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Precision Agriculture and Sustainability

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Abstract. Precision Agriculture (PA) can help in managing crop production inputs in an environmentally friendly way. By using site-specific knowledge, PA can target rates of fertilizer, seed and chemicals for soil and other conditions. PA substitutes information and knowledge for physical inputs. A literature review indicates PA can contribute in many ways to long-term sustainability of production agriculture, confirming the intuitive idea that PA should reduce environmental loading by applying fertilizers and pesticides only where they are needed, and when they are needed. Precision agriculture benefits to the environment come from more targeted use of inputs that reduce losses from excess applications and from reduction of losses due to nutrient imbalances, weed escapes, insect damage, etc. Other benefits include a reduction in pesticide resistance development. One limitation of the papers reviewed is that only a few actually measured directly environmental indices, such as leaching with the use of soil sensors. Most of them estimated indirectly the environmental benefits by measuring the reduced chemical loading. Results from an on-farm trial in Argentina provide an example of how site-specific information and variable rate application could be used in maintaining profitability while reducing N applications. Results of the sensitivity analysis show that PA is a modestly more profitable alternative than whole field management, for a wide range of restrictions on N application levels. These restrictions might be government regulations or the landowner's understanding of environmental stewardship. In the example, variable rate of N maintains farm profitability even when nitrogen is restricted to less than half of the recommended uniform rate.

Keywords: sustainability, environment, GPS, VRT, Argentina

Introduction

The concepts of precision agriculture (PA) and sustainability are inextricably linked. From the first time a global positioning system was used on agricultural equipment the potential for environmental benefits has been discussed. Intuitively, applying fertilizers and pesticides only where and when they are needed, should reduce environmental loading. This paper will explore the realities of PA and sustainability. Exactly how can PA contribute to sustainability? Have the environmental benefits been measured? The paper will start with definitions of sustainable agriculture and precision farming. The next section will review research on the environmental impacts of PA. The last section will provide an example of how site-specific information and variable rate application could be used in maintaining profitability while reducing N applications.

Sustainable agriculture

The meaning of "sustainability" has been long debated. The term was originally used to refer to agricultural and industrial technologies that reduced or prevented the environmental degradation often associated with economic activity. Hartwick (1978) and Solow (1974) defined it economically as the ability to maintain constant consumption or productivity by substituting between natural resources and manmade capital in production. In this context "manmade capital" encompasses anything developed by human effort, including both physical capital (e.g. equipment, structures) and intellectual capital (e.g. information, knowledge). Pearce and Atkinson (1993, 1995) defined it environmentally by stating that natural resources and manmade capital complement each other in a production process and as natural resources are the limiting factor of production, they must be preserved. In 1972, the United Nations defined sustainability in a more general sense as "...aimed to meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). More recently, sustainability has been associated with a holistic consideration of the economic, environmental, and sociological impacts of any development (Caffey *et al.*, 2001) (Figure 1).

Applying the concept to agriculture, the American Society of Agronomy (1989) defines "Sustainable Agriculture as the one that, over the long term, enhances environmental quality and the resource base in which agriculture depends; provides for basic human food and fiber needs; is economically viable; and enhances the quality of life for farmers and the society as a whole."

Precision agriculture

Site-specific management (SSM) is the idea of doing the right thing, at the right place, at the right time. This idea is as old as agriculture, but during the mechani-

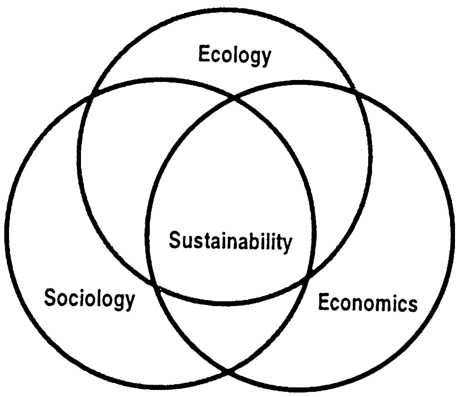

Figure 1. Sustainability as described by the intersection of three disciplines: ecology, economics and sociology.

zation of agriculture in the 20th century there was strong economic pressure to treat large fields with uniform agronomic practices. Precision farming provides a way to automate SSM using information technology, thereby making SSM practical in commercial agriculture. PA includes all those agricultural production practices that use information technology either to tailor input use to achieve desired outcomes, or to monitor those outcomes (e.g. variable rate application (VRA), yield monitors, remote sensing).

Lowenberg-DeBoer and Swinton (1997) define SSM as the "electronic monitoring and control applied to data collection, information processing and decision support for the temporal and spatial allocation of inputs for crop production." They highlight that the focus is on agronomic crops, but the arguments apply to horticultural crops and to the electronic tagging of livestock.

Temporal SSM requires management of inputs based on information about the life cycles of agricultural crops, livestock or pests. This temporal information is often referred to as developmental stage (DS) information (Swinton, 1997). For instance, integrated pest management involves many cases of DS management practices, such as the use of pest scouting to determine the need and timing of pest control. DS management is also used in livestock management: bar-coding and other sensors are used to keep track of individual dairy cow milk production, food consumption, and health (Swinton, 1997).

Ethical debate

Agriculture cannot be sustainable if farmers use practices that are socially unacceptable or not profitable. There are also good practical reasons to be concerned with a deteriorating climate, global change, excessive erosion, water pollution, and increasing resistance of pests to biocides. Such utilitarian concerns are enough for many to embrace sustainability as a goal (van Schilfgaarde, 1999). They are, in fact, the primary driving force behind the research done by the Water Quality and Management ARS National Program that targets PA's effectiveness (Barry-Stelljes, 2000).

Besides the utilitarian, physical aspects, however, there are philosophical and religious issues that deserve attention. One of these is stewardship. Sometimes stewardship of land is seen as a responsibility to future generations. In a religious context it is often seen as the responsibility to preserve and enhance God's creation. In either case, land and nature in general is thought of as something that human beings are given a temporary responsibility to care for. This is in contrast to the view that sees natural resources as assets to be exploited for the personal gain of the current property owner.

A related line of thought sees the farm as a living entity, an organism, and charges the farmer with the task of guiding this entity to produce crops and livestock in harmony with the environment. In some cases this view focuses on the farm as a self-contained entity with minimal dependence on purchased inputs and commodity markets. The objective of the farmer in this view is to enhance a biological balance, where the vitality of the land permits the harvesting of crops (van Schilfgaarde, 1999).

One problem with the "farm as a self-contained organism" concept is the linkage between the farm, the community and the rest of the world. Unless farmers are to be hermits, they are part of a larger community and as part of that larger community they provide agricultural products and in return receive consumer goods and farm inputs made by their non-farm neighbors. The specialization of tasks allows all to achieve a higher standard of living. Whether those neighbors are mainly those in same village as was true in Medieval Europe, or scattered over the world in the globalized economy, nutrients are being exported from the farm and something must be imported to maintain the balance.

Precision agriculture potentially provides producers improved tools to manage those inputs that must be brought to the farm. Instead of indiscriminately applying fertilizer or pesticides at uniform rates over large areas, PA allows producers to better target applications. It is often argued that PA substitutes information and knowledge for some external physical inputs, thereby potentially moving the farm closer to the ideal of biological balance. Of course, information technology and the knowledge that makes PA work are also external inputs. The hope of PA is that its use will be less disruptive of natural systems than uniform application of physical inputs has been.

Challenges

According to Hatfield (2000), a farming system is comprised of many elements, but the variations that exist within a field can be summarized in three classes of variation: (1) natural, such as soil and topography; (2) random, such as rainfall; and (3) managed, the fertilizer or seed application. The interaction among these three sources of variation results in offsite impacts.

The natural variation includes: (a) soil variation, (b) biological variations, and (c) soil process variation (Hatfield, 2000). Soil varies spatially in water-holding capacity, organic matter, and other physical and chemical characteristics by topography, as well as by a series of interacting elements. The challenge is to quantify soil variation. Biological variations within fields are as great as soil variations, including soil microbial populations, weed populations, insect populations, disease occurrence, crop growth, and harvestable yield, which is the variable that allows farmers to realize the outcome of all biological variations. Soil process variations are best understood by looking at N dynamics. One challenge is to quantify the response by varying response levels across soil types and topography, as Bongiovanni and Lowenberg-DeBoer (2001) did. Although the complexity of the interactions between the physical environment and the biological response creates a situation in which it is difficult to quantify the response to different practices, spatial regression analysis of yield monitor data, as related to soil characteristics shows promising results.

Kachanoski and Fairchild (1996) illustrated the spatial scaling problem and the value of taking into account the spatial variability of fields. Their results suggested that since the relationships among yield response, soil test, and applied fertilizer are non-linear, a single soil test calibration cannot exist for fields with different spatial variability.

Another challenge is to show that PA can have a positive impact on the environment. Unfortunately, only few studies deal with this objective directly, most of them arrive to that conclusion as a by-product of other studies (Hatfield, 2000). Such studies can be categorized as (1) nutrient management, (2) pest management, and (3) soil and water quality, and are summarized in Tables 2 through 6.

Literature review of studies on nutrient management

Schepers (1999), summarizes in Table 1 the environmental risks from nutrients and soil organic matter that are perceived to be the greatest for the different processes.

The interactions between factors cited in Table 1 and processes must be addressed in any discussion of environmental quality. NO_3–N losses are influenced by any factor that affects the movement of water within and from the field. This movement of N with water is believed to be one of the causes of hypoxia near the mouth of the Mississippi River, in the Gulf of Mexico, a condition in which water is depleted of its oxygen content, resulting in a serious reduction of biological activity (Hatfield, 2000). Hatfield (2000) also highlighted that the processes outlined by Schepers (1999) cannot be changed, but it is possible to modify the loading of nutrients and pesticides in a field, providing an opportunity for effective management of inputs through PA, while increasing production efficiency.

Nitrogen (N)

According to Wang *et al.*, (2003), studies of economic and environmental impacts of variable N application in crop production have been mixed. They refer to studies that found Variable rate technology (VRT-N) to be superior to uniform rate in terms of economic and water quality benefits (Babcock and Pautsch, 1998; English *et al.*, 1999; Schnitkey *et al.*, 1996; Thrikawala *et al.*, 1999). They also mention that in other papers, the benefits of VRT were not evident (Qiu and Prato, 1999; Watkins

Table 1. Environmental risks from nutrients and soil organic matter

Process	N	P	K	S	OM
Leaching	+	–	–	–	–
Denitrification	+	–	–	–	–
Eutrophication	+	+	–	–	–
Precipitation	+	+	+	–	–
Runoff	+	+	–	–	+
Volatilization	+	–	–	–	–
Saltation	–	–	+	–	–

Source: Schepers (1999), as cited by Hatfield (2000).

Table 2. Studies on the impact of site-specific N management on the environment

Crop	Input/Factor	Region	Methodology	Results of using VRT
Wang et al. (2003)				
Corn	N	Missouri	Used topsoil depth data to develop recommendations with a simulation model.	*VRT was more profitable than uniform rate in 75% of the cases, with a gain in profits up to \$37.14 ha^{-1} in one of the fields.
Roberts et al. (2001)				
Corn	N	Tennessee	EPIC simulation model to estimate N leaching.	*More N was applied with VRT, but less N was lost to the environment N leaching reduced by 2.24–4.48 kg ha^{-1}.
Delgado et al. (2001)				
Barley Potato	N	South Central Colorado	Field trials and use of information to estimate N leaching as a difference.	*N management practices can potentially be improved to reduce potential N losses and conserve water quality.
Kholsa et al. (2001)				
Corn	N	Colorado	Field trials and use of information to estimate N leaching as a difference.	*VRT-N has the highest NUE and lowest leaching compared to other treatments.
Whitley et al. (2000)				
Potato	N	Washington State	Field trials. Measured N leaching with probes.	*Surface soil had high NO_3–N flux. *Subsurface soil NO_3–N flux stable. *NO_3–N leaching was decreased in vulnerable zones due to a lower N rates in these zones.
Griepentrog and Kyhn (2000)				
Wheat Barley	N	Northern Germany	Field trials. Measured reduced chemical loading.	*VRA reduced N by 36% in low areas while maintaining the high yields.
English et al. (1999)				
Corn	N	West Tennessee	EPIC simulation model to estimate N leaching.	*VRT was more profitable than uniform rate and that it generated less nitrogen loss to the environment in most cases.

Rejesus and Hornbaker (1999)	N	Lake Decatur Illinois	EPIC simulation model to estimate N leaching.	*VRT-N has the potential to reduce the mean and variability of NO_3–N pollution, while improving profitability.
Thrikawala et al. (1999) Corn	N	Ontario, Canada	Simulation model (Barry *et al.*, 1993) to estimate N leaching.	*NO_3–N leaching reduced by 13%, average or between 4.2% and 36.3% in high and low fertility areas, respectively.
Watkins et al. (1998) Potatoes	N	Idaho	EPIC simulation model and dynamic programming to estimate N leaching.	*No environmental benefits. *No differences in N applied. *No differences in N losses.
Larson et al. (1997) Continuous Corn	N	Minnesota	LEACHM simulation model to estimate N leaching.	*No_3–N leaching was decreased in 50%, average, or from 60 to 29 kg ha^{-1}. *Decrease was 0 kg ha^{-1} in the loam, but 99 kg ha^{-1} in a loamy sand.
Leiva et al. (1997) Wheat Rapeseed Soybeans	Fertilizers Pesticides	Silsoe England	Measured chemical loading and estimated leaching with simulation.	*PA leads to savings in fertilizers and pesticides, decreasing risk of pollution and energy use, contributing to sustainability.
Hergert et al. (1996) Furrow Irrigated Corn	N	Nebraska	Measured after harvest residual soil NO_3–N and estimated N leaching.	*Improves N use efficiency. *Reduces leaching by minimizing high NO_3–N areas in the field.
Redulla et al. (1996) Irrigated Corn	N	Central Kansas	Measured after harvest residual soil NO_3–N and estimated N leaching.	*No differences in N use efficiency. *No differences in NO_3–N leaching.
Kitchen et al. (1994) Continuous Corn	N	Missouri	Measured grain production, unrecovered N in the crop, and post-harvest NO_3–N.	*The amount of unrecovered N decreased in the least productive soils with VRT. *Gross savings of \$10–\$12 ha^{-1} for using VRT.

Table 3. Studies on the impact of site-specific P management on the environment

Crop	Input/Factor	Region	Methodology	Results of using VRT
Bonham and Bosch (2001) Corn farms (121)	P	Chesapeake Bay watershed Virginia	Used chemical loading information from Virginia Department of Conservation and estimated P leaching with linear programming.	* Use of site-specific information allows for more accurate predictions of P pollution potential.
Larson et al. (1997) Corn Soybeans Wheat Grass	P	U.S.A.	Conceptual framework based upon chemical loading to estimate P leaching as a difference.	* *Potential*: A number of SSM practices can help to reduce the likelihood of P moving from fields into surface waters.

et al., 1998). In their research, Wang *et al*. (2003) evaluated the economic and water quality effects of adopting VRT-N and lime for corn production in Missouri. The methodology used topsoil depth data measured by soil electric conductivity, and developed fertilizer recommendations based upon a simulation model. VRT rates were compared to two different uniform N applications. Water quality benefits of VRT were evaluated based on potential leachable N. Results showed that VRT was more profitable than uniform rate in 75% of the cases, with a gain in profits up to \$37.14 ha^{-1} in one of the fields. They also found that greater variation in topsoil depth and soil pH resulted in higher profitability and greater quality benefits with VRT.

Roberts *et al*. (2001) reported that N losses to the environment were lower with variable VRT than with uniform rate application (URA), except on fields with little spatial variability (Table 2). The authors used the Environmental Policy Integrated Climate (EPIC) simulation model, incorporating weather in the quadratic corn response function to N fertilizer, in Tennessee, to estimate N leaching. They modeled three soil types, and three weather scenarios over a period of 20 years. The analysis of the 63 hypothetical fields showed that even though more N was applied with VRT than with URA, less N was lost to the environment, indicating that with VRT the crop used N more efficiently. Their results suggested that N leaching could be reduced between 2.24 and 4.48 kg ha^{-1} by profit-maximizer farmers that adopt VRT.

Delgado *et al*. (2001) studied best management practices (BMPs) to maximize N use efficiency (NUE) and minimize N losses in the environment for malting barley (*Hordeum vulgare* L.) and potato (*Solanum tuberosum* L.) on N dynamics of irrigated systems of south central Colorado. Their initial studies found a significant correlation between management, soil texture, and NO_3–N available to leach. They showed that by using geospatial information and implementing the application of these new tools, N management practices can potentially be improved to reduce potential N losses and conserve water quality.

Table 4. Studies on the impact of site-specific herbicide management on the environment

Crop	Input/Factor	Region	Methodology	Results of using VRT
Timmermann et al. (2001)				
Wheat Barley Sugar beet Corn	Herbicides	Bonn, Germany	Measured reduced chemical loading.	*Reduction of 54% in herbicide use (∈ 33 ha^{-1}). *Decrease in environmental damage (ground and surface water with herbicides).
Tian et al. (1999)				
Corn	Herbicides	U.S.A.	Measured reduced chemical loading.	*Reduction of 42% in herbicide use.
Clay et al. (1998)				
Soybean	Clomazone Trifluralin (Herbicides)	South Dakota	Measured reduced chemical loading, weed seeds, and estimated savings with a bio-economic model.	*Lower application of herbicides. *Savings of \$82 ha^{-1} with better control of *Setaria sp.* & *Ambrosia artemisiifolia*.
Khakural et al. (1998)				
Corn Soybeans	Imazethapyr Alachlor Acetochlor (Herbicides)	Minnesota	Measured herbicide leaching with auto samplers and area-velocity sensors installed in the watershed.	*VRT of herbicides reduces herbicide use, preserving water quality.
Nordmeyer et al. (1997)				
Cereals	Herbicides	Germany	Measured reduced chemical loading.	*Reduction of 47–80% in herbicide use.
Johnson et al. (1997)				
Corn Soybeans Cereals	Herbicides	U.S.A. Denmark	Conceptual framework based upon chemical herbicide savings.	*Better environmental results due to reductions in total herbicide application. *Avoids herbicide resistance development.
Oriade et al. (1996)				
Corn Soybeans	Herbicides	West Central Minnesota	WEEDSIM, a bio-economic simulation model to measure reduced chemical loading and to estimate pesticide runoff.	*Better environmental results due to reductions in total herbicide application.

Table 4. (*Continued*)

Crop	Input/Factor	Region	Methodology	Results of using VRT
				*Avoids herbicide resistance development. *Economic benefits of \$18.87 ha^{-1} for corn and \$28.82 ha^{-1} for soybeans.
Heisel et al. (1996)				
Barley	Herbicides	Denmark	Measured reduced chemical loading.	*Reduction of 66–75% in herbicide use.
Stafford and Miller (1996)				
Cereals	Herbicides	Silsoe, U.K.	Measured reduced chemical loading.	*Targeting herbicide application to grass weed patches resulted in a 40–60% reduction in herbicide use.
Mortensen et al. (1994)				
Corn	Herbicides	Nebraska	Measured weed populations and estimated herbicide savings.	*Weed mapping and VRT herbicide can reduce herbicide use by 71% and 94%, respectively, for broadleaf and grass weeds. Real-time sensing with discrimination could reduce it by 30–72%.
Khakural et al. (1994)				
Corn and Soybeans	Alachlor (Herbicide)	Southwestern Minnesota	Measured herbicide leaching with soil sensors.	*VRT reduced alachlor concentration in water, sediment and water + sediment by 10%, 24% and 22%, respectively.

Table 5. Studies on the impact of site-specific insecticide management on the environment

Crop	Input/Factor	Region	Methodology	Results of using VRT
Midgarden et al. (1997) Potato	Esfenvalerate Malathion (Insecticides)	Pennsylvania	Field and laboratory tests. Measured pest density and insecticide resistance from season to season.	*Precision IPM significantly reduced the rate of development of insecticide resistance, conserving natural enemies.
Weisz et al. (1996) Potato	Esfenvalerate Malathion (Insecticides)	Pennsylvania	Measured reduced insecticide application.	*Precision IPM significantly reduced insecticide inputs by 30–40%.

Table 6. Studies on the impact of site-specific soil and water management on the environment

Crop	Input/Factor	Region	Methodology	Results of using VRT
Lowenberg-DeBoer and Bongiovanni (2001) Corn Soybeans	Soil density	Central Illinois	Measured yield differences by soils and treatments with yield monitors, and used spatial regression analysis.	*796 kg ha^{-1} year^{-1} increase in corn yields. *No differences in soybean yields. *Economic benefits from \$2.47 to \$69.16 ha^{-1}.
Meyer-Aurich et al. (2001) Corn Wheat Potatoes	Soil erosion Water	Bavaria, Germany	Simulation model MODAM using data from an experimental farm.	*Precision Agricultural practices to prevent soil erosion are effective and profitable.
Carpentier et al. (1998) Dairy farms (246)	N regulations	Pennsylvania Maryland	Linear programming model (SUSFARM).	*N loadings were reduced by 40%, reducing control costs by 75% and policy transaction costs by 80%.

Kholsa *et al.* (2001) reported that the optimal delineation of site-specific management zones (SSMZ) on farm-fields into regions of high, medium, and low productivity based on inherent soil properties insures that the crop in each SSMZ has the required level of N needed to maximize yield in that specific zone. Additionally optimum application of N on SSMZ decreased leaching potential. They compared SSMZ practices to three other methods of N management. These methods included uniform application, grid sampling based application, and farmer decided N application. The yields and NUE of all four treatments were compared using spatial ANOVA analysis. Preliminary results suggested that SSMZ had the highest NUE and lowest leaching, compared to other treatments.

Whitley *et al.* (2000) studied the differences in N leaching under VRT and conventional N management in irrigated potatoes. Two adjacent fields were selected in row crop rotations (potato as the 1999 crop). Each field was soil sampled on a 61 m × 61 m grid to establish background soil N levels. One field was fertilized with variable N rates while the other was fertilized with a single N rate based on the field average. To evaluate field N dynamics, the authors established monitoring sites based on landscape position (knoll, slope, valley) and soil test organic matter content (high, low). They monitored N flux with ion-exchange resin probes at two depths, one in the root zone and one below the root zone. They also monitored soil moisture and soil and petiole nitrate throughout the growing season. Their results suggested that VRT N fertilizer application has the potential to improve N management in potato cropping systems. VRA of pre-plant N fertilizer was associated with reduced soil NO_3–N concentration in areas with high leaching potential. Further, NO_3–N leaching below the root zone was decreased in vulnerable valley positions when VRT was used. Finally, VRT had no adverse effects on crop yields, whereas with uniform rate there was a reduction in both yield and a quality parameter associated with N dynamics. They concluded that both irrigation water management and N fertigation management reduce NO_3–N leaching potential while maintaining crop yield and quality in irrigated potato (Whitley *et al.*, 2000).

English *et al.* (1999) used meta-response functions based on EPIC-generated data to compare variable and uniform rate application technologies for 36 simulated corn fields in West Tennessee, for three different soils and three different rainfall scenarios. They found that VRT was more profitable than uniform rate and that it generated less nitrogen loss to the environment in most cases.

Griepentrog and Kyhn (2000) studied the change in the amount of N fertilizer applied under VRT and conventional N management in wheat and barley in northern Germany. The authors investigated different strategies to increase yield and/or decrease fertilizer inputs in the eastern part of the county Schleswig-Holstein, a highly productive agricultural region. They subdivided the fields into areas of relatively homogenous soil properties and relief, and they determined N requirement based on plant growth rates and on yield potential. They tested the following N application strategies: (i) a variable high rate with a mean close to recommended levels to ask if a variable rate can increase the crop yield, (ii) a variable low input application to try to minimize fertilizer input and keep crop yields high, and (iii) a conventional uniform application for comparison. They also investigated the effect of a variable rate application on grain protein content of winter wheat. They found that an increase in the already high yields by using site-specific fertilization was not possible, but that yields could be maintained with a 36% reduction in N using precision methods. They concluded that site-specific fertilization can increase efficiency and reduce environmental impacts in this region, although yields could not be increased, and that reduced fertilizer input may be incompatible with high grain protein. (Griepentrog and Kyhn, 2000).

Rejesus and Hornbaker (1999) compared the economic and environmental impacts of N timing and rate practices to SSM precision technology for corn, using data of the Lake Decatur watershed of central Illinois, derived from the EPIC simulation model. They developed a variable rate application program for N based on the recommendations from the 1999 Illinois Agronomy Handbook (IAH). Their approach based the spatial yield goals on a 5 year history of average yields for the whole field; spatial yield potentials based on soil types; and 1 year of spatial yield data; without using N levels from soil tests. Their analysis revealed that SSM-N has great potential in reducing the mean and variability of NO_3–N pollution in the watershed, while improving profitability of producers, relative to the current practice of uniformly applying 140 kg ha^{-1} of N during the spring. They also found that SSM reduced the variability of net returns.

Thrikawala *et al.* (1999) showed the environmental benefits of VRT-N in corn in Canada, using a N simulation model that assumed that all excess N applications were lost by leaching to groundwater. They compared three different fertilizer management strategies (uniform rate, manual VRT, and GPS-guided VRT) under different probability distributions for field fertility. They simulated hypothetical fields and generated field fertility levels from a probability distribution, following a first-order autoregressive process, using empirical corn response functions to N, obtained by other authors. The potential leaching loss was calculated as the difference between N inputs (seed, fertilizer, and atmospheric deposition) and N outputs (N removed in harvested crops). VRT-N resulted in significantly less excess N than the uniform rate application. Pollution was reduced in all scenarios, from a minimum of 4.2% to a maximum reduction of 36.3%, due to the significant reduction in N inputs, keeping yield levels constant. In low fertility fields, VRT allowed cells in the field to be identified that did not require the maximum uniform rate. They also found that the environmental benefits of VRT declined with increases in average soil fertility. It should be noted though, that the literature indicates that if the average soil fertility is low, VRT has minimal effect because there is not much of a range in levels if the average soil fertility for the field is low. On the other hand, if the soil fertility for the entire field is very high, with most of it already above agronomic need, then VRT does not have much effect. Therefore, there tends to be an optimum range in average soil fertility for PA to have an impact.

Watkins *et al.* (1998) evaluated the long-term environmental impacts of VRT-N versus uniform rate N application in seed potato production using a simulation model. They simulated seed potato yields for four different areas of a commercial 63-ha field in Idaho using the EPIC crop growth model, and they determined the optimal steady-state N levels for each area of the field and for the entire field. They conducted the simulation over a 3-year rotation of seed potato, spring wheat and feed barley, simulating yield response functions for all three crops, and specifying 16 N rates for potatoes. The EPIC model simulated annual N losses in sediment, runoff, percolation and subsurface flow over a period of 30 years. They evaluated average N losses and economic returns for both uniform and VRT fertilizer application. They found VRT-N to be unprofitable for the field when compared to the uniform rate. They also found little difference between average N losses for the field under VRT and under conventional application. Thus, they achieved minimal environmental benefit for the field from using VRT-N. They proposed, instead, the use of split application of N, which improved N utilization by the plant and reduced both the amount of optimal N applied and the amount of average N loss in their simulation model, especially for areas of the field exhibiting low yield productivity. This is one of the two studies reviewed that did not find environmental benefits to VRT-N.

Larson *et al.* (1997) reviewed the potential environmental benefits from PA in nutrient management. They found that there is only limited direct field information available, and they provided an example of a field containing soils with surface textures ranging from sandy loams to loams in which the average amount of N leached was 29 kg ha^{-1} using PA, compared to 60 kg ha^{-1} using conventional rates of N application. These estimates were made using the LEACHM simulation model in corn, using data from Jackson and Stearn counties, Minnesota. The difference in the amounts of N leached under PA versus conventional practice varied from 99 kg ha^{-1} in a loamy sand to 0 kg ha^{-1} in a loam soil (Larson *et al.*, 1997).

Leiva *et al.* (1997) illustrated a methodology to assess the use of PA technologies in the framework of sustainable agriculture, in two English farms of 150 and 800 ha. They measured N fertilizer applied and estimated leaching with a simulation model. Energy input, energy ratio, air pollution, nitrate leaching, and soil nitrate concentration were calculated using measurements from the farm and data from the literature. They also calculated farming profitability and they conducted a cost–benefit analysis. They concluded that savings of inputs from VRT, such as fertilizers and pesticides, may help to achieve environmentally benign practices, mainly in terms of decreased risk of air and water pollution and decreased energy use, and thereby sustainability. They also cautioned that actual environmental performance of PA depends very much on whether it is used for the maximization of profits or the minimization of environmental risk, and that relative prices did not encourage savings of fertilizers in farming. They concluded that it was possible to achieve financial benefits as a result of savings in herbicide usage. They suggested that this latter area may help considerably to widen the potential contribution of PA to sustainable agriculture, but this requires further research and development. They state that a full PA system would involve significant extra capital costs but there are opportunities for economies of scale at or beyond 400 ha.

Hergert *et al.* (1996) found that VRT-N management improved N use efficiency (NUE) and reduced leaching by minimizing high NO_3–N areas in the field. The authors conducted field trials in three Nebraska fields in 1994 and 1995, aimed to establish relationships among soil chemical and physical properties, irrigation parameters, grain yield, soil nitrate and NUE for furrow-irrigated corn, which received uniformly applied ammonia, variable applied ammonia or variable applied ammonia minus 15%. Soil sampling showed highly variable soil nitrate at each site. Significant grain yield increases were shown for VRT versus uniform rate. Both VRT treatments produced larger decreases in residual soil nitrate and variability than the uniform N rate. The general conclusion is that VRT increased NUE and reduced NO_3–N variability and leaching, by creating more uniformly low nitrate levels in the field.

Redulla *et al.* (1996) studied the effect of VRT-N management in two center-pivot irrigated corn fields during 3 years (1993–1995) in central Kansas. Yield monitor maps were developed using 55 m $\times$ 55 m cells, and used to compute yield goals for the fertilization recommendations of Kansas State University. The yield and the residual soil NO_3–N measured at harvest were statistically similar for the uniform and for the VRT-N treatments at all sites and years. The N use efficiency was slightly higher with the VRT-N treatment, although the difference was not statistically significant. The conclusion was that VRT-N did not produce any change in NUE nor in NO_3–N variability/leaching. This is the other one of the two studies reviewed that did not find environmental benefits to VRT-N.

Kitchen *et al*., (1994) measured grain production, unrecovered N by the crop, and post-harvest soil NO_3–N in corn field trials in Missouri during the 1992 and 1993 growing seasons. They conducted side-by-side uniform rate, following university recommendations; and VRT treatments, following the yield goals for the different management units. Apparent unrecovered fertilizer N was estimated by sampling and analyzing N uptake in the above ground portion of the crop at harvest. They found that the amount of unrecovered N at the end of the growing season was less with SSM than with uniform management in the least productive soils. Economic results showed savings of \$10–\$12 ha^{-1} for using VRT, though they did not consider the extra cost of VRT.

Blackmore *et al*. (1994) discussed three levels of technology adoption in wheat production in England. They defined three possible technology adoption levels and outlined the associated possible farming management strategies. Technology Level One represents conventional practice with no information technology (IT) and is taken as a reference. Technology Level Two has some IT investment and provides the farmer with an increased understanding of the enterprise, but does not include the ability to vary application rates automatically. Farmers can however achieve patch application variation by manually influencing machinery settings. This technology level is seen as an interim to Technology Level Three, which has fully supported variable application rate capability. They concluded that PA has the potential to make a major contribution towards improving agricultural practice in order to reduce the impact on the environment from agrochemical wastage, especially from N fertilizer. They cautioned that if PA is used within a farming strategy that is driven by environmental considerations there would be a need for grants/subsidies to offset financial penalties. As environmental issues are given higher priority when considering the levels of inputs, the financial risks to the enterprise could increase.

Table 2 summarizes the studies on the impact of site-specific N management on the environment.

Phosphorus (P)

Bonham and Bosch (2001) compared the effectiveness of site-specific information about farms and watersheds to predict farm management decisions and profits, with a standard practice of non-point source (NPS) pollution control policy in the Chesapeake Bay Watershed. They used chemical application information from 121 farms from the Virginia Department of Conservation and Recreation (Table 3). The analysis was conducted using a perfect information scenario in which all farm characteristics were included, as well as three other scenarios with lesser information. Each was evaluated under a baseline scenario with no policy constraint and a scenario in which no restriction on P applications was imposed. They used a P-based nutrient management linear programming plan (ECONPLAN) written in a General Algebraic Modeling System (GAMS) to evaluate four scenarios with different amounts of information about farm characteristics, and to estimate management decisions and compliance costs. Results indicated that more accurate predictions can be made using spatial information, and therefore, reduce pollution.

Larson *et al.* (1997) reviewed the potential environmental benefits from PA in P management. They found only limited direct field information available, but provided example fields where the available P contained in surface soils varied widely. For example, in one Minnesota field, the available (extractable) P ranged from 0 to 110 ppm. They speculated that P content in runoff water could also vary with the method of P management (placement, time of application), residue management, and tillage. Application rate and method of management (timing, wind speed, tillage, residue management, application equipment, etc.) also affected the amount of herbicide in surface runoff and that leaching to groundwater (Larson *et al.*, 1997). They concluded that there are ample potential opportunities for PA in P management to reduce P runoff.

Table 3 sums up the studies on the impact of site-specific P management on the environment.

Literature review of studies on pest management

Most pesticides applied in agriculture are for weed control (Hatfield, 2000). The environmental problems facing agriculture from pesticide use have to do mainly with groundwater and surface water quality. Mortensen (1999) indicated that weeds are spatially variable across fields because of organic matter, soil texture, landscape position, and the interaction of these factors with crop management and crop cultivars. PA provides an enabling set of technologies to help reduce potential environmental problems from pest management. These technologies spatial and temporal field maps of weed distribution, VRT to apply herbicide on areas of weed infestation, and yield maps as a diagnosis tool for weed effects on crop yields. Insects and diseases can be treated similarly to weeds using the same principles (Hatfield, 2000). Pesticide management models need to balance the private benefits of lower herbicide costs and the social benefits of reduced herbicide usage with the costs of implementing VRT before PA can become part of preferred pest management strategies.

Herbicides

Timmermann *et al.* (2001) conducted a 4-year experiment in five fields of wheat, barley, sugar beet and corn in the area of Bonn, Germany (Table 4). Weeds were sampled in grids, and then maps were created with the software UNPROG. Herbicide application followed three strategies: whole field spraying, band spraying and site-specific treatment. They found that herbicide savings differ by crop and year, but overall results show an average saving of 54% in herbicides (or 33 Euros ha^{-1} in monetary value). They also found a decrease in environmental damage, due to less around and surface water contaminated with herbicides. The authors also reported that similar studies in site-specific weed control allowed herbicide savings of 47–80% (Nordmeyer *et al.*, 1997) in cereals and of 42% in corn (Tian *et al.*, 1999).

Khakural *et al.* (1998) studied the soil properties that affect the fate and transport of herbicides and weed density across a soil-landscape in Blue Earth County, MN, during two years, in a corn-soybean rotation. They measured herbicide leaching with auto samplers and area-velocity sensors that measured runoff flow and sediment concentration in different watersheds. They found that soil properties such as organic matter, texture, pH and adsorption coefficients of herbicides and weed density varied spatially. They adsorption coefficient (K_d) of the herbicide imazethapyr was strongly correlated with soil pH, while K_d of the herbicide alachlor was strongly correlated with organic matter (OM). Distribution of broad leaf weeds were related to soil-landscape characteristics. Results suggested that site-specific application of herbicide (pre- or postemergence) based on soil properties and weed density, reduced herbicide use.

Clay *et al.* (1998) recorded the spatial variability of weeds in a soybean field in South Dakota, and used it as input information for a bio-economic weed control model to generate preemergence, pre- plus postemergence, and postemergence herbicide strategies at three field locations. Weed control effectiveness, crop production, and profitability were estimated and compared with a producer's blanket herbicide application at each site. The treatments included an untreated control, grower's usual herbicide application, and three computer-generated recommendations for preemergence, pre- plus postemergence and postemergency. Weed seeds were measured by soil sampling each replicate. They evaluated herbicide efficacy and analyzed the data using ANOVA. They found that the recommendations from the bio-economic model were \$82 ha^{-1} less expensive than the producer's treatment and resulted in similar or better weed control *(Setaria sp.* and *Ambrosia artemisiifolia),* soybean yields and net returns. They concluded that site-specific herbicide application and placement optimized economic returns and environmental safety, benefiting the producer and society.

Using a conceptual framework, Johnson *et al.* (1997) demonstrated the potential of site-specific weed management for better environmental results, due to reductions in total herbicide application. They showed that spot treatments avoided herbicide resistance development. They also cited several studies that achieved a reduction in herbicide application: Haggar *et al.* (1983) estimated a 60% reduction in a post-emergence VRT herbicide application. Guyer *et al.* (1986) projected that herbicide use in corn and soybeans in the USA could be reduced by 10,900 t year^{-1} with VRT. Shearer and Jones (1991) reported a 15% saving in herbicide use by using a photoelectric sensor. Johnson *et al.* (1995) also found savings of 50% in herbicides when using VRT. Christensen *et al.* (1996) reported a 47% reduction in herbicide application in cereal grains in Denmark.

Oriade *et al.* (1996) used WEEDSIM, a bio-economic simulation model to explore the potential economic and environmental benefits of SSM as a low input weed-control tool in corn and soybeans, in West Central Minnesota. Biological parameters needed to run the model were taken from agronomic experiments carried out at the University of Minnesota and from the literature. By repeatedly changing the inputs and parameter values for the weed population distribution of the simulation model, the net benefits of SSM were evaluated under a wide range of weed populations, weed species mixes, and dispersion. They found weed patchiness to be the most important factor influencing the benefits of SSM practices, being almost nil at low weed pressures. The benefits were larger as weed populations and level of patchiness increased. They concluded that since there is uncertainty involved in weed patchiness, incentives might be required to promote SSM practices to risk-averse farmers in view of its desirable environmental attributes. Environmental benefits, as measured by a total pesticide index (TPI) were positive (beneficial) for all simulated levels of weed pressure and patchiness. Economic benefits were as high as \$18.87 ha^{-1} for corn and \$28.82 ha^{-1} for soybeans.

Heisel *et al.* (1996) reported herbicide savings of 66–75% in site-specific weed control field tests in barley, in Denmark, compared to normal recommendations. This reduction exceeded the goal of the Danish Ministry of Environment, which was to reduce pesticide use by 50% in the period 1987–1997.

Stafford and Miller (1996) found that targeting herbicide application to grass weed patches in cereal crops in the United Kingdom resulted in a 40–60% reduction in herbicide use.

Khakural *et al.* (1994) found that there was a decrease in alachlor concentrations in surface runoff from soybean fields as a result of SSM in a fine loamy catena in southwestern Minnesota. By adopting site-specific rates of alachlor application instead of applying a uniform rate in the entire field, alachlor concentration in runoff water, sediment and water + sediment was reduced by 10%, 24% and 22%, respectively. The concentration of alachlor in runoff water was less from application of SSM (2.20 or 2.80 kg ha^{-1}) than from uniform management (3.66 kg ha^{-1}).

Mortensen *et al.* (1994) conducted spatial analyses of weed populations in 12 Nebraska farm fields. They sampled weed seedling populations in seven corn and five soybean fields prior to the first cultivation or postemergence herbicide application. In each field, a 4- ha area was sampled in a 7-m grid to facilitate geostatistical analysis. Results indicated that postemergence herbicide applications could be reduced by 71% and 94%, respectively, for broadleaf and grass weeds if herbicides were applied to existing populations. They also estimated that the use of real-time sensing could reduce herbicide use by an average of 30–72% if in-row plant species discrimination were possible.

It should be noted that while SSM of herbicides offers some promise for reducing pesticide concentrations in runoff waters, the benefits would probably be very specific depending upon chemical, soil, landscape, and weed populations. A summary of the studies on the impact of site-specific herbicide management on the environment can be found in Table 4.

Insecticides

Midgarden *et al.* (1997) tested the impact of site-specific integrated pest management (IPM) on the development of insecticide resistance and density of natural enemies in commercial potato fields in Pennsylvania (Table 5). They conducted field and laboratory experiments in the 1994-growing season in six potato fields measuring 1.2 ha each, three fields under standard IPM and three fields with site-specific IPM. The scouting and threshold protocols for the fields under standard IPM were those defined in the PotatoES IPM system. Each site-specific IPM field was subdivided into 0.04 ha management blocks, which were individually sampled and sprayed. Results of the statistical analysis indicates that all standard IPM fields showed a significant increase in Colorado potato beetle *(Leptinotarsa decemlineata* [Say]) insecticide resistance from preseason to postseason. In contrast, there was little to no change in resistance in an unsprayed control and in two of the three site-specific IPM fields. Densities of parasitoids and predators were greater in site-specific IPM fields than in standard IPM fields, demonstrating that site-specific IPM has the potential to slow the development of insecticide resistance and conserve natural enemies.

Weisz *et al*, (1996) conducted 2 years of trials in rotated commercial potato fields in Pennsylvania to compare traditional whole-field IPM with site-specific IPM for Colorado potato beetle *(L. decemlineata* [Say]), green peach aphid *(Myzus persicae* [Sulzer]), and potato leafhopper *(Empoasca Fabae* [Harris]). In the whole field treatment, insect controls recommended by the IPM program were applied to the entire field when the mean pest density exceeded thresholds. In the site-specific treatment, insect controls were similar, except that controls were applied only to specific within-field locations. Pest sampling and mapping was performed weekly, and at the end of each season, statistics were calculated. Overall results indicated that SSM reduced insecticide inputs by 30–40% compared with whole-field integrated IPM, across a broad range of colonization pressures.

Table 5 summarizes the studies on the impact of site-specific insecticide management on the environment.

Literature review of studies on soil and water quality

Soil and water quality are two major components of a sustainable agricultural system. Attributes of soil and water quality are inextricably linked. A good soil does not ensure good water quality, but a poor soil is likely to create conditions that contribute to poor water quality (NRC, 1993).

Larson and Pierce (1991) defined soil quality as ''the capacity of a soil to function in a productive and sustained manner, while maintaining or improving the resource base, environment, and plant, animal, and human health.'' The capability of a soil to function within ecosystem boundaries and interact with the environment, external to that system forms the basis for determining the potential impact of soil management systems on the environment (Larson and Pierce, 1991).

PA has a great potential for environmental protection, not only for soil nutrients and pesticides, but also to control soil erosion and soil compaction. Soil compaction and the resulting impeded water drainage appear to be more common than previously thought. The discovery and quantification of these causes of variability suggest many new applications of PA and the need to develop new methods for assessing soil quality, so that remedial actions can be taken in an analytical way (Hatfield, 2000).

Table 6 reports the studies on the impact of site-specific soil and water management on the environment.

Soil density

Lowenberg-DeBoer and Bongiovanni (2001) used spatial econometrics methods (Anselin, 1988) to perform a spatial regression analysis of the effect of wheels and tracks on soil compaction, among other practices, in a corn–soybean rotation, using data from a 5-year soil density study conducted in central Illinois by the agricultural magazine Farm Journal (Finck, 2001) (Table 6). The spatial regression analysis used yield monitor data, soil type polygons, and other soil information, correcting for spatial autocorrelation and heteroskedasticity. The overall average benefit of use of tracks for corn was 796.42 kg ha^{-1} $year^{-1}$. The overall average soybean yield was not significantly affected by the tracks treatment. The profitability analysis showed benefits from \$2.47 to \$69.16 ha^{-1} from use of tracks compared to conventional tillage operation across the corn–soybean rotation. Heavy, silty clay loam soils showed the strongest response and the light silt loam upland fields showed the smallest (Finck, 2001).

Soil erosion

Meyer-Aurich *et al.* (2001) demonstrated a reduction in environmental impacts and increased profits from using PA in Bavaria, Germany, using a simulation model (MODAM) and information from an experimental farm. The model simulated agricultural land use, calculated the economic returns and did farm optimizations with a linear programming tool. Their 11-year study integrated the different dimensions of sustainability into agriculture, enabling a multiple-goal optimization and the calculation of trade-offs. Results from the simulation model indicated that the PA practices to prevent soil erosion, such as reduced tillage, direct seeding methods, catch crops, etc. were effective and profitable.

Record keeping

As Swinton (1997) pointed out, it is extremely difficult to monitor NPS water pollution, which explains why the evidence of environmental benefits is based on either (1) changes in input use, or (2) results using data from field trials but modeled in computers. Therefore, it is easier to create environmental regulations based on observed practices, rather than based on actual NPS outcomes. In this sense, PA—as a means to gather and record information on applied inputs, as well as a technique to vary the rate of inputs on the field according to what is needed-, could be used to implement environmental regulations, reducing the costs of regulation while improving yields on the overall field, as it will be shown later in this paper.

Record keeping by farmers could facilitate meeting environmental goals while permitting agricultural producers maximum flexibility in making production decisions. Site-specific farm production data could be subpoenaed to verify compliance with the law where there appeared to be probable cause of environmental risk, something analogous to income tax audits. Better spatial information may lead to government restrictions on the use of certain inputs in environmentally sensitive zones (Swinton, 1997).

Nowak *et al.* (1993) discussed regulations that encourage SSM as a cost-effective means to attain public environmental goals. They favor input-use restrictions in environmentally susceptible zones, such as the State of Wisconsin law that bans application of atrazine herbicide over shallow, permeable aquifers under karst formations.

Carpentier *et al.* (1998) showed that spatial information could allow for the targeting of farms with lower costs of complying with a N runoff control policy. They provided a conceptual framework that assumed that society has chosen the pollution reduction goal and wishes to minimize costs of achieving the goals. They provided an example in which the policy was to reduce N loadings by 40%. They showed that using spatial information to target specific farms reduced control costs by 75% and transaction costs by 80% over a uniform implementation of the policy. In addition to the lower compliance costs, savings were made because fewer farms were required to participate, which lowered contracting and enforcement costs, and because some farms had very high costs of achieving the 40% reduction under the uniform policy.

In addition to the papers reviewed, it is important to mention that at the time this paper was written, the USDA-ARS was working on the relationship between PA and sustainable agriculture, as a part of the Water Quality and Management project with headquarters at Beltsville, Maryland. They were studying all possible variables that could affect yield—to determine which were most significant, and they were also measuring how PA can be used to optimize the amounts of farming inputs needed—such as water, nutrients, and pesticides—and whether the environment benefited from this intensive management. The goal was to help farmers optimally manage all parts of fields in a sustainable manner. The multidisciplinary team was looking at water distribution, N management, nutrient availability, weeds, insects, diseases, herbicide application, and a variety of soil characteristics like organic matter and texture to assess their relative impacts on yield. Preliminary results showed that N fertilizer could be reduced by 31.26 kg ha^{-1} without reducing grain yield. Another area that would benefit from this approach was weed control. Researchers were looking for correlations between the weed population and other data collected that may lead to faster and less expensive ways to make weed maps (Barry-Stelljes, 2000).

Impact of site-specific nitrogen management on the environment in Argentina

An example of the potential benefits of precision agriculture for sustainability can be developed using the site-specific N response functions developed by Bongiovanni and Lowenberg-DeBoer (2001) for the Río Cuarto area, Province of Córdoba, Argentina. This example will show how site-specific knowledge and variable rate N application can maintain or even increase farm income while reducing environmental chemical loading. It should be noted that this is a conservative estimate of potential benefits because it focuses on N only. Environmental benefits, like profitability of PA are likely to be enhanced by an integrated system management of several inputs.

Bongiovanni and Lowenberg-DeBoer (2001) used corn yield monitor data from on-farm N trials in Argentina to estimate site-specific crop response functions using a Spatial Auto Regressive (SAR) model. The study was a collaboration between the National Institute of Agricultural Technology (INTA) of Argentina and Purdue University, West Lafayette, IN. The design involved a strip trial with a uniform N rate along the strip and a randomized complete block design, with regression estimation of N response curves by landscape position. The strips were the width of the N applicator (9.8 m), with a zero N control and five other rates of elemental N: 29, 53, 66, 106, and 131.5 kg ha^{-1}. The N rate was constant for the whole strip, across the four topographies identified. The highest N rate for each field was higher than the expected yield maximizing level. The N source was urea incorporated as a sidedress between rows of growing corn. The trial field had been in continuous crop production for about 10 years. Prior to that it had been in a long-term crop–pasture rotation. These are sandy soils, with organic matter levels ranging from about 0.7% on the hilltop to 1.7% in the lowland areas. Rainfall in the area is highly variable, but averages about 800 mm annually. Mid-growing season dry periods of 3 weeks or more are common. Because the field was relatively recently placed into continuous cropping, organic matter may not yet have reached equilibrium and may be providing more N through mineralization than would be the case in the long term. For more details about the field trial, see Bongiovanni (2002).

Data was collected with a standard AgLeader^{TM} yield monitor. Spatial autocorrelation and spatial heterogeneity were taken into account using a spatial error model and a groupwise heteroskedasticity model. A partial budget was used to calculate uniform rate and VRT returns. Regression results using the traditional OLS indicate no significant difference in N response. Regression results using the SAR model reveal that three out of four regions are significantly different from the mean response to N (Figure 2). N response was significantly different from the average at the 1% probability level in Low East and Hilltop and at the 10% probability level in the Slope W. In the Low East there was high yield and low response to N, while in the Hilltop there was low yield and high response to N. It should be noted that N responses show low NUE; it takes more fertilizer than normal to produce rather modest yield increases. This is may be due to the fact that the study was conducted in an area with relative low and irregular rainfall, and because the trial was conducted on soils only recently converted to continuous cropping.

Economic analysis

Net returns from N were calculated using marginal analysis, which states that when the value of the increased yield from added N equals the cost of applying one

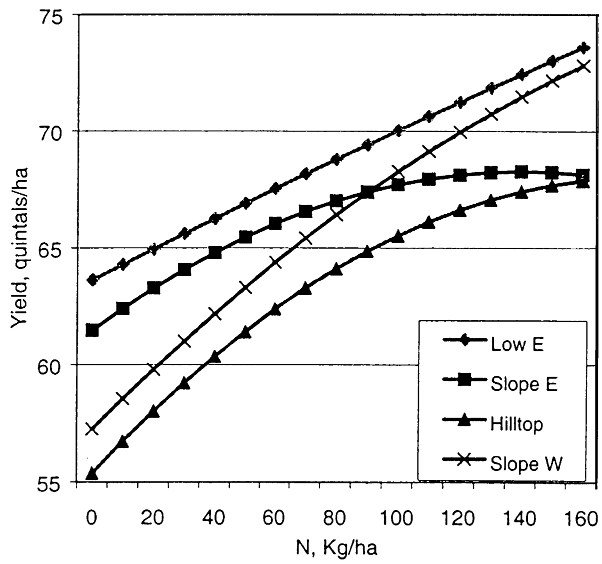

Figure 2. Crop response functions to N by landscape position, SAR model.

additional unit, profit is maximized; or when the marginal value product equals the marginal factor cost (MVP = MFC).

The profit-maximization problem is

$$\max \pi = \sum_{i=1}^{4} \text{area}_i * [p_c * (\alpha_i + \beta_i * N_i + \gamma_i * N_i^2) - r_N * N_i] \tag{1}$$

where π is the total net returns over N fertilizer (\$ ha^{-1}), area$_i$ the proportion of area i (i = 1,..., 4), i the landscape area: 1 = Low East, 2 = Slope East, 3 = Hilltop, 4 = Slope West, P_c the price of corn, α_i the intercept estimate from the spatial autoregressive model, β_i the linear coefficient estimate, γ_i the quadratic coefficient estimate, N_i the quantity of elemental N applied in area i, r_N the price of elemental N fertilizer, plus interest for 6 months at 15% annual rate and N_{total} is the maximum quantity of N fertilizer that can be applied in the total area.

Profit maximizing N rates were considered because they are the alternative to "agronomic rates" when response curve information is available. When the estimated coefficients from the SAR model are used and N use is unlimited, results indicate that average net returns from the profit maximizing uniform rate (71.42 kg of N) are \$498.29 ha^{-1} and average net returns from using VRT-N (weighted average of 67 kg ha^{-1}) are \$502.94 ha^{-1} without subtracting a VRT fee.

In the U.S. VRT N custom application typical would cost about \$6 ha^{-1} more than uniform application (Whipker and Akridge, 2001). In the long run the VRT custom application fee should cover all extra cost related to site-specific application including higher depreciation, opportunity cost of capital and labor, though in the short run retailers may use VRT application as a "loss leader" to maintain or expand market share. Variable rate fertilizer application of any kind is currently rare in Argentina and there is no market test of custom rates. In addition low cost manual site-specific N application is an alternative in Argentina because of low labor costs and the Pampas soil types, which are often found in relatively large areas with smooth contours. For instance, one approach being used by a few producers is to apply nitrogen only on hilltops. Because of the lack of a market test of VRT fees in Argentina and the possibility that low cost approaches can be used, VRT fees are omitted in the remainder of this example. Currency is in US dollars.

Environmental impact

With regulations limiting total N use, the profit-maximization problem is the same as before, but subject to the constraint that the sum of the total quantity of N applied in each of the areas is not greater than the total quantity allowed: $\sum_{i=1}^{4} N_i \leq N_{total}$, where N_{total} is the maximum quantity of N fertilizer that can be applied in the total area. The initial example assumes governmental regulatory constraints imposing a restriction that a maximum uniform rate of 60 kg of N per hectare or of 60 t of N can be applied on 1000 ha of corn in Argentina, in order to avoid NO_3–N pollution in surface or underground water. This may also be the case where the estancia owner wishes to improve environmental stewardship by reducing N use. The constrained profit-maximization problem was written in the GAMS software.

With any constraint on N availability the VRT approach concentrates N applications were the response is greatest. Given a 60,000 kg limit for 1000 ha, the profit maximizing approach is to eliminate N application on the low land area (Low East), while cutting back in the other landscape zones (Table 7). It should be noted that because the N application is constrained to less than the profit-maximizing rate the constraint is binding and the VRT average rate and the uniform rate are the same. With VRT the constraint reduces profitability only \$0.15 ha^{-1}, while the return with uniform application drops by \$0.45 ha^{-1}. With 1000 ha of corn, the VRT advantage would be \$4946, not counting VRT application cost.

This example shows how SSM of inputs may help maintain profitability while using fewer inputs. With higher nitrogen use efficiency the ability of VRT to maintain profitability with lower average N applications is expected to be improved. Also with a better understanding of site-specific N response and with lower costs as VRT application equipment becomes more standard, VRT profitability should improve relative to uniform application returns.

Sensitivity analysis

If the N availability is cut to 45,000 kg, N application is almost eliminated on the Slope East landscape zone. Depending on layout of the fields the producer may decide that 8 kg ha^{-1} is not worth the application cost and only spread on the Hilltop and Slope West zones. Compared to the unconstrained case, VRT returns are reduced by \$1.51 ha^{-1}, while profitability with uniform application is reduced by \$1.77 ha^{-1}. With 1000 ha of corn limited to using 45 kg of N, the VRT advantage would be \$4915.

Table 7. VRT nitrogen rates and average returns per hectare for various regulatory scenarios for an estancia with 1000 ha of corn

	Total quantity of nitrogen allowed per farm (kg)			
Landscape zone	Unconstrained	60,000	45,000	30,000
VRT N rates				
Low East (kg ha^{-1})	0	0	0	0
Slope East (kg ha^{-1})	33	25	8	0
Hilltop (kg ha^{-1})	85	78	64	47
Slope West (kg ha^{-1})	134	122	95	64
VRT average (kg ha^{-1})	67	60	45	30
Uniform rate (kg ha^{-1})	71	60	45	30
VRT average return* (\$ ha^{-1})	\$502.94	\$502.79	\$501.43	\$498.61
Uniform average Return (\$ ha^{-1})	\$498.29	\$497.85	\$496.52	\$494.35
Difference (\$ ha^{-1})	\$4.65	\$4.95	\$4.92	\$4.26

*Does not include the VRT fee.

With a constraint of 30,000 kg of N on 1000 ha, the VRT approach would zero out application on the Low East and Slope East landscape zones, concentrating N application on the Hilltop and Slope West zones. Compared to the unconstrained case, VRT returns are reduced by \$4.33 ha^{-1}, while uniform application profitability are cut by \$3.94 ha^{-1}. With 1000 ha of corn limited to using 30 mg of N, the VRT advantage would be \$4.260.

Conclusions

If the inevitability of some external farm inputs is acknowledged, PA can help in managing those inputs in an environmentally friendly way. By using site-specific knowledge, PA can target rates of fertilizer, seed and chemicals for soil and other conditions. One example is that spatial management of N can reduce overall N application, and reduce N on sensitive areas, while maintaining profitability. Another example is that spatial management of insecticides and herbicides can reduce overall applications of those chemicals by applying them only where the problem exists. PA can be part of an environmentally benign economically viable system. If the need for external inputs is accepted, information is also needed for proper spatial allocation of the external inputs.

Most of the papers reviewed indicate that PA can contribute in many ways to long-term sustainability of production agriculture, confirming the intuitive idea that PA should reduce environmental loading by applying fertilizers and pesticides only where they are needed, when they are needed. PA benefits to the environment come from more targeted use of inputs that reduce losses from excess applications and from reduction of losses due to nutrient imbalances (K deficiency reducing N efficiency, for example), weed escapes, insect damage, etc. Other benefits include a reduction in pesticide resistance development. One limitation of the papers reviewed is that only a few actually measured directly the environmental indices, such as leaching with the use of soil sensors. Most of them estimated indirectly the environmental benefits by measuring the reduced chemical loading. One key research need is field measurement of the environmental impact of precision agriculture technologies.

Results from the on-farm trial in Argentina provides a good example of how site-specific information and variable rate application could be used in maintaining profitability while reducing N applications. Results of the sensitivity analysis show that PA is a modestly more profitable alternative than whole field management, for a wide range of restrictions on N application levels. These restrictions might be government regulations or the landowner's understanding of environmental stewardship. In the example, VRT N maintains farm profitability even when N is restricted to less than half of the profit-maximizing uniform rate.

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