pests (Baki 1993, Dobermann 1994, Dobermann et a1 l994, 1995, 1997a, 1997c, Gravois and Helms 1994, Miller 1990, Or and Hanks 1992).

This led us to conclude that significant gains in productivity and input use efficiency can be achieved by soil and crop management technologies that are much more tailored to the specific characteristics of individual farms, rice fields, and variation within fields (Cassman et a1 1997, Dobermann et a1 1996). We are also convinced that the methods for characterizing, interpreting, and managing variability in large fields can also be used for smaller fields found in irrigated rice-cropping systems. Farmers already integrate a lot of knowledge and often already have a sense of the variability they have in fields and crops (eg, which fields are typically weedy, which fields or parts of fields always give a higher yield, etc.). What we need are more reliable tools to support them in their decisions.

Is SSCM feasible?

While much of the purpose of precision farming in developed countries is to break down variability across large fields to smaller uniform units, in Asia much of this division has already taken place due to the typically small farm size. Conceptually, adjusting tillage, sowing, fertilizer, or pesticide rates separately for many small fields or farms (<1 ha to 5 10 ha) in an Asian domain is similar to adjustment according to soil variation within a large field (>10 ha to 2 100 ha) in North America. There is a continuum, however, as there is still variability within these small fields. An "Asian variant" of SSCM in the intensive rice system would probably include operations at different spatial scales and with very different information demand. The first major step is to refine regional recommendations to individual field-level recommendations — further advances can be made in the future to within-field recommendations.

Practical options for SSCM in irrigated rice are very much determined by the general shifts in these production systems, including:

- Labor shortages – fewer agricultural field workers.
- Water shortages for rice – less water for agriculture as urban demands and alternate uses increase.
- Less land for rice production – as cities grow over production areas and alternate land use increases.
- Shifts in rice quality preferences – as economies develop throughout the region, quality preferences will become more important in some countries.

With these trends in the socioeconomic farming environment, we expect to see significant changes in the structure and production technologies of Asian rice farms (Fig. 5). The major scenario is one of technological changes triggered and driven by increasing labor cost for agriculture and socioeconomic changes favoring the formation of relatively larger farms and adoption of mechanized technologies. Land preparation, crop establishment, harvest, and postharvest activities are labor-intensive farm operations and farmers will increasingly seek ways to reduce costs associated with them. They will also seek ways to add value to production by improving the quality of harvest or improving use of various by-products.

There are many linkages between the processes shown in Fig. 5, because they are driven by socioeconomic changes such as the increasing cost of labor and other agricultural inputs or prices for agricultural commodities. In some advanced post-Green Revolution areas such as the Indian Punjab, Thailand, or parts of China, many of these transformations have already started, whereas other regions may not be much affected at all during the next decade.

Ongoing and expected socioeconomic changes in rice farming create opportunities for establishing new, site-specific crop management concepts.

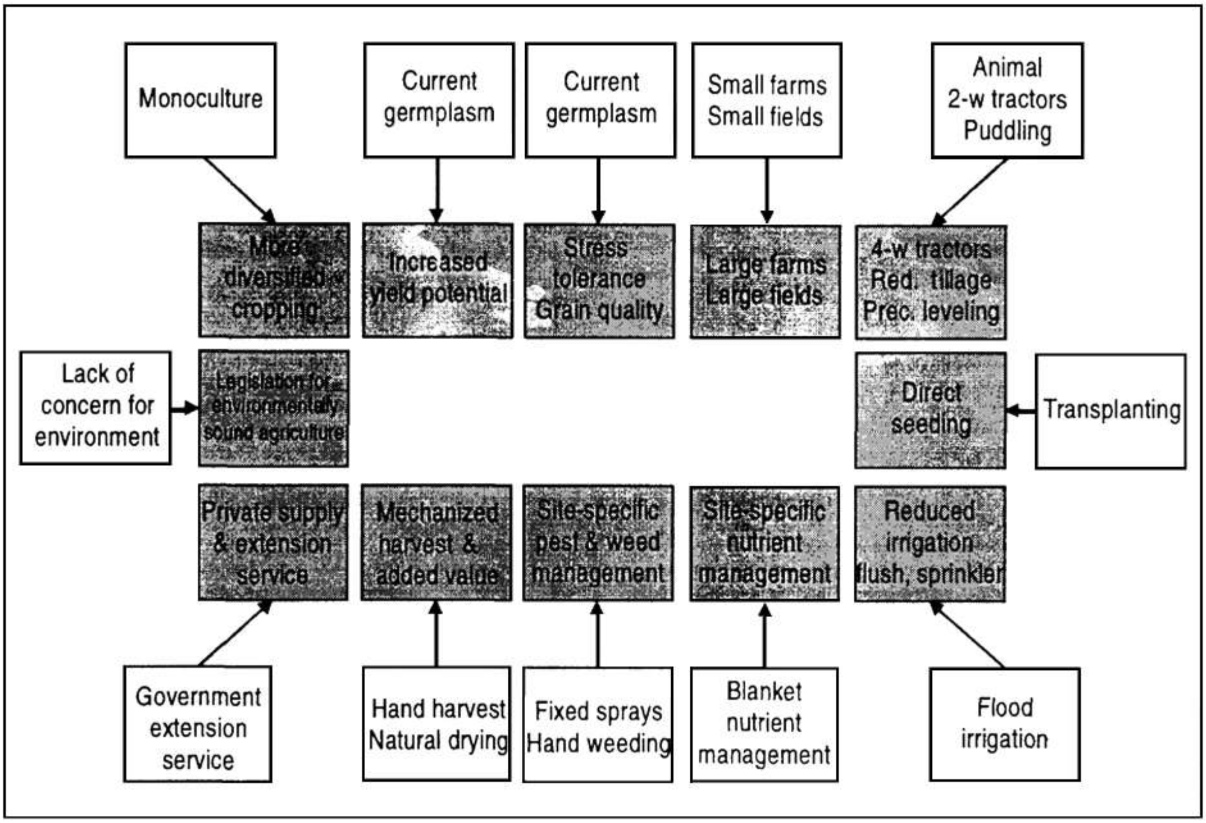


Fig. 5. Pathways of future intensification of soil and crop management in intensive, irrigated rice systems.

The target group: irrigated rice farmers in Asia

To identify potential and suitable technologies for SSCM in irrigated rice, we need to understand the variation in socioeconomic farm characteristics among countries and regions within a country. There are about 30 to 60 million irrigated rice farms in Asia[1] and they differ in their needs for modern farming practices. Appendix 3 shows fundamental farm characteristics for a sample of intensive rice farmers from key irrigated rice domains in South and Southeast Asia (Moya et al 1997). Farm sizes, education, sources of income, labor input, crop management methods, and proportional costs of key production inputs vary widely among regions and within each domain (data not shown).

In this sample, Tamil Nadu farmers represent those with the highest labor input and a very low degree of mechanization. In Tamil Nadu, all rice is still transplanted, pesticide use is low, almost no herbicide is applied, most farmers apply fertilizer in four or even five splits, and most harvest/postharvest activities are done by hand. Intensive crop care resulted in high average yields of 6.4 t ha^{-1} (Appendix 3). As we move from the Mekong Delta to Central Luzon and Central Thailand, we can distinguish a trend of decreasing labor use, increasing mechanization, adoption of direct-seeding, reduction in the number of N split applications, increasing pesticide use, and increasing field and farm sizes. In Central Thailand, farms have become larger than in many other regions, adoption of wet seeding is 100%, soil tillage is

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[1] The total harvested area of irrigated rice is 74 million ha per year. Of this, 22 million ha are cropped with rice-wheat (= 22 million ha physical area), 30 million ha are cropped with rice-rice-rice (about 14 million ha physical area, of which 12 million ha are under rice-rice and 2 million ha are under triple cropping), and 22 million ha are cropped with other rice-based systems (= 22 million ha physical area). Assuming average farm sizes (under rice) of 1 to 12 ha per farm (Table 1), we get (22 + 14 + 22) / (1 or 2) = 29 to 58 million farmers.

done by 4-wheel or at least 2-wheel tractors, pesticides are heavily used (weed control), and combine harvesting is predominant. Thus, total labor input is only 15 person-days ha^{-1} compared with 210 person-days ha^{-1} in Tamil Nadu (Appendix 3).

In the adoption of different SSCM technologies, we can distinguish three major types of rice farms:

Type I: small, labor-intensive farms

Farms (4-2 ha) and individual fields are small (usually <0.2 ha) and mechanization is limited to the use of 2-wheel tractors or other smaller equipment for land preparation. Transplanting is the dominant crop establishment method and harvest is done by hand. Much family labor is involved. The ratio of income from rice and income from other activities may vary widely. Use of production inputs and farmers' decisions depend very much on the financial situation.

In such farms, site-specific management will probably be limited by the low degree of mechanization, limited financial resources for contracting services or buying better inputs, and limited access to the required expertise. There will, however, be options to focus on managing fields on a per-field basis using simple technologies and tools for decision making. We find such farms in regions such as the Red River Delta (Vietnam), Java (Indonesia), and South India, but also in many parts of rural China.

Type 2: small-medium, less labor-intensive farms

Farms (3-5 ha) and individual fields (>0.2-1 ha) are of medium size and mechanization is already more advanced. Land preparation is done by 2- or 4-wheel tractors, many farmers use direct-seeding for crop establishment, herbicides are used for weed control, harvest is done by hand or small combines, and postharvest operations are mechanized. Rice production is a major source of total farm income and much contract labor/rented service is involved. For SSCM, both field-specific operations (basal fertilizer application, sowing, harvest) and managing variability within a single field are feasible (precision leveling using small laser technology; weed, insect, and disease control based on observation; N topdressed application). We find such farms in the Mekong Delta (Vietnam), Central Luzon (Philippines), Central Thailand, Northern India, and Malaysia.

Type 3: medium-large, mechanized rice farms

Farms (>5-10 ha) and individual fields (>1 ha) are larger and most operations are mechanized. Direct-seeding is predominant, 4-wheel tractors are used for tillage, and combine harvesting is common. These are more commercial rice farms where rice is the dominant source of income. A wide range of SSCM technology can be used, including treating fields homogeneously or based on variability within the field for most crop management activities (Fig. 2). These are farms where current SSCM concepts and VRT developed in North America and other countries can be used. In Asia, there are not many rice farms of this type. We might find them, for example, in Central Thailand, Malaysia, and Northern India, or, more recently, as pilot farms in southern China.

Technologies for SSCM in Asia

The issue of application scale (Fig. 1) leads to two questions, namely: (1) Where can large-scale technologies be applied within rice farms of Asia? and (2) What technologies are scale-neutral or particularly suited for small rice farms? For large-scale automated systems, we can draw directly from experience in other countries. However, options for small to medium-scale applications are required.

Within-field management options will depend upon (1) tools and farmer skills available (knowledge capture), and (2) sources of information available to farmers (for

There is no such thing as a "typical" irrigated rice farmer; thus, our recipes for modern farming must be tailored to different groups of farms. Their socioeconomic and biophysical differences determine the choice of site-specific technologies.

Table 1. Examples of technologies for site-specific crop management operations in large and small rice farms.

	Component of site-specific crop management	Technologies for large irrigated rice farms (highly mechanized)	Technologies for small irrigated rice farms (partly mechanized)
Homogeneous treatment of a single field (field-specific application)	Soil tillage	4-wheel tractor	2- to 4-wheel tractor, buffalo
	Crop establishment	Direct-seeding, 4-wheel tractor/aircraft	Transplanting or direct-seeding, by hand, mechanical transplanter, row seeder
	Mechanical weed control	4-wheel tractor	Hand-weeding
	Pesticide application	4-wheel tractor + sprayer, aircraft, field-specific or general recommendation	Hand-held sprayer, field-specific or general recommendation
	Fertilizer application	Conventional machinery or aircraft, field-specific soil test recommendation, plant diagnosis	By hand, general or field-specific recommendation, plant diagnosis (SPAD, LCC)
	Harvest	Combine	By hand or small combine
Heterogeneous treatment according to variation within a single field (continuously varying or patch-specific application)	Soil tillage (depth)	Compaction map-appl. map-VRT[a]	???[b]
	Land leveling	Laser leveling	Laser leveling
	Sowing rate/ planting density	Hydrology map-appl. map-VRT	???, patch-specific variation possible
	Liming	Soil pH map-appl. map-VRT	???
	Basal fertilizer application	Soil NPK map-appl. map-VRT	???, patch-specific variation possible
	Topdressed fertilizer application	Soil N map-appl. map-VRT, or real-time soil or plant sensor-VRT	???, SPAD, LCC could be used for patch-specific application
	Weed control	Weed sensor coupled with VRT or patch-specific herbicide application	Patch-specific hand-weeding/ herbicide application
	Pesticide applications	Real-time damage sensor-VRT	IPM monitoring, patch-specific variation possible based on observation
	Yield monitoring	Combine harvesters with GPS and yield monitor	???, small combine harvesters with GPS and yield monitor not vet used

[a] VRT = variable-rate technology. GPS = global positioning systems, SPAD = soil-plant analysis development, LCC = leaf color chart.
[b] ??? =currently not done.

information interpretation) combined with (3) understanding and availability of management options based on farmers' natural resource base (action options). This may well be a more knowledge-intensive exercise, relative to larger scale applications, because it is likely that at a larger scale there will be more service in the form of private sector input and more prepackaged options.

Going through a set of principal farm operations in irrigated rice cultivation, the important questions are: (1) How can it be done? and (2) Who could do it (farmer, contractor, government)? Table 1 summarizes some of the options for site-specific crop management in rice fields.

Regional SSCM decisions

How? Even in an SSCM approach, recommendations and decisions at regional scales play a role. At scales such as a district, province, or country, important agronomic advice can be given to farmers. Information captured may include (1) information about most suitable varieties for a given environment, (2) general recommendations for soil fertility management based on delineation of soil types, (3) weather forecasting and real-time seasonal variation in weather, and (4) pest forecasting and seasonal variation in pest populations. This would help farmers to make decisions about varieties, seedling age, planting date, fertilizer application, pest management, and harvest time. The major tools involved in this are remote sensing (e.g., high-resolution radar images), geographic information systems (GIS), crop models (Matthews et al 1997, Singh et al 1991), and pest models (Kropff et al 1995, Pinnschmidt et al 1994). Mass media (TV, radio, newspapers) and extension systems are the main information providers.

Who? Government agencies have to provide this "regional technology" so that it can be used by all farmers, regardless of their socioeconomic differences and without imposing additional costs on them.

Variety selection

How? Most rice farmers select their varieties based on knowledge about adoption to site characteristics and agronomic fitness. Most modem varieties released are resistant to some common pests and are also screened for adaptation to soil stresses such as severe P and Zn deficiency or Fe toxicity. There is probably some scope for refining selection of varieties in an SSCM approach for (1) fitness for dry or wet seeding, (2) resistance to pests, (3) nutrient requirements, (4) grain quality, and (5) seed health. In nutrient requirements, better knowledge about the capacity for external nutrient acquisition at different growth stages and information about internal nutrient use efficiency would help in designing balanced fertilization schemes with a high synchronicity for supply and crop demand. This appears to be particularly important in the case of hybrids relative to other modem varieties.

Who? More variety-specific information should be jointly established by breeders, agronomists, plant protection specialists, and postproduction specialists (e.g., millers) and released through the national seed distribution and extension systems. Crop consultants may also play a role in providing this information as part of a more complex SSCM service to farmers.

Land preparation

How? SSCM options for land preparation vary widely. In many small to medium-size farms of Asia, the lowest feasible TAD for plowing with a 4-wheel tractor is a whole field, is., plowing depth would be uniform. Examples of field-specific SSCM decisions include (1) Is there need for plowing and puddling in each rice crop?, (2) Is there need for occasional deep plowing?, or (3) Is precision leveling feasible? During the past 20 years, many farmers have switched to shallow tillage machinery such as hydrotillers. This may lead to formation of shallow plow pans and a reduction in the rooted layer. Sporadic deep tillage to break hardpans and facilitate better root growth and soil percolation is another promising strategy, particularly in rice-nonrice systems (Kundu et al 1996, Yadav et al 1996).

There is much scope for using laser-guided equipment for precision leveling even within small rice fields in direct-seeded areas. Laser leveling has been used in large rice farms in the US, Southern Russia, and Australia for many years, but the equipment is also available for leveling small fields of only about 0.2-ha size (Spectra Precision 1997). The depth of the leveling instrument would vary continuously according to a prescribed cut and fill map so that surfaces with no, unidirectional, or bidirectional slope can be precisely created. This technology offers new opportunities for direct dry and wet seeding because in precisely leveled fields water management is much more uniform so that crop emergence, weed control, snail control, and nutrient management can be much improved. Other options for site-specific soil tillage could be decisions in which fields and which cropping seasons minimum or even zero tillage can be used. Tools and rules for making SSCM decisions about soil tillage need further development.

Who? Presumably, options for site-specific tillage are mostly of interest for managing variability between and within fields in type II and III farms (see earlier). Direct-seeding areas are a primary target area and most of the operations would be contracted out to specialized companies.

Crop establishment

How? Two types of site-specific crop establishment decisions and operations are important: (1) assess whether a (whole) field is suited for a particular crop establishment method, and (2) vary sowing rates or transplanting density according to variation in soil properties and microrelief within a field. Decisions about suitability of a specific crop establishment technology and varying the sowing rate require expert knowledge and basic soil and climatic information. If this information is available, farmers could do field-specific or spot-based variation within a field in either sowing/planting by hand or modified mechanical transplanters or row seeders that allow easy adjustment on the go. For large farms, drill seeders with VRT features are available and can be modified for use in dry-seeded rice.

Who? Although many farmers will follow their own judgment, a more quantitative approach is warranted, which would probably be under the responsibility of the extension service or, if they exist, crop consultants. Access to specialized equipment will likely be through contractors.

Water management

How? Site-specific water management is closely linked with technologies available for soil tillage (e.g., puddling requirements). In particular, precise leveling is the most important factor in efficient irrigation management (Hill et a1 1991), but it would also reduce variability in weed growth, soil properties, and rice growth caused by heterogeneous water flow patterns within fields (Dobermann et a1 1997a). Various kinds of reduced irrigation, including reduced water depth, periodical flush irrigation, or sprinkler irrigation are options, but in most of them a single field would be treated homogeneously. Bypass flow in cracking clays may cause huge unproductive water losses during land soaking, i.e., during initial irrigation flush to achieve water saturation (Tuong et a1 1996). Dry shallow tillage soon after harvesting reduces soil drying and cracking during the fallow period and water need for the subsequent rice crop. In SSCM, soils and fields where this may be beneficial need to be identified. The same relates to decisions about need and type of drainage.

Who? The primary focus is on capture of suitable field- or farm-specific information to make a decision about the most appropriate water management technology. At this stage, we do not know who would be the best choice for this. Shallow tillage of dry soil requires high-powered tractors (preferably 4-wheel) so that this option appears restricted to type II and type III farms with somewhat larger field sizes.

Fertilizer application

How? Site-specific nutrient management in rice requires more quantitative information such as soil tests, leaf N monitoring, and accurate measurements of yields and externally provided nutrient inputs (Dobermann et a1 1996). Therefore, in type I or type II farms it will probably focus on managing between-field spatial variability and temporal variability occurring within 1 yr or growing season. Only in large type III farms can flexible, smaller VRT with application maps (e.g., tractors with disk spreaders) be used if sufficient information is generated. The situation may further improve once equipment with on-the-go sensors becomes fully developed. However, much of this technology exists for preplant or dry field conditions (Appendix 2). Suitable mechanized VRT for application in paddies during the cropping season is still scarce.

In most rice farms, a fertilizer recommendation is probably available only for a single (whole) field or farm or even larger areas. Field-specific decisions about fertilizer rates, types, splits, and application technology are required. However, farmers can easily vary N rates according to observation of actual plant N status by spot application of N fertilizer, i.e., manage within-field variability.

Tools for accurate, affordable field monitoring, data storage, and decision making play a pivotal role in site-specific fertilizer management, and many of them are already available. Examples include mobile soil testing laboratories used in Tamil Nadu, quick soil test kits, dynamic soil tests for in situ nutrient extraction (Dobermann et a1 1997c), chlorophyll meter or green leaf color charts for assessing plant N status (Peng et a1 1996), simple N-management crop models (ten Berge et a1 1997), and nutrient decision-support systems for specifying fertilizer recommendations (Dobermann et a1 1996). Over the shorter term, readily available soil information such as maps, local “soft” knowledge, or simple agronomic soil classification systems may be used to improve fertilizer recommendations at village or district scales.

Who? The huge number of single management units (field, parcel) that must be handled and the demand for quantitative information (e.g., soil testing) create physical limitations. Currently, it seems difficult to conduct soil testing or regular plant monitoring on a field-specific basis or, if done so, their costs per hectare may become too high. In most regions, the demand for service would easily exceed current facilities and the extension systems are inadequate to handle site-specific nutrient management. Training of farmers in information capture (tools) will be required, but government and private agencies will have to play the major role in information capture and processing. Farmers will likely be the ones applying the tools.

Pest management

How? Field-specific decisions may be based on both qualitative and quantitative information. There are three major agronomic options for site-specific management of weeds, insects, diseases, and other pests and they are applicable to all farm types:

- control via combination with other SSCM measures
- homogeneous, prophylactic control (spray the whole field)
- variable rate control based on observation or sensing (spray only on hot spots)

Hand-held sprayers dominate in pesticide applications, and improvements in their design allow more accurate and variable adjustment of rates during field operation. The heavy machinery (or even aircraft) used for variable rate application of pesticides in regions such as North America is only of interest to a few large type III farms.

Precision leveling allows precise water management as one important measure for field-specific weed control, particularly in direct-seeded rice (Williams et al 1990). Weeds, particularly annual species, tend to occur in patches (Baki 1993) so that spot applications or variable rates of herbicides are feasible even when farmers use hand-held sprayers. Identification of suitable post-emergence herbicides will be required for this approach.

Ecologically sound site-specific pest management includes measures such as selection of resistant varieties, reduction in amount of pesticides used, substitution of less hazardous chemicals for more hazardous ones, and use of pesticides or nonchemical control measures based on knowledge of pest pressure. Following an IPM concept, application of insecticides could be restricted to spots with high infestation only, i.e., farmers would use a TAD of much smaller size to manage within-field variation with simple means (Fig. 2). With farm yields in tropical Asia expected to rise to 7-8 t ha^{-1} and more, we will see an increasing need for disease control using fungicides, cultural practices, or improved host-plant resistance (Heong et al 1995). Presumably, most of these are prophylactic measures applied to whole fields with less scope for managing variability within a field.

Who? Unlike in fertilizer management, much of the information required can be captured by observation so that site-specific pest management would mainly be the responsibility of farmers or farm managers. Training to improve farmers' knowledge about capturing information and translating it into application decisions plays a vital role.

Postproduction—harvest and on

How? SSCM can be interpreted in various ways after harvest. First, yield maps such as those being developed automatically by yield monitors (such as in the US, etc.) can be used as guides to refine management both of fields and within a field. They can be used to identify management effects (e.g., variety, fertilizer, rotation, etc.) on yields, and so management can be refined. While yield monitors are not expected to be common except in a few type III farms, good record keeping of yields on a field- or parcel-specific basis could be used to provide such management guidance in small farms.

The second aspect relates to maximizing returns during postproduction. While farmers can see their yield, many of the subsequent effects of their harvest and losses are unseen.

For example, variety, harvest date, and postproduction management (e.g., drying, storage) can have large effects on head rice yields and quality (e.g., discoloration). These factors are essentially hidden from farmers, who will likely lose interest once the grain leaves their farm gate. However, as premiums for quality (taste and head rice yields) become important, they will strive for improvement in postproduction systems and add incentives (if credit systems allow) to maximize the added value of their crops. A major consideration in this is the method of harvest and handling. The major SSCM aspect is, therefore, variety selection and timely (i.e., optimum moisture content) harvest.

Although options for by-product use (e.g., hulls, straw) are generally known, they will require system (total farm) management. For example, straw removal (e.g., integrated animal systems, mushroom production) will require fertilizer substitution and straw enrichment for animals.

Who? Farmers will need greater information on variety effects on quality and effects of harvest time (grain moisture content) and by-product use options. This will require training to improve farmers' knowledge and incentives for the multiple players in the postproduction chain. Mechanized harvest will likely be done by contractors.

Present primary needs

SSCM or precision farming is an emerging, not a mature, management system. As such, there are a number of research and verification requirements. We summarize some of these below (ASAE 1997):

1. Knowledge capture: Identify and quantify (map) the variability of key input parameters at the scale needed to make a decision about the specific SSCM operation.
   - Clarify information to monitor the different scales of production.
   - Identify suitable tools to quantify variation in key information at different production scales.
   - Identify appropriate sensors (more for large-scale VRT).

2. Knowledge interpretation: Translate the information into decisions about management (application) by understanding sources of variability and their impact on yield.
   - Validate response functions to identify optimum management for the range of soil and climatic conditions encountered.
   - Identify what tools are available/needed for information to be interpreted.
   - Identify appropriate crop management options for the different production scales.
   - Improve analysis tools for interpreting yield maps and effects of management decisions.
   - Improve model simulation to predict management effects and on-the-go management options.
   - Improve record keeping for data storage, retrieval, and interpretation.

3. Application: Identify available application technology and optimal size of technology application domain. Apply differential amounts of inputs to the TADs.
   - What technologies are available/needed to apply the treatment?
   - How can the whole approach be communicated and implemented?

4. Communication: Identify who will pass the message and how.
   - Identify improved communication channels to facilitate transfer of precision farming concepts at all levels of resource and production. This has implications for the public (research and extension) and private sectors (dealers and contractors).
   - Identify the effect of changing demographics of farming (e.g., increasing age?).

5. General
   - Identify incentives to adopt technologies.
   - Build in environmental concerns.
   - Ensure compatibility of different system components (primarily for large-scale VRT).
   - Document benefits.

Summary

Historically, institutes such as IRRI have focused on providing global solutions (package approach) based on strategic research, with the local solutions being the responsibility of the NARS (research and extension). This transfer process has not always worked well and at times the science developed has not reached the farmer.

We believe that the components now exist to move from a regional approach to resource management recommendations to the farm- or even field-specific level (i.e., SSCM). This has to include land preparation, crop establishment, water management, pest management, and nutrient management plus all their interactions as the basic components. Such SSCM will help increase production and profitability while protecting the environment. The new system will, however, come with new demands in management and extension expertise. Thus, if the traditional research-extension model had problems, we can expect the system to be even more heavily "taxed" with requirements of a more knowledge-intensive system. In addition to the scientific work required, we have to identify what system will best accommodate the needed changes in information/knowledge transfer and whether new agents of change need to be included in the approach.

In countries where SSCM has evolved, the technology is advancing fast, but the theoretical work has lagged behind. Development of sound procedures for information collection and accurate decision making is insufficient and the long-term biophysical and economic benefits of SSCM remain to be demonstrated. Further, many of the input response functions still have to be verified under a range of conditions. Nevertheless, we believe that the concept of SSCM is right and that many of the initial difficulties can be overcome as the technologies develop.

In China, SSCM may provide the basis for sustaining high rice yields in the coastal regions as well as achieving substantial yield increases in the central and western parts of the country where yields are lower. We believe that SSCM can lead to substantial improvements in input use efficiency (i.e., product/unit input). One important opportunity will be to design integrated farms (e.g., rice-animal) where rice by-product use (e.g., straw) is examined in terms of the optimal flows of nutrients, water, energy, and labor at the whole farm level.

SSCM aims at integrating the knowledge generated by various scientific disciplines into more complex but site-specific guidelines for action at the farm level. The principles of precision farming or SSCM are applicable to farms and fields of any size, including those found in Asia, but the specific technological solutions differ from case to case.

Acknowledgments

Data on socioeconomic farm characteristics (Appendix 3) were collected by researchers from India, Indonesia, the Philippines, Thailand, and Vietnam participating in the Reversing Trends of Declining Productivity (RTDP) project.

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Appendix 1
Currently used definitions

Terms such as precision agriculture, precision farming, prescription farming, site-specific farming, site-specific crop management, soil-specific crop management, farming by soil, local resources management, or knowledge-intensive management are used to describe modem farming concepts that try to find a profitable and sustainable balance between agricultural food production and quality of land and water resources by using more and better knowledge. Some definitions include:

- *"Site-specific crop management* (SSCM) is an information and technology-based agricultural management system to identify, analyze, and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment" (Robert et al 1995a).
- *"Site-specific crop management* is the use of local soil and crop parameters to make precise applications of production inputs to small areas with similar characteristics" (Searcy 1995).
- *"Precision farming* involves collecting and managing information to make practical, economical, and environmentally sound crop production decisions. Site-specific farming embodies the practice of applying crop inputs in each part of a field according to its unique set of conditions..." (Ag-Chem 1997).
- *Precision farming* ..."To optimize the use of soil and water resources and chemical inputs (fertilizers and pesticides) on a site-specific basis." Such management improves farm profitability and protects the environment. (From: "Optimizing Management for Precision Farming: A Systems Approach," Training Program, Gainesville, University of Florida.)
- *Precision farming* "means managing each crop production input — fertilizer,limestone, herbicide, insecticide, seed, etc.—on a site-specific basis to reduce waste, increase profits, and maintain the quality of the environment" (Deere and Company 1997).
- "The basic concept of precision agriculture is to match inputs and practices to localized conditions within a field to do the right thing, in the right place, at the right time, and in the right way" (ASAE 1997).

Appendix 2
SSCM technologies for managing variability in large fields

Real-time positioning systems

Global positioning systems (GPS) and local triangulation between multiple beacons are the two principal technologies for achieving precise positioning of machinery in the field. GPS receivers mounted on equipment (tractor, combine, other equipment) receive signals from a number of geostationary satellites launched by various countries. With differential GPS systems, accuracy of 5 m or less is now a reality and usually sufficient for varying the rate of an application to match conditions in the field (Palmer 1995, Tyler 1993). Sophisticated radio frequency systems such as the Accutrak System allow accuracies in the order of 15 cm and can be used for driving guidance systems (Palmer 1995).

GPS receivers have become very affordable and positioning technology has advanced very fast during the past few years. It is hardly a limiting factor in current SSCM approaches.

On-the-go sensors

Development of on-the-go sensors has focused on yield monitors attached to combines and other harvest equipment. This technology is now very well established and has become affordable for many farmers in North America and other regions. In the United States, about 10,000 combines are already equipped with yield monitors and GPS (P. Fixen, PPI, personal communication) and intensive research continues to develop such devices for a wide variety of crops (Borgelt 1993). Most companies expect new combines to have such equipment as standard.

On the other hand, development of soil or crop sensors as a fundamental component of continuous information processing—application technologies (Fig. 3)-appears to have lagged behind. After some initial results much of this work was taken over by the industry and is now highly secretive. Examples include:

- Single or multiple wavelength sensors that project light into the soil and estimate soil organic matter content based on the energy reflected (e.g., S.M.A.R.T., Tyler, MN).
- The Soil Doctor (Crop Technologies, Inc.), a system tested since 1987. The different models have either rolling electrode systems or electrode-equipped sensor knives. According to the manufacturer, those sensors measure organic matter, soil moisture, and nitrate levels to prescribe and deliver fertilizer on-the-go (Borgelt 1993), but details about the accuracy and performance are not well known.
- Ion selective electrodes or field effect transistors (ISFET) to measure soil nitrate (Borgelt 1993).
- Remote laser sensors for measuring chlorophyll content of plants. Norsk Hydro has recently developed a device that is mounted on the front of a tractor and scans the canopy for chlorophyll content on the go. At the same time, the rate of N application is continuously adjusted to those readings (J. Wollring, Norsk Hydro, personal communication).
- Color index or reflectance-based weed detection sensors (Felton et al 1991, Woebbecke et al 1995).

So far, none of these technologies seems to be in widespread use, but the industry puts much effort into their development. The lack of continuous, mobile devices for sensing soil chemical properties is a major factor limiting the adoption of SSCM (Schueller 1992).

Processing and storage of digital data

When a field is managed as a collection of distinct smaller areas, the number of management decisions is greatly increased. In many cases, farmers will rely on consultants to help implement SSCM (Searcy 1995). Software and hardware needed includes facilities for image processing, geographical information systems, statistical analysis, models for decision making, and graphic displays.

Many products are available. However, most so-called decision support systems (DSS) for SSCM are limited to a rather simple combination of data layers in a GIs. Some of the problems associated with this are discussed below.

Variable-rate technology

The ability to vary application rates while traveling through a field is critical to the SSCM concept. Besides the tremendous advances in positioning systems and computer technology, VRT equipment is probably the best-developed part of SSCM systems (Searcy 1995). The major manufacturers of agricultural equipment have stepped into the business of developing and manufacturing VRT for site-specific management. Depending on the specific SSCM system used (Fig. 3), VRT can be map-based (an application map controls the applicator) or sensor-based (a sensor controls the applicator in a closed-loop system).

Map-based applicators are available for a wide range of agronomic operations, including soil tillage, drill-seeding, or application of granular and liquid chemicals. Sensor-based VRT is not yet widely used (Searcy 1995), but may develop fast.

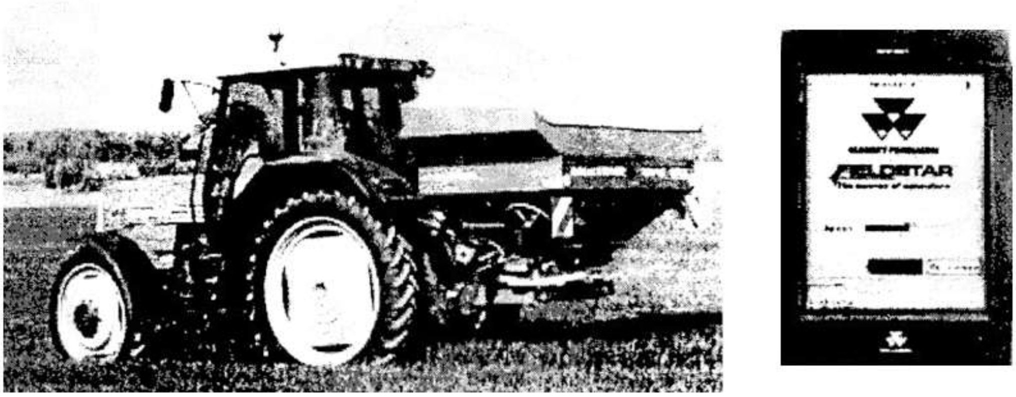
According to design and customer specification, we can distinguish between:

1. Modular designs with an open architecture. These are mostly modifications of conventional equipment in which some of the devices can be combined with different pieces of VRT. Such machinery is usually more flexible and affordable for smaller farmers who often have to switch from one operation to another.

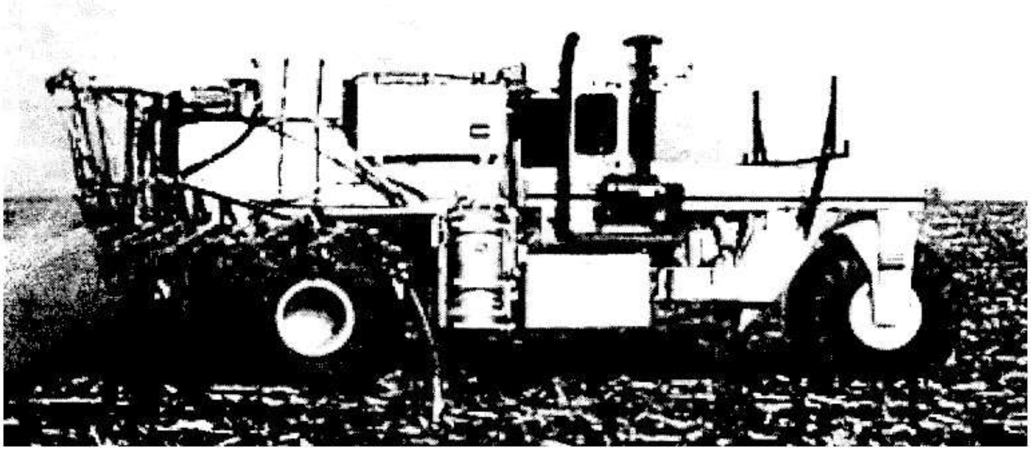
One example of this is the Massey Ferguson FIELDSTAR™ system, in which main components such as the GPS receiver and the Datavision terminal can be easily installed on different tractors or combines. The data terminal is used for storing all field information (application maps, yield maps) and controls specific equipment such as fertilizer spreader, plow, or drill seeder.

2. Highly specific machinery exclusively designed to perform one or a few specific tasks. This is usually large equipment developed for the custom application market and most suitable for managing large fields.

Perhaps the most impressive machine in this category is the Terra-Gator© 1903 with Soilection Twin Bin™ (Ag-Chem 1997). Powered by a 400-hp engine, it applies up to five chemicals (3 granular, 2 liquid) simultaneously in one go, with each chemical continuously varying based on five different field application maps fed into the controller. On a normal work day, this $200,000 machine applies fertilizers and other chemicals on 300 ha, provided the company operating it has enough transport capacity to truck all the fertilizers needed to the field fast enough. Another example is the big laser-guided carryall scraper used for precision leveling (Spectra Precision 1997).



Massey Ferguson FIELDSTAW™ with AMAZONE ZA-M MAX variable fertilizer spreader.



Terra-Gatoa 1903 with Soilection Twin Bin™.

Appendix 3
Characteristics of rice farms in Asia

Selected socioeconomic and performance characteristics of farms in major irrigated rice domains of South and Southeast Asia. Only average data for two cropping seasons with the highest yield potential (dry season) sampled between 1995 and 1996 are shown (based on Moya et al 1996).

	Central Plain Thailand	Central Luzon Philippines	Mekong Delta Vietnam	Tamil Nadu India	West Java Indonesia
No. of farms sampled	26	33	32	28	30
Total farm size (ha)	4.3	2.6	1.1	4.6	1.6
Area planted to rice (ha)	2.1	1.8	0.9	2.1	1.2
Age of household head (years)	46	50	47	46	42
Education (years in school)	5	7	7	10	7
Household size (no.)	5	6	6	6	4
Transplanting (% of area)[a]	0	16	0	100	100
Wet-seeding (% of area)	100	76	100	0	0
Rice yield (t ha^{-1})[b]	4.6	6.4	5.4	6.4	5.5
Total revenue (US$ ha^{-1})	821	2018	847	663	1351
Total costs (US$ ha^{-1})	354	439	268	344	552
Net return (US$ ha^{-1})	467	1579	578	319	799
Factor shares (% of total revenue)					
Fertilizers	11.1	5.5	8.9	13.5	5.1
Pesticides	3.9	1.5	2.6	0.7	2.8
Other inputs"	5.3	5.5	6.2	5.1	4.6
Family labor	5.1	2.2	4.9	1.8	3.3
Hired labor	17.8	7.0	9.2	30.9	25.1
Net return[d]	56.8	78.3	68.2	48.0	59.1
Labor use (8 h person-day ha")					
Land preparation	3.3	9.9	11.7	12.9	20.2
Crop establishment	0.9	7.9	11.0	53.1	19.0
Crop care	4.5	3.9	12.2	99.8	32.0
Harvest/postharvest	6.7	27.9	29.3	44.2	24.3
Total	15.4	49.6	64.2	210.0	95.5
No. of fertilizer applications (%)					
One or two times per crop	42	62	20	0	100
Three or four times per crop	58	38	78	55	0
More than four times per crop	0	0	2	45	0
Pesticide use (kg ai ha^{-1})[e]					
Insecticide	0.84 (92)	0.26 (61)	0.59 (89)	0.51 (59)	0.81 (97)
Herbicide	0.80 (92)	0.39 (96)	0.27 (80)	0.06 (5)	0.87 (97)

[a] Some farmers in Central Luzon practiced both transplanting and wet-seeding so that the total is not 100.

[b] Average yield of two seasons measured by researchers in one farmer's field.

[c] Includes fuel, irrigation, and machine rental.

[d] Includes farmer's surplus and return to land.

[e] The number in parentheses shows the % of farmers using the pesticide.