3 Improving food security through increasing the precision of agricultural development

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Introduction

Although long practised intuitively by subsistence farmers (Vanlauwe *et al.*, 2010; Heijting *et al.*, 2011), precision agriculture (PA) came of age in the 1990s as a technically driven means to improve industrialized agriculture. It promised benefits to both farmers and society through increasing production efficiency while improving stewardship of the environment (Srinivasan, 2006). These principles are central to the recent resurgence of interest in eco-efficiency (Keating *et al.*, 2010), driven by global food price spikes overlying progressive concern about the degradation of agroecosystems worldwide. These drivers have refocused global concern on the dual aims of improving food security while protecting the environment (Godfray *et al.*, 2010; Mueller *et al.*, 2012). This makes it a particularly appropriate time to take stock of the relevance of the principles of PA for agricultural improvement in developing countries.

Industrial agriculture, based on inorganic fertilizers, pesticides and other inputs, generally uses the risk-averse premise that given uncertainty in space and time, uniform within-field treatment is the best strategy (McBratney and Whelan, 1999). In contrast, PA recognizes the fine-scale heterogeneity of agricultural fields, as many subsistence farmers have traditionally done. Whereas subsistence farmers often have to concentrate inputs in fertile microsites as a risk-minimizing strategy (Vanlauwe *et al.*, 2010), in industrialized agriculture PA focuses on optimizing farm inputs by translating site-specific crop demands into variable management practices (Srinivasan, 2006; Mueller *et al.*, 2012).

In the early days of PA the ultimate goal was to understand within-field variation in plants and soil and then to tailor management to address this variability (e.g. Bouma, 1997). Precision agriculture was very much driven by technological advance, both in global navigation satellite systems as well as microcomputers and farm machinery. After 15 years of research and implementation of PA mainly in Europe and the USA, scientists came to the conclusion that it was more fruitful to identify the main processes that limit yield rather than to address all of the fine-scale variability (e.g. Dobermann *et al.*, 2002). This shifted the focus from a technically driven to a more results orientated approach. Still, the overall impression people have of PA is of an intensive crop management system, served by high-end technology (Cook *et al.*, 2003; Gebbers and Adamchuk, 2010).

Precision agriculture has been demonstrably successful in large-scale, mechanized, commercial or what can be termed industrial farming (Lowenberg-DeBoer, 2001) and especially with high-value cash crops that receive large amounts of agrochemical inputs and enter markets with strong differentiation based on quality, such as viticulture and horticulture (Srinivasan, 2006; Gebbers and Adamchuk, 2010). There are few documented examples of PA being applied to smallholder farms in developing countries. This is consistent with the predominance of high input industrial farming in North America and Europe (referred to as the North), with concomitant environmental impacts, whereas smallholders in developing countries (referred to as the South) often struggle to apply sufficient agrochemicals or irrigation water to maintain reasonable yields (Mueller *et al.*, 2012). Precision agriculture technologies in the North were developed largely to reduce wastage and leakage of agrochemicals, whereas in the South they are aimed at maximizing the effects of small quantities of agronomic inputs (Donovan and Casey, 1998; Srinivasan, 2006). It has been argued that high investment costs and associated increases in risk make PA unsuitable for smallholder farmers in developing countries (Cook *et al.*, 2003; Mohd Noor *et al.*, 2005).

While PA has not delivered the technological revolution in the agricultural sector that was predicted (Tey and Brindal, 2012), it has succeeded in reintroducing the concept of locally adapted interventions to both agricultural practitioners and scientists and in highlighting the need for information about the spatial and temporal variation of factors affecting yield. In the light of the current food crisis, especially in sub-Saharan Africa, the region with the highest demographic growth in the world, development agencies and governments are debating strategies to achieve a 'new green revolution for Africa' (Godfray *et al.*, 2010; Mueller *et al.*, 2012). Proponents of large-scale agricultural commodification argue that the millions of dollars of foreign investment involved will develop local infrastructure, facilitate transfer of skills and technology, create jobs, alleviate poverty and help to ensure food security in host countries. Others emphasize that tailor-made solutions that are inclusive, responsive to the needs of the poor and mindful of existing knowledge and local realities are more likely to bring about success in the fight against hunger in Africa (Nord and Luckscheiter, 2010). Whichever view prevails, it is clear that small-scale agriculture, dominated by fine-scale variation in yield determining factors, will continue to be a major source of livelihood for millions of rural people in Africa for a long time to come. In this chapter we take stock of the relevance of PA for addressing the needs of smallholder farmers and suggest extensions of the concepts for application in the smallholder context.

PA technologies for subsistence farmers

In a classical sense PA addresses mainly agronomic factors that influence crop yields, but social factors are mainly seen as drivers of these. The standard recipe for PA is a stepwise process that entails:

1 defining the yield-limiting factor or factors at a given time;
2 mapping these factors across the region of interest;

3 designing a variable-rate management strategy that addresses the spatial variability of these factors and
4 assessing and monitoring environmental and economic benefits of implementing variable-rate management strategies.

The gap between average yields presently achieved by farmers and yield potential is determined by the yielding ability of available crop varieties or hybrids and the degree to which crop and soil management practices allow expression of this genetic potential (Cassman, 1999; Mueller *et al.*, 2012). Supporting the expression of this genetic potential while increasing the efficiency of use of farm resources by adjusting crop management according to field variability and site-specific conditions is intuitively appealing to most agricultural practitioners. At face value, PA technologies seem to be especially appropriate tools for agriculture in developing countries, where policies that promote management of land and water resources for sustainable intensification have remained elusive (Gebbers and Adamchuk, 2010; Godfray *et al.*, 2010).

For classical PA to improve yields successfully, the yield-limiting factors need to be clearly defined and responsive to agronomic practices. The yield potential of a crop variety grown by a farmer does not only depend on its genetic makeup, but also on the inherent agronomic potential of the site. No increase in yield can be expected if the field chosen for planting is not suitable for the growth of the crop.

Cassman (1999) points out that most of the achievements of the green revolution in Asia were made on irrigated fields. He argues that the success of ecological intensification of cropping systems in unfavourable rainfed environments will be relatively small because present yields are very small and the primary constraint is lack of water. Approaches to management of soil fertility are often overly simplistic and the complex interaction between soil and plant interactions poorly understood. For example, long-term fertilizer trials have shown that nutrient imbalance, rather than a simple deficiency, can have more severe effects on yields (Cassman, 1999). There is other evidence that mineral fertilizers alone cannot address soil fertility as the yield-limiting factor because the underlying soil biology accounts for much variation in responsiveness of crop yield (Barrios *et al.*, 2012). Soil degradation is a major cause of small yields in Africa, Asia, and South and Central America. Inappropriate farming methods, deforestation and overgrazing were identified as the primary causes, leaving substantial areas unsuitable for intensive agriculture (Godfray *et al.*, 2010). Although the production practices and physical processes that cause erosion are well understood, technical solutions to prevent this kind of degradation are rarely adopted (Mueller *et al.*, 2012).

Before we discuss in detail why, in a smallholder context, a more holistic view of PA is needed, we look at how development practitioners have integrated PA technologies into their natural resource management programmes. These are selected examples that illustrate how the application of PA principles has played out in the developing world rather than an exhaustive catalogue.

Site-specific nutrient management of cereal in Asia

Site-specific nutrient management (SSNM) aims to record and predict the spatial variation of the nutrient supply in fields and to address this with variable fertilizer rates (Srinivasan, 2006). The principles of SSNM were developed for rice through more than a decade of research beginning in the mid 1990s and involving countries across Asia and in Africa. The experiences with rice were subsequently used to develop SSNM principles for maize and wheat, which were ready for delivery by 2010. Delivery of SSNM for rice from 2002 to 2008 focused on developing and promoting printed guidelines for large rice-growing regions. Uptake by farmers was limited because of the amount and sophistication of knowledge required to use the printed materials to develop field-specific guidelines for individual farms (Timsina *et al.*, 2010; Global Rice Science Partnership, 2010).

Micro-dosing fertilizer application in millet production systems in Niger

Micro-dosing technology has been developed by the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in an attempt to increase the affordability of mineral fertilizer while giving plants enough nutrients for optimal growth. This micro-dosing technology consists of applying relatively small quantities of fertilizer (from 2 to 6 g $hill^{-1}$) at sowing time, thus substantially reducing the recommended amount of fertilizer that subsistence farmers need to apply, for example 10-fold for di-ammonium phosphate from 200 to 20 kg ha^{-1}. The implementation of this technology has resulted in greater nutrient use efficiency (Twomlow *et al.*, 2010).

Precision conservation agriculture

Precision conservation agriculture (PCA) assists farmers to be successful when applying conservation agriculture by tailoring practices to local circumstances (Jerich, 2011). Conservation agriculture (CA) is defined by three simple principles: (1) minimizing soil disturbance, (2) using crop rotations and or associations and (3) keeping soil covered with crop residue (Giller *et al.*, 2011). An example of PCA land preparation could include hand-dug planting holes, precise lime application around the root zone of each plant and precise spatial positioning of plants (Jerich, 2011). The universal applicability of CA principles for smallholder farmers in Africa has been questioned. More tailored approaches that adapt some or all three principles for different circumstances are seen as critical to their appropriateness (Giller *et al.*, 2011).

Precision manuring

Results indicate that farmers can improve management of manure applied to cropped areas simply by rotating the night-time tethering sites of their animals.

Through this strategy of precision manuring, they can concentrate manure application on the 'bad spots' or 'tired soils' that are most in need of nutrients and organic matter. Deliberate application of manure, compost and other fertilizers to low-yielding parts of fields is a common strategy employed by smallholder farmers (Vanlauwe *et al.*, 2010). The practice is especially useful for poor farmers, since they do not have enough land to ignore areas of declining soil fertility. Village-level management of precision manuring shows promise for enabling dryland communities to fine-tune the management of agro-pastoral systems across whole landscapes, resulting in larger and more sustainable yields (Taddesse *et al.*, 2003).

Supplementary irrigation

Supplementary irrigation (SI) is the addition of water to essentially rainfed crops during times of serious rainfall deficits. The combined use of rainfall and irrigation water is a potentially valuable management principle under conditions of water scarcity. The aim is to reduce the risk of crop failure and to stabilize yields where rainfall is normally sufficient, but vulnerability to drought is considerable. In the dryland farming area of northern Syria the International Center for Agricultural Research in Dry Areas (ICARDA) found substantial increases in crop yield in response to the application of relatively small amounts of irrigation water. The impact of SI goes beyond yield increases to substantially improve water productivity. Both the productivity of irrigation water and that of rainwater are improved when both are used together. The technology is considered to have large potential across West Asia and North Africa if combined with efficient water harvesting and adequate training of farmers (Oweis and Hachum, 2006).

Characteristics of smallholder farms in developing countries

Smallholder farming systems in developing countries are very variable, but do have some general characteristics that distinguish them from industrial farming. Typically they are characterized by small farm sizes, fragmented holdings and multiple production objectives. Integrated production for food, fodder, cash crops, fuel and housing often lead to complex systems that involve interactions amongst trees, crops and livestock. Levels of mechanization are generally low, and production is, therefore, labour-intensive. Smallholders are exposed to a multitude of risks, such as high variance in rainfall amount and distribution, and pests and diseases of crops and animals. Furthermore, agricultural production is also affected by flooding, frost, illness of household members, war and crime, all of which can have major effects on rural livelihoods. Investment and production decisions by smallholders are made within very unpredictable environments (Table 3.1).

Smallholder farmers often live in areas with little infrastructure and face high transaction costs that significantly reduce their incentives and opportunities

Table 3.1 Comparison between typical smallholder or family farms and commercial agriculture

Characteristics	*Family farms*	*Commercial agriculture*
Role of household labour	Major	Little or none
Community linkages	Strong – based on solidarity and mutual help between households and broader groups	Weak – often based on social connections between entrepreneur and local community
Priority objectives	Consume Stock Sell	Sell Buy Consume
Diversification	High, to reduce exposure to risk	Low – specialization in very few crops and activities to benefit from economies of scale
Size of holdings	Small, average 2 ha[a]	Large – exceeding 100 ha
Land access	Inheritance and social arrangements	Purchase

Source: adapted from Toulmin and Guèye, 2005.

Note

a Von Braun (2005) reports that the average farm size both in Africa and Asia is about 1.6 ha, whereas farm averages are 27 ha in Western Europe, 67 ha in Latin America and the Caribbean and 121 ha in Canada and the United States.

for market participation. In addition, small farms with few assets often have limited access to services, including extension and rural credit, which are often important prerequisites for increasing productivity (Fischer and Qaim, 2011). Smallholders have often been slow adopters of what scientists and extension staff consider optimal use of fertilizer, improved seeds and other production inputs (Shiferaw *et al.*, 2009). One contributing factor for this is that recommendations rarely take within- and between-season variability of rainfall into account. Farmers are aware that this contributes to risk associated with investment and are often unwilling to adopt interventions that have high expected outcomes (as estimated by economists) but also have inherently greater risk (Donovan and Casey, 1998; Akponikpè *et al.*, 2011).

Smallholder farms are hugely variable in terms of soil fertility status, as well as other biophysical determinants of production. This heterogeneity is evident at a range of scales: amongst farms within a locality, amongst fields within a farm that are not necessarily contiguous and within fields (Dobermann *et al.*, 2002; Vanlauwe *et al.*, 2010; Tittonell *et al.*, 2011). The between-field variability at the individual farm level may be as large as differences between different agro-ecological zones, with obvious consequences for crop productivity (Table 3.2).

Variability of smallholder farms is not confined only to biophysical properties, they also vary in their availability of labour, livestock ownership, income, production orientation, cultural norms and wealth (Ojiem *et al.*, 2006). In general, household income increases with the size of the landholding, despite

Table 3.2 Topsoil fertility status for different agroecological zones and for various fields within a farm in Burkina Faso

Area	*Organic C* *g kg⁻¹*	*Total N* *g kg⁻¹*	*Available P* *mg kg⁻¹*	*Exchangeable K* *mmol kg⁻¹*
Agroecozones				
Equatorial forests	24.5	1.6	–	–
Guinea savanna	11.7	1.4	–	–
Sudan savanna	3.3	0.5	–	–
Fields within a village				
Home garden	11–22	0.9–1.8	20–220	4.0–24
Village field	5–10	0.5–0.9	13–16	4.1–11
Bush field	2–5	0.2–0.5	5–16	0.6–1

Source: adapted from Vanlauwe et al., 2010.
Note: Home gardens are near the homestead, bush fields furthest away from the homestead and village fields are at intermediate distances.

the fact that the proportion of non-farm income tends to be greater among land-poor households (Jayne *et al.*, 2005). Limited land resources result in household members engaging in non-farm work, with returns per hour often lower or less reliable than those from work within the smallholding. Off-farm activities with the greatest potential for income generation are also those with the highest barriers to entry so tend to be concentrated among wealthier rural households (Rigg, 2006). Cultural differences condition how households differ in resource endowment, production orientation and objectives, education, past experience, management skills and attitude towards risk. These culturally conditioned differences lead to different natural resource management strategies and fine-scale variation in farmer practice and productivity (Tittonell *et al.*, 2010). Increasing population density and pressure on land amplifies livelihood constraints so that they become ever more predominant in driving observed variability.

Using principles of precision agriculture to customize interventions for smallholder farmers

Smallholder agriculture is the basis for food security and rural livelihoods in most developing countries and it is generally underperforming. Given the fine-scale variability of smallholder farming systems, and the fact that PA is designed to optimize farming under heterogeneity, PA principles could be expected to contribute to their improvement. In this section we review what can be learnt from the adoption of PA in commercial farming and combine this with an understanding of smallholder systems to make suggestions for the effective use of PA principles to enhance productivity of smallholder farms.

There has been no comprehensive study of PA adoption rates in developing countries, but it appears that interventions based on PA technologies follow the same fate as other natural resource management strategies (Tey and Brindal, 2012). While economic and environmental benefits are demonstrated in intensively supported projects, wide-scale adoption outside these projects is rarely observed (Shiferaw *et al.*, 2009). In Europe and the USA, despite positive net returns from PA experiments on commercial farms (Lowenberg-DeBoer, 2001), strong scientific approval and massive outreach campaigns by agro-industry, adoption rates have fallen short of expectations (Tey and Brindal, 2012). Studies in Germany, Denmark and the USA agree that high adoption rates are strongly linked to large farm sizes, a high level of mechanization and overall dependency on large agrochemical inputs. This is especially true where products are heading for markets with strong market differentiation based on quality, such as viticulture and horticulture and where there is access to consultants and extension workers (Lowenberg-DeBoer, 2001; Tey and Brindal, 2012).

Low rates of adoption are associated with the lack of awareness of PA technology among farmers, lack of access to sources of information, insufficient quality of information, time requirements, lack of technical knowledge, problems with the incompatibility of different hardware devices and the high cost of the technology (Kutter *et al.*, 2011; Tey and Brindal, 2012). One of the fundamental problems of PA is that its benefits are greatest when analysed using a holistic systems approach that includes putting values on environmental protection, food safety and other external benefits, while at a farm level, without realizing these values, the costs often outweigh perceived benefit (Lowenberg-DeBoer, 2001; Srinivasan, 2006).

In summary, the European and American experience with PA teaches us that a set of conditions have to be met before farmers are able and willing to adopt PA. These are:

- yield-limiting factors that can be addressed with PA;
- access to agronomic data;
- perceived economic benefits;
- access to extension services and or consultants.

A summary of the challenges in meeting these requirements in smallholder systems, and potential solutions, is provided in Table 3.3. This leads us to propose the following four main elements of a strategy for using PA principles to enhance smallholder productivity:

1 Build on farmers' knowledge and expertise by facilitating local experimentation, observation and learning.
2 Use high-resolution spatial and temporal data to inform farmers and target interventions.
3 Match extension methods to local circumstances and demand.
4 Manage social and economic factors within the PA framework at a range of scales.

Together these elements constitute widening the classical PA focus from concentrating only on yield-limiting factors to embrace development inhibiting

Table 3.3 Precision agriculture's requirements, enabling factors, challenges and potential solutions in smallholder systems

Requirements	*Enabling factors*	*Challenges in smallholder systems*	*Solutions*
Perceived economic benefits	• access to information • demonstration plots and or working examples • payments for ecosystem services	• limited access to resources, such as fertilizers, labour and land leading to unsustainable land uses • lack of economic incentives for environmental stewardship • social capital required to manage ecosystem services manifest at landscape scale is often lacking • institutional barriers	• create opportunities for income diversification to allow higher inputs into land • provide better support for long-term sustainable strategies versus quick gains • support environmental stewardship with PES schemes • build institutions for collective management of landscape-scale processes
Access to agronomic data	• technology for data collection • functional dissemination systems	• relevant data not readily available to farmers and extension staff • most farmers rely on radio and telephone usage rather than Internet • weak social networks beyond friends and relatives	• investment in national agricultural databases • work at larger spatial scale in which mapping is feasible • make use of local knowledge • develop capacity for local informal experimentation by farmers, farmer groups and extension staff • improve communication flows within farming communities as well as between farmers, extension workers and research organizations
Extension services and or consultants	• demand-driven extension support or service providers • well-functioning social networks both vertical between research institutions, extension workers and farmer groups, and horizontal amongst farmers	• small-scale farmers lack capacity and mechanisms to articulate their demands • low levels of organization amongst farmers and weak negotiation power • technologies not available and low priority to supply them • low capacity to use these technologies at farm or research level	• develop tools that facilitate extension workers and farmer groups to employ principles in their specific contexts rather than pushing prescriptions • identify which extension methods are appropriate for different messages and contexts • facilitate farmer-to-farmer dissemination where appropriate • invest in private and public rural support centres where input and knowledge supply are combined • connect research and extension by embracing local experimentation, observation and learning • scale up local learning through embedding research within development and generalizing about what interventions work, where and for whom
Identifying yield-limiting factors that can be addressed with PA	• access to fertile land • understanding macro-level economic factors that influence farm gate prices • understanding the complex interaction of soil biochemical and plant physiological interactions	• insecure tenure • very small farm sizes • rainfed agriculture • market imperfections • no access to credit • strong link between culture, ethnicity and farming practices	• widen the classical PA focus from biophysical factors to also include social and economic factors • use advances in remotely sensed data availability and processing to characterize and map variability of smallholder farm systems

factors that are the ultimate causes of underperformance in smallholder agriculture. These four factors are each examined in detail below together with their integration to improve the precision of agricultural development.

Build on farmers' knowledge and expertise by facilitating local experimentation, observation and learning

There are numerous examples of variable management technologies that follow the fundamental principles of PA and that evolved as a result of farmers' local knowledge (Vanlauwe *et al.*, 2010; Heijting *et al.*, 2011). Tailoring soil and crop management to match local within-field variation has been a common strategy for Asian farmers. The growers traditionally noted yield variability both in space and time, and adjusted farm practices according to local site conditions (Srinavasan, 2006). In Malaysia, for example, this is reflected in small farm and field sizes of traditional agricultural communities (Mohd Noor *et al.*, 2005). In sub-Saharan Africa smallholder farms often consist of multiple plots managed differently in terms of allocation of crops, fertilizers and labour resources (Vanlauwe *et al.*, 2010). Three well-documented examples of such traditional PA practices are set out below.

Field dispersion in Niger

The subsistence mixed millet production system in Niger is characterized by intercropping with a range of secondary crops, either dual-purpose legumes (cowpea) or cash crops (sesame, sorrel). Smallholder farmers have adopted a variety of management strategies to secure at least a minimum yield each year by reducing agro-climatic risk. One such strategy is the dispersion of fields cultivated by a single household throughout the village territory, with farmers using varieties of differing time to maturity in order to distribute labour and other resource use across a longer period. Small and remote fields, in particular, are sown with early maturing varieties because these are the ones where seeding may be delayed as a result of labour shortages and problems of access. Using the APSIM crop simulation model Akponikpè *et al.* (2011) were able to provide evidence that field dispersion does indeed reduce inter-annual yield variability at household level and hence reduces the risk of severe household food deficits.

Management of microvariability in communal land in Zimbabwe

Ecologists and social scientists have documented the complex ways in which Zimbabwean farmers have coped with environmental variability since the early 1980s. As in other parts of Africa, input in the form of labour or nutrient amendments has to be adjusted carefully to both climatic as well as edaphic variability to maximize returns to labour. In a case study from the Mutoko area in northeastern Zimbabwe, Carter and Murwira (1995) point out that the different farm-management strategies used by households also depend strongly on their wealth status. Wealthier farmers, with access to cows and manure, tend to outbalance natural soil variation by applying nutrients to low fertility patches in the field, whereas farmers with few assets will concentrate their efforts on the more promising and fertile areas. Resources used are cattle, goat and chicken manure, composted crop residues and leaf litter, undecomposed leaf litter or termite-mound soil. At the beginning of the season farmers plant as much as they can as part of a deliberate strategy to give flexibility in the face of uncertain rainfall. Once the nature of the season is clear, they are able to concentrate on those crops, niches and patches within fields where successful yields are most likely. Farmers tend to grow cash crops (maize) on the best fields and patches and, if labour shortage becomes a problem during the season, concentrate management on these fields (Vanlauwe *et al.*, 2010).

Rice-production zones in Senegal and Gambia

Carney (1991) provides a detailed account of the traditional rice production in Senegal and Gambia. Over the past millennia farmers in Senegal and Gambia have fine-tuned rice cultivation to a range of agroecological zones with differing edaphic properties and moisture regimes. The system recognizes six micro-environments, each one combining hydrological regimes (rainfed, tidal and rainfall combined with marine tides) and soil properties in unique ways. Cultivation schedules, agronomic practices and seed selection are adjusted to the specific characteristics of each micro-environment. Diola women in southern Senegal plant as many as 15 rice varieties throughout the production zones, whereas Mandinka women in central Gambia name nearly 30 varieties, local as well as introduced, that are cultivated.

It is clear from these examples that smallholder farmers often recognize and address environmental variability at patch, field and landscape scales in their cropping practices. It is also well established that in many traditional systems, significant nutrient transfers are made via livestock at landscape scales to concentrate fertility on crop fields (Vanlauwe *et al.*, 2010) and that farmers have detailed understanding of tree–crop interactions and how different species affect yield and other ecosystem services, and their variability in space and time (Cerdan *et al.*, 2012). Increasingly, farmers' knowledge is being found to be dynamic and explanatory, consistent with the now well-established notion that farmers actively observe and experiment (Shiferaw *et al.*, 2009; Cerdan *et al.*, 2012). A key requirement to address heterogeneity in smallholder farming systems is for research and extension staff to acknowledge the limitations of their ability to match interventions to sites and farmer circumstances and the resulting risk that farmers face in adopting them (Tittonell *et al.*, 2011). This can be addressed by acknowledging that agricultural development at a fine scale involves local experimentation, observation, risk-taking and learning by farmers that build on their local knowledge and expertise.

Use of high-resolution spatial and temporal data to inform farmers and target interventions

Classical PA is measurement- and knowledge-intensive (Srinivasan, 2006; Tey and Brindal, 2012). This creates two challenges in a development context. First getting relevant information to famers, and second building their capacity to use this information. Mohd Noor *et al.* (2005) suggested that implementation of PA without major investment in building the capacity of the smallholder sector would widen social divisions and marginalize smallholders even more, as only commercial farms are presently capable of taking advantage of this knowledge-intensive technology. There are several examples that demonstrate that appropriate technological solutions to provide real-time data to smallholders do now exist.

In 2008, IRRI implemented a computer-based decision tool to address these issues, disseminated as a CD, web-based and mobile phone-based application. The tool consists of 10 to 15 questions regarding crop performance, easily answered within 15 minutes by an extension worker and farmer. Based on responses to the questions, a field-specific guideline with amounts of fertilizer by crop growth stage is provided (Global Rice Science Partnership, 2010; Timsina *et al.*, 2010). There are other examples of knowledge-based systems being developed and used to customize extension information across heterogeneous smallholder farm environments, for example FORMAT (Thorne *et al.*, 1997), LEGINC and LEXSYS (Moss *et al.*, 2003).

In 2005 Esoko, an agricultural market information platform, launched a new initiative to provide information on farming and agricultural produce. Farmers can request information such as produce price alerts, bids and offers, and news and advisories. MTN is sponsoring training of 500 farmers on the use and benefits of the Esoko Information Product. These farmers will also enjoy free SMS subscription to Esoko's market information for one year. Currently, the Esoko platform has registered over 14,000 contacts (users of Esoko), 847,000 prices, 517 trade groups and 480 markets (David-West, 2011).

The Grameen Foundation started the Community Knowledge Worker (CKW) initiative, which is building on a self-sustaining, scalable network of rural information providers. By disseminating and collecting relevant information via mobile phones the CKW provides access to up-to-date information on best farming practices, market conditions, pests and disease control, weather forecasts and market access. Upon request from a farmer, a CKW will use his or her mobile to access actionable information to meet farmer needs. In Uganda, CKWs have proved to be a vital link between farmers, government programmes, non-governmental organizations and other entities (e.g. Kiiza and Pederson, 2012).

The Africa Soil Information Service (AfSIS, http://africasoils.net) is a pioneering effort funded by the Bill and Melinda Gates Foundation (BMGF), and the Alliance for a Green Revolution in Africa (AGRA) to fill one of the major gaps in spatial information worldwide. The AfSIS produces timely, cost-effective, soil health surveillance maps at a scale useful to smallholders and rural development practitioners (Terhoeven-Urselmans *et al.*, 2010).

The Seeing Is Believing – West Africa (SIBWA) project provides farmers with real-time data about the spatial and temporal variation of the landscape they are in. Teams on the ground verify the data and update the database of information that they can use to develop an accurate map of each farm. The SIBWA partners translate the information into local languages and take the detailed maps back to the individual farmers, who can use them to plan and manage their crops for the coming growing season (Traore, 2009).

It is clear from these examples that progress is being made in using modern remote sensing and information technology to provide farmers and research and extension staff with fine-scale data on biophysical and socio-economic variables. More challenging is the need to develop tools and build capacity to use this information effectively in farmer decision-making and in targeting intervention options to sites and farmer circumstances. Examples exist of knowledge-based systems tools for customizing extension messages to local circumstances, but mainstreaming the development and use of such approaches remains in its infancy.

Match extension methods to message and context

The conventional wisdom in PA has been that smallholders lack process-based knowledge concerning agroecosystem function, creating uncertainty that obstructs sound decision-making under conditions of change. Therefore, providing farmers with spatial information about how best to use their resources can improve their practice (Cook *et al.*, 2003). But this view that smallholders have largely descriptive rather than explanatory agroecological knowledge does not stand up to scrutiny, with accumulating evidence that smallholder farmers in a range of contexts in Africa, Asia and Latin America display a well-developed understanding of agroecosystem function (Shiferaw *et al.*, 2009; Cerdan *et al.*, 2012). This farmer knowledge of ecosystem function, discussed in the previous sections, is bounded by their means of observation and comparison, and is often largely complementary to that of scientists and extension workers. Appreciating the sophistication of farmers' local knowledge, while recognizing both gaps in this knowledge and that farmers are often looking for innovations, opens the way towards the extension of principles that farmers can incorporate into their practice, rather than prescriptions that have to be customized to local circumstances, as discussed in the preceding section.

Many African and Asian countries are undergoing a progressive policy change towards more demand-driven and market-orientated agricultural services. This includes a policy shift from centralized extension systems, for example, Training and Visit (T&V), to decentralized, demand-driven agricultural advisory systems (Friis-Hansen and Duveskog, 2012). Traditional research and extension systems view farmers as end-users who must be persuaded into adopting research outputs, rather than as partners in the process. Advisory services for PA technologies can only be demand-driven if there is both a choice of advisers who are able to offer quality advisory services at an appropriate price as well as farmers that are capable of articulating their needs (Friis-Hansen and Duveskog, 2012). Farmers also need to be well informed about the different services and service providers, as well as being capable of recognizing quality services. Three examples of extension methods aiming to address a demand-led agenda are set out below.

Farmer field schools

The Farmer Field School Extension (FFS) approach originated in the context of integrated pest management in wet paddy fields in the Philippines and Indonesia. The success in these two countries has since been documented and used to promote and expand FFS and FFS-type activities to other countries and to other crops. The FFS is a group approach to agricultural technology development, focusing on adult, non-formal education through hands-on field-discovery learning (Friis-Hansen and Duveskog, 2012). These activities consist of simple field experiments, regular field visits and participatory analysis. A typical group of trainees includes 20–25 participants; the duration is about 8–12 weeks within a single crop-growing season. A facilitator leads the programme, conveying knowledge of and facilitating discussion of good crop-management decision procedures and practices. The knowledge gained from these activities enables participants to make their own locally specific decisions about crop-management practices. The success of FFS depends strongly on the dissemination of the knowledge and experience gained by participants to other farmers outside the FFS (Feder *et al.*, 2004). It therefore goes hand in hand with farmer-to-farmer dissemination.

Farmer-to-farmer dissemination

Using farmers as extension agents follows the theory of agents of change. The idea is that if one farmer adopts a technology successfully, other farmers may learn the innovation from him or her and share with others, thereby developing a multiplier effect. Rather than simply being agents for technologies imposed from outside, champion farmers are expected to become catalysts, mobilizing other farmers to experiment, recognizing local innovations and helping to assess and encourage innovation. Farmer-to-farmer dissemination builds on strong, socially based processes of learning, promulgating innovations through informal social networks such as friendships, kinships and farmer groups. This concept is being formalized and refined in the use of volunteer farmer trainers as a novel extension approach (Lukuyu *et al.*, 2012).

Farmer participatory research and innovation systems

Farmer participatory research describes a process that is based on a dialogue between farmers and researchers to develop improved technologies that are practical, effective, profitable and will address identified agricultural production constraints. Collaboration and communication between farmers and scientists ensures that research findings are relevant to farmers' needs and applicable within their biophysical and socio-economic environments. With assistance from moderators, farmers themselves discover solutions to their problems during informal discussions (Nain *et al.*, 2012). This sort of approach sits at the centre of the use of innovation platforms that bring stakeholders together to address problems at a range of scales from national to local (Hounkonnou *et al.*, 2012). Innovation system approaches are in use both for generally positioned integrated rural development and research-led projects that focus on particular aspects of smallholder productivity, such as the N2Africa project that focuses on the use of legumes (http://www.n2africa.org/).

Extension approaches themselves need to be evaluated on the basis of a continuously refined understanding of what works where and for whom. This requires systematic evaluation of different methods across a range of messages and contexts rather than reliance on the *post hoc* comparative analyses of case studies that has been more commonly used in this field. It requires research embedded within development praxis. Global networking exists that could facilitate this, but it remains to be seen whether systematic studies will be conducted and precision in the use of extension methods improved (Veldhuizen and Wettasinha, 2010).

Incorporate social and economic dimensions within the precision agriculture framework at a range of scales.

The concept of tailor-made crop-management interventions did influence the thinking of scientists working within the development domain in the late 1990s. The classical PA approach focuses mainly on biophysical factors, with anthropogenic factors recognized as drivers of farm-level heterogeneity but not targeted by interventions. The International Food Policy Research Institute (IFPRI) is trying to address this shortcoming by combining the idea of PA with those of economic geography (Chamberlin *et al.*, 2006). The concept of the agricultural domain was developed in the early 2000s and has been widely used by IFPRI to assist African governments in developing strategic priorities (Adeogun, 2009).

Looking from a broader development perspective rather than a narrow agronomic perspective, IFPRI is asking whether there is a set of indicators that explains the comparative advantage of one location over another location in terms of opportunities and constraints for sustainable agricultural development. Pender and colleagues proposed that the main factors that describe these localized comparative advantages are agricultural potential, access to markets and population density (Chamberlin *et al.*, 2006). Areas that are similar with respect to these three factors are called development domains and development interventions should be designed for each within a country. This approach thus uses PA ideas at a scale beyond the farm, producing options while having a much more local relevance than the traditional agricultural ecozone approach.

Tittonell *et al.* (2010) grouped smallholder farms in the highland and midland humid zones of East Africa based on resource endowment, dependence on off-farm income and production objectives into five farm types. They argue that efforts to enhance farmers' livelihoods can be successful only if these different farm typologies are taken into consideration when designing technological innovations and or development efforts. Households with a more agriculture-based livelihood strategy are more likely to implement and eventually adopt proposed technologies for agricultural intensification, whereas poorer farmers may be the major beneficiaries of social promotion (policy and or development) interventions. Compared to IFPRI's approach, Tittonell *et al.* (2011) bring the use of PA principles down a scale to account for between-farm variation within a development domain.

Another concept that incorporates a social dimension within an agronomic-centred PA frame is the concept of the socio-ecological niche (Ojiem *et al.*, 2006), which defines a multidimensional space of environmental, economic and social factors that affect the success of a farm-level intervention (Figure 3.1). This recognizes that farmers' decision-making depends largely on the farmer's evaluation frame of reference. This in turn is determined mainly by their belief in the technical and socio-economic consequences of decisions, their perception of the likelihood that these consequences will emerge and their evaluation of such consequences in relation to a set of aspirations (Donovan and Casey, 1998; Shiferaw *et al.*, 2009).

Applying precision agriculture principles to rural development

In classical agronomic theory, the limiting factor is that which prohibits a crop attaining its full yield potential when all other factors are optimal (Liebig, 1840). In a rural development context there are many interacting and overlapping factors constraining livelihoods, and there is controversy about how best to address rural poverty and the extent to which agricultural innovations can do so (Rigg, 2006; Harris and Orr, in press). Widening our focus on limiting factors from the crop to the livelihood involves traversing scales from the plant, field, farm and landscape to incorporate wider social networks and markets. This leads to fundamental questions in which agronomic interventions may or may not be appropriate, for example:

- What hinders a smallholder moving from subsistence to commercial production?
- Are the main constraints institutional or political, economic, agroecological or socio-cultural?
- Can these barriers be addressed by farm-level interventions or do they need much larger political interventions?
- What is the site-specific 'development' potential?
- Will farmers ever be able to produce sufficient products from their farm to ensure a life above the poverty line or should they be supported to abandon the farm and turn to more economically sustainable livelihoods?

Investigations of development interventions often reveal that the solution to rural poverty lies in the invigoration of farming and the redistribution of land. But patterns and associations of wealth and poverty have become more diffuse

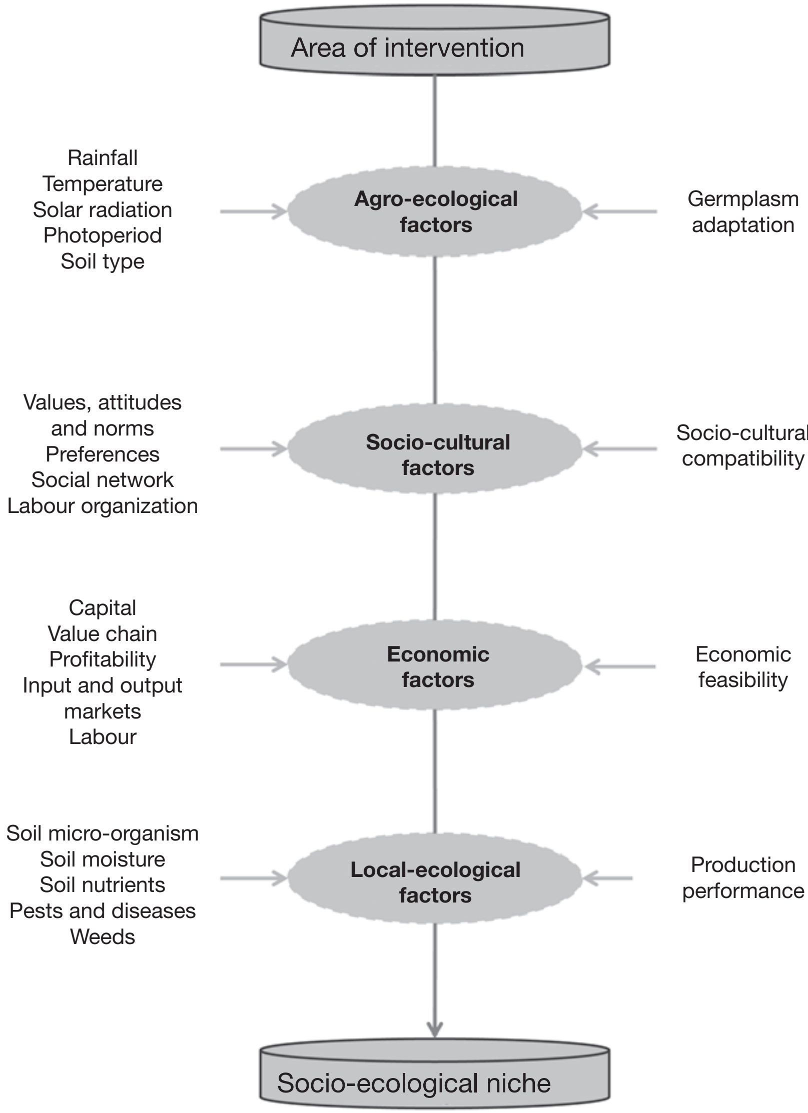

Figure 3.1 Schematic diagram depicting the concept of the socio-ecological niche, the hierarchical arrangement of factors that influence the delineation of the niche and the functions and outputs of the factors (Ojiem *et al.*, 2006).

and diverse as non-farm opportunities have expanded and heightened levels of mobility have led to livelihoods becoming less locally situated (Rigg, 2006). Investing in agriculture may preferentially support the wealthier households and thereby widen inequalities in the countryside (Tittonell *et al.*, 2011). Ersado (2006) cites research showing that in more remote areas of Zimbabwe, off-farm income sources increase income inequality because only the better-off and well-connected farmers can diversify, whereas in areas better connected to the major urban markets, it decreases income inequality because opportunities are more widely available. Understanding both the change in rural farming communities in terms of resource access as well as socio-economics and the variability between households or regions is essential to identify where and what the limiting factors are for farmers to reach prosperity. Rural communities operate within a fast-changing environment, both biophysically and socio-economically. Common drivers of change include the following:

1 declining soil health and increasing shortages of fertile land,
2 the erosion of profitability and returns to smallholder agricultural production,
3 the emergence of new opportunities in the non-farm sector, both local and distant,
4 high levels of mobility leading to livelihoods with increasing dependence on remittances from elsewhere,
5 increasing population and declining landholding size,
6 climate change.

Practitioners of PA have recognized the importance of addressing temporal variation in crop performance (Odgaard *et al.*, 2011). Plant and soil properties that depend on climate, such as nutrient availability and severity of pests and diseases, can have large inter-annual variations. Time-series of yield maps, either produced from modelling or based on annual measurements, are an integral tool of PA. Distinctive spatial and temporal trends in yield maps can often be identified by eye. Spatial trend maps are used to visualize consistently high- and low-yielding areas of fields or landscapes and temporal yield stability maps to identify distinctive management zones (McKinion *et al.*, 2010). The same approach could be applied to livelihood metrics to produce spatial trend and stability maps for livelihoods as opposed to crop yield.

Development practitioners have struggled to link information on social capital to that on natural capital. Often-stated reasons are the problem of integrating socio-economic and biophysical data because they have usually been collected at different scales (Thornton *et al.*, 2006; Carletto *et al.*, 2011) and the fundamentally different understanding of scale between social and environmental research (Gibson *et al.*, 2000). However, the spatial dimension of social processes and the context that defines them have come back into sharp focus among social and behavioural scientists. Social network and spatial analytic strategies in particular are placing social phenomena in relational and physical contexts. Social networks are described by the propinquity effect, the phenomenon that people who are located closer together in physical space have a higher probability of forming relationships (Adams *et al.*, 2012). This spatial autocorrelation of social ties between farmers provides bias-free criteria for domain selection. In addition it provides a social variable with the same spatial dimension as other biophysical variables measured, resolving the scale problem.

Conclusions

Although long practised intuitively by subsistence farmers, precision agriculture came of age in the 1990s as a technically driven means to improve industrialized agriculture. By analysing the multiple crop and soil physiological factors that lead to spatial and temporal yield variations and then designing site-specific management strategies to close yield gaps, PA promised benefits to both farmers and society through increasing production efficiency while improving stewardship of the environment. Although PA has not delivered the technological revolution in the agricultural sector that was predicted, it has succeeded in highlighting the importance of locally adapted interventions to both agricultural practitioners and scientists.

In the context of intensification of smallholder production in developing countries the ability to adapt interventions locally is critically important. With average farm sizes in both Africa and Asia well below 2 ha, there can be little doubt that meeting the rising global demand for food will require closing yield gaps on smallholder farms. These farms and the contexts in which they operate are highly heterogeneous at fine scales, so that interventions to improve productivity need to be tailored to sites, farmer circumstances and institutional settings. This involves a focus on applying the principles of PA at a range of spatial scales to improve the precision of agricultural development, rather than directly trying to support the field- and farm-level agronomic decisions of millions of smallholder farmers. To achieve this, the classical PA approach that focuses mainly on biophysical factors clearly has to be broadened to include variability in resource endowment, culture, market access and gender realities. This means using PA concepts at a range of scales, not just for variable within-field management. Such approaches show promise and are being implemented, but remain in their infancy.

Further application of PA concepts to bring benefits to smallholder farmers requires (a) increased understanding of the processes and principles determining farm performance, (b) increased capacity for local experimentation, monitoring and learning and its aggregation across scaling domains and (c) increased access to real-time information on both biophysical and socio-economic factors. Precision agriculture principles of using and adapting to spatial heterogeneity need to be made more important within research and extension thinking. It also requires adjustment of the research development continuum from research for development to research in development. The concept of eco-efficiency is emerging as a dominant paradigm for smallholder agricultural development. It stresses the need to tighten nutrient and water cycles to intensify production sustainably, without increasing the risk to which smallholder farmers are exposed. The principles of PA, if applied appropriately, readily lend themselves to improving resource use efficiency and reducing leakage at field, farm and landscape scales. They can also contribute to reducing the risk that farmers face in adopting and adapting innovations when applied across large scaling domains, by involving integrated research and extension teams, using interdisciplinary and participatory approaches to agricultural innovation.

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