# On the Economics of Precision Agriculture: Technical, Informational and Environmental Aspects

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A B S T R A C T

The paper presents an integrated framework of biophysical and economic modelling as a novel approach towards precision agriculture research. A theoretical economic model determining the optimal number of precision agriculture management units within a given field of land is presented. The model is expanded to account for the value of the research information provided by precision agriculture researchers. Since the inherent environmental values associated with precision agriculture are often omitted from the economic analysis, an attempt is made to incorporate these values into the model. The versions of the model are empirically tested using the data available.

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## Uniform vs. Heterogenous input management in agriculture

The quest for continually increasing and economically efficient food production has resulted in farmers managing farms of ever increasing size. This has led to uniform management of the agricultural inputs, substituting for the more site-specific management approach of the smaller farms. As the average size of the agricultural fields increased, it became cost effective, technologically efficient and convenient to manage all agricultural inputs at a uniform rate. Although this has brought an undisputable progress in food production, it has also led to mismanagement of resources, land degradation and a host of other environmental problems associated with modern day agriculture. In recent years, the heterogeneity of agricultural land has been recognized as an important factor in agricultural input management, and the site-specific approach to agricultural production has been rediscovered in agricultural and economic literature (McBratney, 1984; Weiss, 1996).

## What is Precision Agriculture?

Precision agriculture may be viewed as a scientific endeavour to improve the management of agricultural production (McBratney and Whelan, 1999). It may also be viewed as an application of information technology in agriculture (Lowenberg-DeBoer and Boehlje, 1996). The concept of precision agriculture is closely related to the site-specific crop management (SSCM) which can be defined as: "Matching resource application and agronomic practices with soil and crop requirements as they vary in space and time within a field" (McBratney and Whelan, 1999). This definition is quite intuitive since it implies that the yield response is not uniform within a heterogeneous agricultural field, but is rather dependent on the spatial characteristics of the smaller areas within the field.

## Problems with precision agriculture

Even though the concept of precision agriculture (PA) is intuitive and straightforward, its adoption in the farming practice has been limited (Bongiovanni and Lowenberg-DeBoer, 2001). This lack of practical application of the site-specific crop management (SSCM) technologies is a result of several factors. First, gathering of information required for devising a SSCM strategy can be quite expensive and time consuming (Akridge and Whipker, 2001). Many farmers are not willing to incur these costs, in expectation of uncertain gains spread over longer period of time. In addition, the gains are usually distributed among a whole range of stakeholders, and are not exclusive to the adopting farmer. Even though the cost of SSCM are diminishing, they are still too high for many farmers to see the profitability of PA. This in particular is the case with farmers of extensive crops, where the value of inputs is generally lower. For example, the PA has been adopted much faster in more input intensive crops (like sugar beets in the Northern Hemisphere) (Daberkow and McBride, 2003), than in extensive crops (wheat, canola, cotton, etc.). In the perspective of Australian agriculture, this implies that the potential for wider adoption of PA may be limited because of the predominant extensive character of the agricultural production.

Another and possibly more important problem with the PA is that the benefits of SSCM are not immediately apparent, are dynamic in nature, and are distributed within the society. The benefits of PA may be divided in three broad categories: immediate private benefits to the farmer, where the profitability of the farm business increases due to SSCM; sustainability benefits (both private and social), where natural resources used in agriculture are maintained at desirable levels over time due to SSCM; and environmental benefits to the society, where the negative environmental impacts from agriculture are reduced due to the SSCM. The problem is that most of the literature, as well as most of the farmers, only account for the first benefit category. In economics parlance there is a "market failure". Because the markets for sustainability and environmental quality are either missing or utterly imperfect, they fail to assign the correct value for these two benefit categories to the PA concept. And when only the most apparent and simplistic benefits are accounted, the PA concept is often found unprofitable and is therefore not applied in practice.

As an application of information technology to agriculture, the PA concept has another aspect that is often overlooked and not accounted for. The research needed to prepare a ground for a possible SSCM is extremely information intensive. In the process, many million of terabytes of information are collected, processed and classified. This information pertains to topographic, soil, hydrological, biological and other characteristics of agricultural land. Even though the research may not immediately result in widespread application of PA technology in practice, the collected information has a genuine value that will eventually emerge as a benefit to the society. This value is overlooked when analysing the profitability of the PA (Lowenberg-DeBoer and Boehlje, 1996).

## Objectives

The objective of this paper is to extend the previous theoretical and applied work in the field of PA to account for broader benefits and beneficial aspects associated with the concept of PA. Specifically, the paper aims to devise a formal criterion (test statistics) that incorporates all benefit categories pertaining to PA technology. This criterion is designed to be used in sequential hypothesis testing to determine whether PA should be used in a given field, and if so, to determine the optimal number of management zones within the filed.

## Previous Literature

The concept of PA has been given much greater attention in the general agriculture and soil science literature than in the agricultural economics literature. The agricultural economics literature has focused on spatial econometric aspects of the PA (Hurley, Malzer and Kilian, 2003) and on estimation of variable yield response functions (Bongiovani and Lowenberg-DeBoer, 2001). In addition, a number of studies conducted partial budgeting analysis, aiming at evaluation of the profitability of SSCM (Redulla et al. 1996; Ostergard 1997). The environmental, sustainability and informational issues have been largely absent from the literature.

The attempts in agricultural and soil science literature have been focused on devising better geostatistical models to describe spatial variability (McBratney and Pringle, 1997). Since the spatial variation and autocorrelation of yield is the main phenomenon characterizing spatial variability, sophisticated models have been devised and reported (Viscarra Rossel et al.). Also, the temporal variability has been modelled as possibly even more important for PA (Mc Bratney et al., 1997). Even though the agricultural literature has long recognized the importance of economics and the environmental values for the assessment of the PA, the attempts in this direction have been only emerging (McBratney, 2001). Some recent articles have set a stage suitable for incorporating economic and environmental values in the PA calculation. McBratney and Whelan, (1999) have proposed the so called "null hypothesis" of precision agriculture as: "Given the large temporal (and spatial) variability evident in crop yield relative to the scale of a single field, the optimal risk aversion strategy is uniform input management." This null hypothesis has a direct economic reference in using the term "risk aversion", which will be of some interest of this paper.[1]

The null hypothesis is presented in a Popperian framework and evidence is sought that will lead to its refute.[2] In the general context of hypothesis testing, the evidence should be succinctly summarized in form of a criterion, or test statistics, for one to be able to make a conclusive judgment about the validity of the hypothesis. McBratney et al. (1997) made a step toward determination of such a criterion, termed "opportunity index for PA". The opportunity index consists of the magnitude of spatial variation, spatial structure, and an economic/environmental component. While the first two components were treated in detail, the economic/environmental aspects were assumed constant and were not modelled in the study.

The present paper builds on the previous work and develops a framework for sequential hypothesis testing. Improved criteria, incorporating economic, environmental and informational aspects are proposed, and used to make judgments about the stated hypotheses. The main contribution of the paper is that it explicitly incorporates all identifiable benefits pertaining to SSCM. Further, the paper devises a formal framework for determination of the optimal number of management zones within a filed, which can be potentially developed in an automated algorithm easily applied in practice.

## On the meaning of Risk Aversion in the Null Hypothesis of PA

To determine a credible decision rule about the SSCM one needs to formulate testable hypotheses. As mentioned, the null hypothesis of precision agriculture has been proposed and has been widely adopted in the agricultural and soil science literature. For

[1] It seems that the term "risk aversion" was used with different meaning from what we are usually accustomed in the economics literature.

the purposes of this paper the proposed null hypothesis has to be modified, to serve as a starting point in a sequential hypothesis test. In particular, the proposed null hypothesis of PA has to be examined with respect to the risk aversion it assumes. In its original version the null hypothesis refers to risk aversion more in the sense of adoption of changes. Here, we formally explore the risk aversion in its pure economic meaning. Risk preferences in economics are usually discussed within the framework of the expected utility theory (Von Neuman and Morgenstern, 1944). In this framework, the expected utility $EU(x)$ is defined as a function of risky outcomes represented by a random variable $x$, usually referring to income. Preferences about the income are based on income magnitude and income variability. In essence, each income magnitude has an associated variability. The attitudes towards risk have to do with the tradeoffs between the magnitude and the variability of income. Three basic cases of attitudes toward risk are identified based on the shape of the expected utility function. Any expected utility function is characterised with $dEU(X) / dx > 0$, implying the usual fact of life that more income is preferred to less. The attitudes toward risk are defined by the curvature of the expected utility. In particular, $d^2 EU(X) / dx^2 > 0$, implies risk taking, in a sense that some sure income would be traded for increase in income variance (increased prospects of high incomes). If $d^2 EU(X) / dx^2 = 0$, it implies risk neutrality, in a sense that the agent is indifferent between a sure income and the variability of income. If $d^2 EU(X) / dx^2 < 0$, it implies risk-aversion in a sense that some sure income would be traded for a decrease in income variance (decreased prospects of low incomes). This last situation is what is usually assumed for individuals, and most certainly for farmers. Risk averse individuals (and farmers in particular) seek to decrease the probability of bad outcomes (low income) by buying insurance. Decreasing the probability of bad outcomes is directly related to decreasing the variability of income. From a perspective of precision agriculture, if the SSCM is reducing the variability of income, it will be seen as a preferred management choice for risk averse farmers. The question to be answered then is whether the PA reduces the variance of farm income? It would be plausible to think that PA management would reduce the variability of yield, but the effects on the net income to the farmers would depend on the cost structure of the PA technology. This is an avenue for another

[2] Science may be defined as: "a collection of not yet rejected null hypotheses".

research, which is beyond the scope of the present paper. For now, we just modify the null hypothesis of PA, excluding to term risk-aversion. The meaning of "risk aversion" as an aversion towards management change will probably continue to be used in non-economic literature.

Formulating Hypotheses

A further modification to the design of the PA hypotheses is to consider the alternative hypothesis against which the null will be tested. Some proposed alternative hypotheses have not been specific enough, only stating that SSCM would be an improvement over the uniform management (McBratney and Whelan, 1999). This type of alternative hypothesis does not describe how exactly will the SSCM be implemented, and in particular does not describe the number and the type of management zones that would be optimally used. Another, more specific alternative hypothesis is needed, which will address the type and number of SSCM zones. There are two types of SSCM, discrete management zones and continuous management (McBratney and Whelan, 1995). The null hypothesis should be tested against each of these two types of management.

Based on this, the following modified null hypothesis of PA is proposed:

*$H_o$ : Given the large temporal and spatial variability evident in crop yield relative to the scale of a single field, treating the field as a single management zone (uniform input management) is optimal.*

This null hypothesis will be tested against two alternative hypotheses simultaneously. One alternative hypothesis (applying to the discrete management zones approach) is:

*HA1: Given the large temporal and spatial variability evident in crop yield relative to the scale of a single field, managing the inputs in two different management zones is optimal.*

The other alternative hypothesis (pertaining to the continuous management approach) is:

*HA2: Given the large temporal and spatial variability evident in crop yield relative to the scale of a single field, continuous input management is optimal.*

The possible outcomes from this hypothesis test and their implications are summarised in the Table 1.

Table 1. Outcomes and Implications of testing the Modified Null Hypothesis of PA.

| Outcome | $H_0$ not rejected | $H_0$ rejected in favour of HA1 | $H_0$ rejected in favour of HA2 | $H_0$ rejected in favour of both HA1 and HA2 |
|---|---|---|---|---|
| | | | | |
| Implication for PA | Uniform is optimal | Uniform is not optimal, but continue with testing to determine the optimal no. of management zones | Uniform is not optimal, and continuous management is optimal | Uniform is not optimal, but continue with testing to determine if greater no. of management zones are optimal ; or if continuous management optimal |

Inspecting the possible outcomes and implications suggests that more than one test is quite likely needed to determine the optimal number and type of SSCM. Therefore, a sequential hypothesis test need to be performed (Johnsson, 2003).

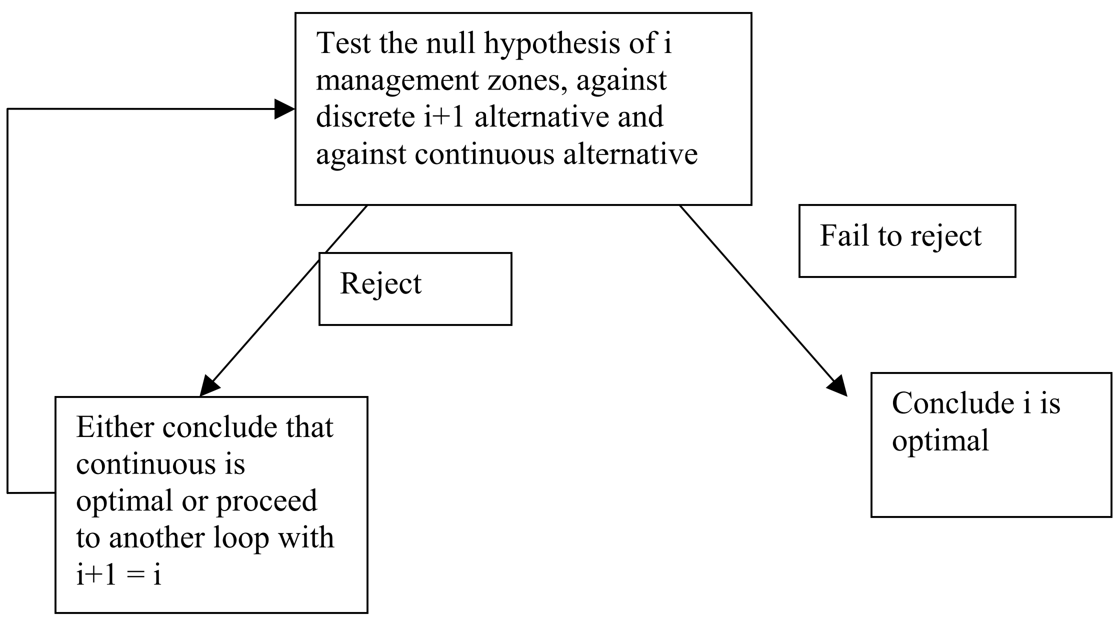
To illustrate this, suppose that the null was rejected in favour of both alternative hypotheses. The next step would than be to adopt the original HA1 as a new $H_0$ and to test it against the HA2 and a newly formulated HA1: *Given the large temporal and spatial variability evident in crop yield relative to the scale of a single field, managing the inputs in three different management zones is optimal*. The possible outcomes and implications of this hypothesis test are summarised in Table 2.

Again there are several possible outcomes, and a sequential hypothesis testing could be run over and over again until the null hypothesis has not been rejected, or other decisively conclusive result has been obtained. An algorithm for doing this sequential hypothesis test could be approximated by the Figure 1. Following the procedure presented in this algorithm will lead to determination of an optimal number of management zones or the optimality of continuous management.

Table 2. Outcomes and Implications of testing the Modified Null Hypothesis of PA in the second loop

| Outcome | $H_0$ not rejected | $H_0$ rejected in favour of HA1 | $H_0$ rejected in favour of HA2 | $H_0$ rejected in favour of both HA1 and HA2 |
|---|---|---|---|---|
| | | | | |
| Implication for PA | Two management zones optimal | Two management zones are not optimal, but continue with testing to determine the optimal no. of management zones | Two management zones are not optimal, and continuous management is optimal | Two management zones are not optimal, but continue with testing to determine if greater no. of management zones are optimal ; or if continuous management optimal |

Figure 1. Graphical Representation of the Sequential Hypotheses Test Algorithm.



The criterion for hypothesis tests

The concepts developed so far, although novel, are quite straight forward. The main challenge in the PA debate is to devise an adequate criterion that will be used to assess the truthfulness of the tested hypothesis. This criterion would in effect be used as a test statistics in the proposed hypothesis testing framework. As noted above, it is necessary that this criterion encompasses all aspects of PA concept, spatial and temporal variability of yield, profitability of the agricultural enterprise, sustainability of the resource use (soil, water), environmental and informational aspects. In the usual statistical tests the test statistics are computed, their theoretical distribution is assumed and the value of test statistics are than compared to some critical value from the assumed distribution. For the purposes of this study strict statistical tests are not conducted, but rather only the broad concept of scientific hypothesis testing is used. The criteria are designed for each of the three hypothesis tested in a single loop of the sequential testing. The criterion for the initial null hypothesis (uniform treatment) may be represented by

$$(1.1) \qquad \max_{\mathbf{x}_t} TB_0 = \sum_{t=1}^{\infty} \frac{1}{(1+r)^t} \left[ E_{t-1} Py_t \, f_t\left(\mathbf{x_t}, \mathbf{z_t}(\mathbf{x_t}), \boldsymbol{\varepsilon}_\mathbf{t}\right) - \mathbf{c_t x_t} \right] - EDC_t\left(\mathbf{x_t}, \mathbf{z_t}(\mathbf{x_t}), \boldsymbol{\varepsilon}_\mathbf{t}\right)$$

s.t.

$$(1.2) \qquad y_t \le f_t\left(\mathbf{x_t}, \mathbf{z_t}(\mathbf{x_t}), \boldsymbol{\varepsilon}_\mathbf{t}\right)$$

$$(1.3) \qquad \sum_{t=1}^{\infty} \mathbf{z_t}(\mathbf{x_t}) \ge \mathbf{Z}$$

where the choice of the vector of controlled inputs **x** in each year *t* has to be made so as to maximise total benefits from the given agricultural enterprise under the uniform input treatment ($TB_0$), which represent a sum of all future discounted profits to the farmer net of environmental damage costs $EDC_t(\mathbf{x_t}, \mathbf{z_t}(\mathbf{x_t}), \boldsymbol{\varepsilon}_\mathbf{t})$ . Expectations about output price ($Py_t$) are made in each prior period ($E_{t-1}$). The output ($y_t$) is a function of controlled inputs ($\mathbf{x_t}$), uncontrolled inputs ($\mathbf{z_t}(\mathbf{x_t})$) influenced by $\mathbf{x_t}$, and uncontrolled inputs ($\boldsymbol{\varepsilon}_\mathbf{t}$) independent of any agronomic influence. Affected uncontrolled inputs ($\mathbf{z_t}(\mathbf{x_t})$) (soil structure, pH, organic matter content, salinity etc.) are subject to the sustainability constraint which is assumed to be a social goal, whereby the level of these inputs is not allowed to drop below some desired value **Z**. *r* represents a discount rate. The environmental damage costs are a function of all managed and unmanaged inputs. Although this function is often difficult to estimate, some new advances to be discussed further below offer such opportunities.

The criterion for discrete management zones hypotheses may be represented by

$$(2.1)\ \max_{\mathbf{x_{it}}} TB_i = \sum_{i=1}^{n} \sum_{t=1}^{\infty} \frac{1}{(1+r)^t} \begin{Bmatrix} \left[ E_{t-1} P y_t\, f_{it}\left(\mathbf{x_{it}}, \mathbf{z_{it}}(\mathbf{x_{it}}), \boldsymbol{\varepsilon}_{\mathbf{it}}\right) - \mathbf{c_{it}}^T \mathbf{x_{it}} - c_{pa}(n) \right] - \\ EDC_{it}\left(\mathbf{x_{it}}, \mathbf{z_{it}}(\mathbf{x_{it}}), \boldsymbol{\varepsilon}_{\mathbf{it}}\right) + VI\left(n, \mathbf{x_{it}}, \mathbf{z_{it}}(\mathbf{x_{it}}), \boldsymbol{\varepsilon}_{\mathbf{it}}\right) \end{Bmatrix}$$

s.t.

$$(2.2)\qquad y_{it} \le f_{it}\left(\mathbf{x_{it}}, \mathbf{z_{it}}(\mathbf{x_{it}}), \boldsymbol{\varepsilon}_{\mathbf{it}}\right)$$

$$(2.3)\qquad \sum_{i=1}^{n} \sum_{t=1}^{\infty} \mathbf{z_{it}}(\mathbf{x_{it}}) \ge \mathbf{Z} \qquad ,$$

where a choice of input quantity **x** in each management zone *i* and in each year *t*, for a given number of management zones *n*, has to be made so as to maximize total benefits. Total benefits are composed of a sum of discounted farmers profits net of environmental damage costs $EDC_{it}$ ($\mathbf{x_{it}}, \mathbf{z_{it,}}(\mathbf{x_{it}})\ \boldsymbol{\varepsilon}_{\mathbf{it}}$) and the cost related to the use of precision agriculture ($c_{pa}(n)$) plus the value of the information provided by the non-uniform management of the agricultural field $VI$ $(n,$ ($\mathbf{x_{it}}, \mathbf{z_{it,}}(\mathbf{x_{it}})\ \boldsymbol{\varepsilon}_{\mathbf{it}}$). The output is now determined by a site-specific yield response function $f_{it}$(($\mathbf{x_{it}}, \mathbf{z_{it,}}(\mathbf{x_{it}})\ \boldsymbol{\varepsilon}_{\mathbf{it}}$). This function is characterised with spatial and temporal variability, determined by $z_{it,}$and $\varepsilon_{it}$. The yield variability has two important implications with respect to the optimal number of the management zones. First, if the variance of yield across time and space in the field is low than managing inputs non-uniformly would not be very beneficial while it would require additional cost This has been previously measured as a magnitude of variation (McBratney et al. 1997). Second, if the spatial covariance structure exhibits high level of correlation, low number of management zones would be optimal which will presumably result in lower cost. This has been previously measured as a spatial structure. Everything else equal, there would be some threshold for the spatial covariance structure for which it would be optimal to manage inputs non-uniformly.

The criterion for continuous site specific management may be represented as

(3.1) $$\max_{\mathbf{x}_{it}} TB_c = \int_1^n \int_1^\infty \begin{Bmatrix} \left[ EPy(t) f\left(\mathbf{x}(n,t), \mathbf{z}(\mathbf{x},n,t), \boldsymbol{\varepsilon}(n,t)\right) - \mathbf{c}^T \mathbf{x}(n,t) - c_{pa}(n) \right] - \\ EDC\left(\mathbf{x}(n,t), \mathbf{z}(\mathbf{x},n,t), \boldsymbol{\varepsilon}(n,t)\right) + VI\left(n, \mathbf{x}(n,t), \mathbf{z}(\mathbf{x},n,t), \boldsymbol{\varepsilon}(n,t)\right) \end{Bmatrix} dn\, dt$$

s.t.

(3.2) $$y \le f\left(\mathbf{x}(n,t), \mathbf{z}(\mathbf{x},n,t), \boldsymbol{\varepsilon}(n,t)\right)$$

(3.3) $$\int_1^n \int_1^\infty \mathbf{z}(\mathbf{x},n,t)\ dn\ dt \ge \mathbf{Z}$$

The meaning of the symbols are the same as in the discrete management zones case, except that now the symbol *n* denotes the resolution of the continuous input management which is determined by the technical characteristics of the application equipment.

Once these criteria are determined they can be used in hypothesis testing in the following manner. To test the null hypothesis of uniform treatment against the alternative of two management zones one has to set $i = 2$ in equation 2.1 and compare the values for $TB_0$ and $TB_i$ . If $TB_0 > TB_i$, one can not reject the null hypothesis and has to conclude that the uniform management is an optimal strategy. If $TB_i > TB_0$, then the null hypothesis can be rejected and the sequential hypothesis testing continues by setting i =3 in Eq. (2.1) and comparing $TB_2$ with $TB_3$ and $TB_c$, and so forth.

The stated criteria represent solutions to optimisation problems. In essence, the criteria are computed by choosing optimal input quantities. The accuracy of the optimisation is dependent on the yield response function which in turn is dependent on the number of management zones within the field. If the input is supplied uniformly, than the response function will only represent the average response over the whole field. Within the field, there will be some areas that are more responsive to the input, some that are not responsive at all, and some that indeed respond negatively. This has a significant impact, not only on profitability but also on the environmental implications. As the number of management zone increases, while still remaining discrete, the average responses get more and more precise, but they are still average rather than marginal responses. The marginal response, at the highest level of precision is obtained only with the continuous input management.

Methods and Data

The discussion about the methodological treatment of the proposed criteria for hypothesis testing is conducted on the separate components of these criteria. For each component, the method of the empirical analysis and description of the available data and further data needs are outlined.

Yield response function

The majority of empirical studies in both agricultural and economic literature have focussed on determining the site specific response functions as a first step towards the evaluation of the PA concept. This is quite logical, since PA would likely be beneficial only if the responses to inputs vary spatially within the fields and across time. If the responses were fairly constant across space and time, there would be little need for SSCM. Suppose that we maintain that the response is indeed uniform and that it is only affected by the level of controlled inputs. In addition, the usual assumption is that other factors (uncontrolled inputs like weather, soil characteristics etc.) affect the yield in a uniform manner (i.e. independent of space and time). This leads to the following usual specification: $y = f(\mathbf{x}) + \mu$, where $y$ represents yield, $f(\bullet)$ represents a production function (often assumed to exhibit decreasing marginal productivity), $\mathbf{x}$ is a vector of controlled inputs and $\mu$ is a random error term (usually assumed to follow a normal distribution with mean zero). This is in contrast with the one proposed here $y_{it} = f_{it}\left(\mathbf{x_{it}}, \mathbf{z_{it}}(\mathbf{x_{it}}), \boldsymbol{\varepsilon}_{\mathbf{it}}\right)$ (rewritten from Eq. 2.2). In the site specific approach these are represented with $\mathbf{z_{it}}(\mathbf{x_{it}})$ and $\boldsymbol{\varepsilon}_{\mathbf{it}}$. In general one can say that a yield response function is composed of five components: input effects (fixed), spatial effects (fixed and random, like soil type, pH, OM etc.), temporal effects (random, like rainfall, temperature), various kinds of interactions between these three components, and a true random error due to measurement and approximation imprecision. Another theoretical aspect is to distinguish between uncontrolled inputs that are affected by the controlled input choice (pH, OM) and the purely unaffected inputs (weather, soil type etc.). However, even though the data related to SSCM are becoming more abundant, the data on the uncontrolled inputs is still rare.

Using the yield monitor data, one could really only model the spatial variability by using the spatial coordinates as explanatory variables in addition to the input variable. Since the yield monitor data from an experiment with three nitrogen application rates management zones and four control strips within each zone was available, the yield response function estimated for the purposes of this study was formulated as

(4) $$Y\left(E,N,X\right)=\alpha_0+\alpha_1 X+\alpha_2 X^2+\alpha_3 E+\alpha_4 N+\alpha_5 E^2+\alpha_6 N^2+\alpha_7 ENX+\mu,$$

where $X$ represents the urea application rate, $E$ represents easting coordinate (with minimum subtracted to prevent numerical overflow), $N$ represents northing coordinate and $\mu \sim N(0,\sigma^2\Omega)$ is a random error term. This mean equation was estimated using maximum likelihood. Because the variability of the yield is of great importance, the variance equation is also specified, by using a spherical model to relate the variance of the residuals to the in-field distance. The spherical model is of the following general form

(5) $$\gamma(h)=\left\{\begin{array}{ll} 0 & h=0 \\ C_0+C\left[\frac{3}{2}\left(\frac{h}{a}\right)-\frac{1}{2}\left(\frac{h}{a}\right)^3\right] & 0<h<a \\ C_0+C & h>a \end{array}\right\},$$

where $\gamma(h)$ is the variogram, $h$ represents distance in meters, $a$ is the lag in meters, and $C_0$ and $C$ are parameters to be estimated. Specification of the covariance structure of the yield residuals takes care of both spatial autocorrelation and heteroscedasticity.

Cost structure

The cost of sorghum production was adopted from the partial budgets published by the Department of Agriculture of NSW. Since the available data was on the sorghum yield the expected price of sorghum had to be specified. The price data was obtained from ABARE. The cost of SSCM varies greatly with the number and type of inputs that are managed on site specific basis, and with the number of management zones within a field. There is not a reliable data on the cost of the SSCM, and the estimates have to be based on the anecdotal evidence and the experience of the precision agriculture professionals. For example, simple division of a field in two or three management zones with respect to fertiliser application will typically cost very little. The main cost would be in the need to change the speed of the applicator. Based on evidence from certain farms, these costs were estimated at about $1/ha. These costs will increase as the number of management zones increases. The exact dependence of the costs of management on the number of management zones is not known at the present, and will need to be assessed on the case by case basis for any specific field.

With respect to the continuous SSCM, there are currently several commercial providers that offer the service of continuous spatial management of fertiliser application. Based on information obtained from farmers, the cost of managing fertiliser continuously is approximately $10/ha.

Gathering of the required information in terms of GPS monitoring, research, data evaluation, soil and yield data maps is also commercially offered. Again, based on anecdotal evidence, the cost of this information is estimated at about $8-10 / ha.

Pooling the costs of management and the cost of information together, the total cost of SSCM at a given field would vary between $2-25 per hectare, and would be dependent on the various characteristics, including field size and topography, type and number of management zones, type and number of managed inputs and other characteristics.

Environmental Damage Costs

As specified in the above criteria, the costs of environmental damages from an agricultural activity are a function of the controlled and uncontrolled inputs to that activity, and their interactions thereof. Stable social preferences are assumed in the specification. Going in further detail, the environmental cost function could be separated in two subsequent segments. First there is a pollutant emission function, which relates controlled and uncontrolled inputs to the amount of emission of pollutants from a given agricultural activity. The second segment is the costs of damages caused by these emissions. This can be written as

(6) $$EDC_{it}\,(\mathbf{x}_{it}, \mathbf{z}_{it,}(\mathbf{x}_{it})\, \boldsymbol{\varepsilon}_{it}) = DC_t(E_t(\mathbf{x}_{it}, \mathbf{z}_{it,}(\mathbf{x}_{it})\, \boldsymbol{\varepsilon}_{it}),$$

where $DC_t$ (•) is a damage cost function, and the $E_t$(•) is a pollution emission function. The pollution emission functions are difficult to estimate and generalise, due to the specific nature of every agricultural field and the associated complex processes. The pollution emissions are usually simulated with many available computer simulation models (EPIC, APEX, SWAT etc.) (Ancev, Stoecker and Storm, 2003). These simulation models are utilised to numerically determine the relationship between the inputs and the pollution emissions from the agricultural activities on a field or watershed basis. Based on these simulations, one would be able to derive a pollution emission function and use it to calculate the environmental damage cost function.

The costs of environmental damages are also very difficult to assess. The economic literature has been quite silent on this issue, since it involves some serious estimation problems. Usually, there are two types of values considered in assessing environmental aspects, use and non-use values. Use values are based on the utilitarian values of environmental quality, clean drinking water, clean air, clean lakes and seas for fishing and swimming, etc. Some of these use values are traded in the markets and their value can be therefore easily determined using the available market information. For other use values, even though direct market information may not be available, their values can be derived from related market information, through the so called revealed preference methods of Hedonic Pricing and the Travel Cost Method. If the majority of the environmental values involved is composed of the use values there are relatively inexpensive methods and techniques to measure the costs of environmental damages (Ancev, Stoecker and Storm, 2003).

The things get more complex when the non-use values are dominant. Non-use values refer to environmental features that people value, even though there is no direct use of these features. These non-use values have to do with the existence (just knowing that the Great Barrier Reef (GBR) exists and is in good health is of value to some person who will never even visit it), bequest (I want my children and their children to be able to also enjoy the GBR), and option (there is a potential that some currently not used feature of the environment, may become useful in the future). The techniques to estimate these values are expensive, complex and often imprecise. These techniques for valuation of the non-use values rely on creation of hypothetical markets through the stated preferences approach. The contingent valuation method is based on surveys that are used to elicit individuals willingness-to–pay for non-use environmental values.

Even though the valuation of the costs of environmental damages is complex and sometimes time consuming and expensive endeavour, it offers a possibility to arrive at a reasonable estimate for environmental damages. The main issue limiting this approach is the data availability. More and better biophysical data is needed to improve the simulation models of pollution emission functions. The data could be obtained either by intensive sampling, which may be quite expensive, or by some proxy method. These methods could be computerised simulations, or just approximation of the nutrient losses, by accounting for example, for the protein content in the yield. In addition, improvements in the economic models for valuation of use and non-use value are also required. In combination with better data on recreational visitations, hedonic prices, and better survey techniques, this will lead toward more precise estimation of the cost of environmental damages from agricultural activities.

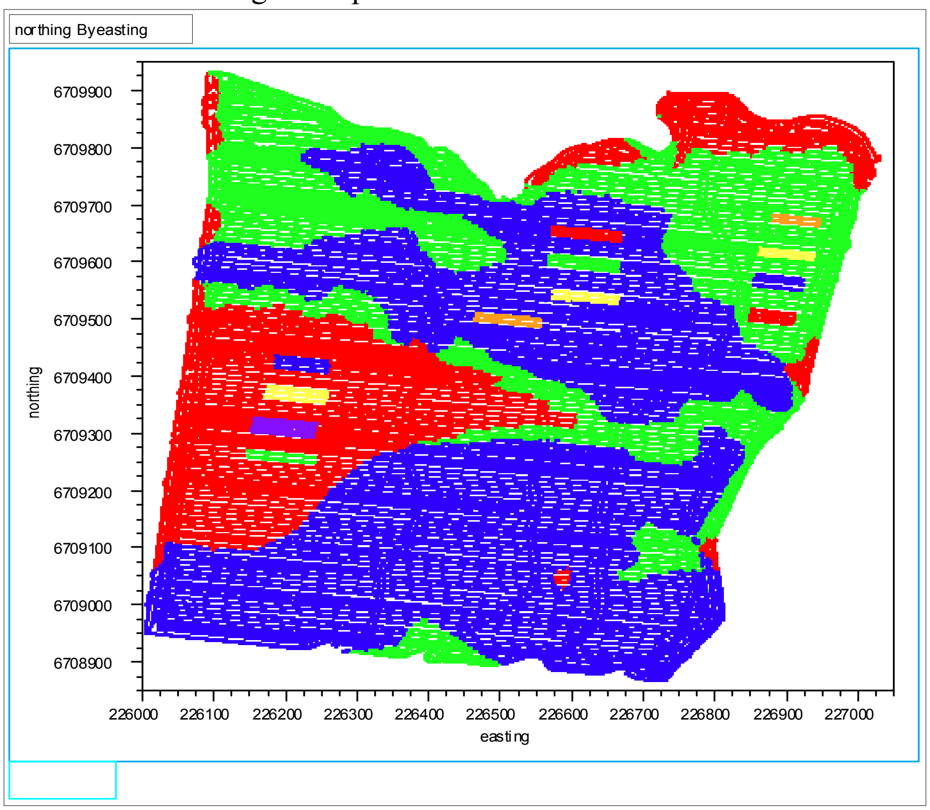
Value of the PA Information

The value of information is difficult to quantify in monetary terms, especially ex-ante (before the actual hypothesis test). An ex-post value of the information could be obtained by simply finding the difference between the optimal management and uniform management. If the information is gathered and it turns out that the uniform management is optimal than the cost of information gathering can not be directly justified. A broader social justification of these costs may be present in terms of increased amount of information available for further broadening of the knowledge (Lowenberg-DeBoer and Boehlje, 1996). It is nevertheless desirable to conduct a detailed data gathering on the agricultural fields where there is good indication that the SSCM may be optimal. Therefore, a pre-screening should be undertaken, whereby information on soil heterogeneity, topographic heterogeneity and historic within field yield variability will be considered before conducting a full fledged PA data collection. In addition, an initial assessment of the environmental impacts of the given agricultural activity should be undertaken. The value of PA information will tend to be greater for heterogenous fields with associated pollution problems.

An example

Yield monitor data was collected from a field on the "Romaka" property in West Creek, NSW. A variable rate nitrogen application experiment was run on sorghum in 1999-2000 growing season. The field was divided on three management zones, within which the nitrogen treatment was uniform. In each of this three zones, strips of other four nitrogen fertiliser rates were applied. This is represented in Figure 1.

Figure 1. Zone and Nitrogen Strips Delineation of the Field




The red colour represents zone 1 with 160 kg/ha of Urea. Green colour represents zone 2 with 220 kg/ha Urea, while blue colour represents zone 3 with 250 kg/ha. Within each zone, there were additional four fertiliser treatments represented by the following colours: Yellow (30 kg/ha Urea), Purple (85 kg/ha Urea) and Orange (300 kg/ha Urea). The results from the yield monitors for the three main zones are presented in Table 3.

Table 3. Yields From each of the Main Zones

| Zone | Urea Application | Yield | Standard Error |
|---|---|---|---|
| | kg/ha | t/ha | t/ha |
| 1 | 160 | 3.91 | 0.78 |
| 2 | 220 | 5.12 | 0.89 |
| 3 | 250 | 5.96 | 0.94 |

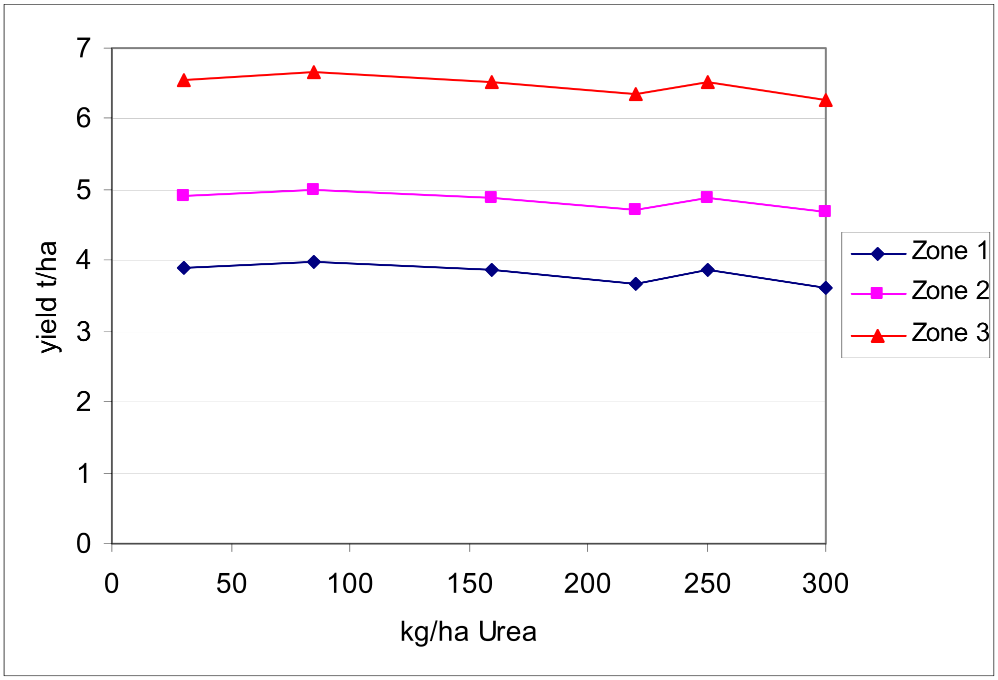
These results suggest that the division of the management zones was successful and optimal, since the yield in each zone is significantly different from the other zones. Also, it appears that the responsiveness to nitrogen fertilisation rate is quite significant. These conclusions are erroneous, however. To see this, the results for the fertilisation strips are displayed in Table 4.

Table 4. Yields Variable N rate Experiments

| Zone | Urea Applied | No. of observation | Yield | St. Dev |
|---|---|---|---|---|
| 1 | 30 | 147 | 3.95 | 0.44 |
| | 85 | 142 | 3.98 | 0.56 |
| | 160 | 419 | 3.96 | 0.61 |
| | 220 | 105 | 3.47 | 0.53 |
| | 250 | 124 | 3.60 | 0.41 |
| 2 | 30 | 109 | 4.83 | 0.40 |
| | 160 | 124 | 4.36 | 0.81 |
| | 220 | 463 | 4.72 | 0.79 |
| | 250 | 139 | 4.71 | 0.81 |
| | 300 | 86 | 4.69 | 0.74 |
| 3 | 30 | 152 | 6.55 | 0.71 |
| | 160 | 158 | 6.65 | 0.57 |
| | 220 | 218 | 6.41 | 0.65 |
| | 250 | 770 | 6.61 | 0.62 |
| | 300 | 175 | 6.78 | 0.60 |

Based on these results, a response function was estimated for each zone, first only as a function of nitrogen application rate. The estimated response functions are represented in Figure 2.

Figure 2. Estimated yield response functions to Urea application




As the figure suggests, the response is fairly linear and it appears that the optimal urea application rates are the same across the three zones. In particular, in each zone the optimal profit maximizing application rate was determined at around 70 kg/ha urea. This suggests that the uniform treatment would be an optimal management strategy for this field. The formal hypothesis testing, following the previously described method, supports this finding, with the $TB_0$ (the criterion for uniform treatment) being \$217.45, and the $TB_3$ (the criterion for three zones) being \$99.22. The value of environmental damage cost and the value of information were not directly estimated due to lack of data. Nevertheless, some indication about their beneficial impact is given by several facts from this exercise. First, if it were not for the conducted experiment, the usual Urea application rate on this particular field would have been around 210 kg/ha (around 100 kg/ha N). Application at this rate, would not only result in profit losses (with calculated $TB_0$ at 210 kg/ha Urea being 77.45), but would also result in significant potential for pollution via nitrate leaching and runoff. This reflects the indirect benefits of the PA research. Even though in this instance, the SSCM was not found optimal, an optimal uniform rate was determined in the course of the research, which if adopted would both increase farmers profitability and decrease the environmental problems associated with this agricultural activity.

Calculation of the criterion for continuous management $TB_c$ was not completed due to some methodological difficulties not yet resolved. Essentially, to be able to calculate this criterion one would need to have a response function estimated at each point where the SSCM will be conducted. This depends on the resolution of the SSCM technology. For example, if the resolution is 1x1 meter, than one has to estimate response function for each of these cells. If the spatial structure is strong (high spatial correlation) the response functions in cells closer together will be very similar. Nevertheless, one would still need to estimate the relevant parameters for each cell, which is cumbersome and tedious. At present, efforts are under way to overcome this problem and to enable estimation of yield responses from high resolution yield monitor data, in a practical and efficient manner. The first step is to estimate a response function as specified in Eq.4. This has been done and the results are given in Table 5.

Table 5. Estimated Yield Response with Nitrogen and Spatial Effects

| Variable | | Estimate | St. error | t-statistic | p-value |
|---|---|---|---|---|---|
| Indicator zone 1 | | 3880.37 | 78.21 | 49.61 | <.0001 |
| Indicator zone 2 | | 4708.82 | 75.57 | 62.31 | <.0001 |
| Indicator zone 3 | | 6751.41 | 62.41 | 108.18 | <.0001 |
| Urea rate | 30 | -911.67 | 125.56 | -7.26 | <.0001 |
| Urea rate | 85 | -776.20 | 143.53 | -5.41 | <.0001 |
| Urea rate | 160 | -433.34 | 82.31 | -5.26 | <.0001 |
| Urea rate | 220 | -513.31 | 80.96 | -6.34 | <.0001 |
| Urea rate | 250 | -570.97 | 80.05 | -7.13 | <.0001 |
| Urea rate | 300 | 0.00 | . | . | . |
| Easting | | -5.61 | 1.04 | -5.39 | <.0001 |
| Northing | | 16.88 | 1.13 | 14.90 | <.0001 |
| Easting squared | | 0.04 | 0.00 | 9.48 | <.0001 |
| Northing squared | | -0.06 | 0.01 | -9.67 | <.0001 |
| Easting x Northing x Urea rate | 30 | -0.01 | 0.01 | -0.84 | 0.40 |
| Easting x Northing x Urea rate | 85 | 0.08 | 0.04 | 2.09 | 0.04 |
| Easting x Northing x Urea rate | 160 | -0.04 | 0.01 | -7.31 | <.0001 |
| Easting x Northing x Urea rate | 220 | -0.07 | 0.01 | -9.33 | <.0001 |
| Easting x Northing x Urea rate | 250 | -0.05 | 0.01 | -10.13 | <.0001 |
| Easting x Northing x Urea rate | 300 | 0.08 | 0.01 | 6.72 | <.0001 |

The results show that the spatial structure has a significant impact in determining yield both apart of the nitrogen input and in conjunction with it. Northern parts of the field are characterized with greater yield irrespective of the nitrogen application. In addition, the interaction of the nitrogen application rate and the spatial coordinates is significant for all but the lowest urea application rate. These results suggest that one should jointly use the nitrogen input and the spatial co-ordinates in an attempt to compute the criterion for the continuous SSCM. With the estimated coefficients in hand one could effectively plug them back in the data (for each coordinate) and for each urea application rate. Then for each data point one would have to determine the optimal urea rate, compute the resulting yield and integrate over all points to get the desired criterion. This is a complex work and for this reason, a more elegant way around it is presently sought.

## Summary and Conclusion

Precision agriculture is a promising concept for the modern farming. For it to be more widely accepted it is necessary to include the environmental and informational values when evaluating the concept on the farm field. A formal testing in the form of sequential hypothesis tests was proposed. The original null hypothesis of precision agriculture was modified to serve as a starting point for this testing. The sequential hypothesis testing offers an opportunity for systematic, straight forward and possibly automated evaluation of various management options for an agricultural field. The resulting optimal management, whether it is uniform, in discrete management zones, or continuous SSCM, will produce maximum benefits from a social point of view, accounting for both farmers' income and environmental and sustainability preferences of the society. Crucial elements of the hypothesis tests are the criteria designed to perform the tests. A further refinement of these criteria may be needed for the intended practical purpose.

Main issue with the empirical work in this field is the data limitations. This especially refers to data on the environmental impacts of agriculture. Either computer modelling or some proxy measures (like nitrogen content of grain) have to be used on site-specific basis to quantify the emission of pollutants from the agricultural fields. Also, an economic technique has to be carefully chosen from a range of the available options.

An additional shortcoming is the unavailability of the data on the value of PA information.

An example of the workings of the proposed model was provided using yield monitor data from a field scale nitrogen response experiment. In this particular case it was found optimal to apply uniform rate of about 70 kg/ha of Urea. Even though this conclusion suggests that PA is not optimal in this field, a more in-depth look reveals the value of the information collected for this PA exercise. Without that information, a likely rate of 210 kg/ha Urea would have been applied, leading to profitability losses and high potential environmental costs.

The need for environmental quality and for maintaining the level of natural resources in agriculture at sustainable levels, points to the site specific crop management (SSCM) as an viable and sound practice. To evaluate fully all the benefits of the SSCM, intensive research on the economics of the technical, environmental and informational aspects is needed. This paper we hope, presents a first step in that direction.

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