Agricultural innovations for sustainable crop production intensification

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Abstract

Sustainable crop production intensification should be the primary strategic objective of innovative agronomic research for the coming decades. A range of often very location-specific options exists for farming practices, approaches and technologies that can strengthen sustainability and at the same time intensify crop production in terms of increased output and productivity (efficiency). The main challenge is to encourage farmers in the use of ecologically-appropriate technologies and practices and to ensure that knowledge about sustainable production practices is increasingly accepted, applied and innovated upon by farmers. There is a large but underutilized potential to integrate farmers' local knowledge with science-based formal knowledge. This integration aims at innovating improved practices and technological options through favourable institutional arrangements to foster an innovation system. The same holds true for the design, implementation and monitoring of improved natural resource management that links community initiatives to new external expertise and knowledge. A comprehensive effort should also be undertaken to measure different stages of the innovation system, including technological adoption, adaptation and diffusion at the farm level, and to investigate the impact of agricultural policies on technological change, technical efficiency and production intensification.

This paper provides a review of agronomic management practices supporting sustainable crop production systems and intensification, and testifying to developments in the selection of crops and cultivars. The paper also describes crop farming systems taking a predominantly ecosystem approach and it discusses the scientific application of this approach for the management of pest and weed populations. In addition, it reviews the improvements in fertilizer and nutrient management which are at the basis of productivity growth and it describes the benefits and drawbacks of irrigation technologies. Finally, it suggests a way forward based on seven changes in agricultural development that heighten the need to examine how innovation occurs in the agricultural sector.

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Introduction

Over the last 40 years, world population has increased by more than 4 billion and in the next 40 years it is expected to increase from the estimated 7 billion in 2011 to around 9.1 billion in 2050 (Figure 1). Nearly all of this population increase will take place in the part of the world comprising today's developing countries, while the greatest relative population increase (120%) is expected in today's least-developed countries. This ever-growing population will lead to an increase in the global demand for food for at least 40 years to come. In order to meet the additional food demand – excluding additional demand for agricultural products used as feedstock in biofuel production – agricultural production must increase by 70% globally, and by almost 100% in developing countries. This increase is equivalent to an extra billion tonne of cereals and 200 million tonnes of meat to be produced annually by 2050, compared with the production between 2005 and 2007 (Bruinsma, 2009).

In the past, the primary solution to food shortages was to bring more land into agriculture and to exploit new fish stocks. In the future, our ability to produce food will be affected by growing competition for land, water, and energy , and by the urgent requirement to reduce the impact of the food system on the environment. The effects of climate change are a further threat to food security (Godfray *et al.*, 2010; Government Office for Science, 2011). The relationship between resource demand and supply is unbalanced. Yet, in the last 5 decades, though grain production has more than doubled, the amount of land globally devoted to arable agriculture has increased by only 9% (Pretty, 2008). In the last 50 years there has been a marked growth in food production which dramatically decreased the proportion of people seasonally or chronically hungry, despite the doubling of the total population (Figure 2).

Some new land could be brought into cultivation in Sub-Saharan Africa and South America, but the demand for land from other human activities makes this an increasingly unlikely and costly solution, particularly if protecting biodiversity and the public goods provided by *natural* ecosystems (for example, carbon storage in rainforest) are given higher priority (Balmford *et al.*, 2005). In recent decades, agricultural land that was formerly productive has been taken away by urbanization and other human uses, as well as by desertification, salinization, soil erosion, and other consequences of unsustainable land management. Further losses of agriculture's natural resource base, especially water loss which may be exacerbated by climate change, are likely to happen (IPCC, 2007). Recent policy decisions to produce first generation biofuels on good quality agricultural land have added to the competitive pressures (Fargione *et al.*, 2008). Thus, the most likely scenario is that more food will need to be produced from the same amount of (or even less) land (Godfray *et al.*, 2010).

The challenge of increasing food production, food security and farmer income is, then, to increase productivity. Productivity growth refers to the change in output/input ratios over time. Therefore, it is a resource efficiency indicator used per unit of output. However, over the last forty years much of the increase in productivity has been related to improved genetic resources, increased utilization of pesticides, increased input of agricultural mineral nutrients, increased use of mechanised farm power and fossil fuel and greater irrigation intensity (Figure 3).

To feed a growing world population, we have no option but to intensify crop production sustainably (FAO, 2011). A renewed focus on defining concrete actions to improve agricultural productivity growth on a sustainable basis is needed now. Intertwining challenges of climate change and competition for land, water, and energy require attention in the following areas: bridging the gap between actual and potential productivity levels in the agriculture of developing countries; investing in agricultural innovation, broadly defined; and improving national and international research collaboration (OECD, 2011).

The new paradigms of *sustainable crop production intensification* recognize the need for a productive and remunerative agriculture which at the same time preserves and enhances the natural resource base and environment, and positively contributes to harnessing the environmental services. Sustainable crop production intensification must not only reduce the impact of climate change on crop production but also mitigate the factors that cause climate change by reducing emissions and by contributing to carbon sequestration in soils. Intensification should also enhance biodiversity – above and below the ground level – in crop production systems so as to improve ecosystem services for a better productivity and a healthier environment.

A set of soil-crop-nutrient-water-landscape system management practices known as Conservation Agriculture (CA) has the potential to achieve all of these goals (Derpsch and Friedrich, 2010; Friedrich *et al.*, 2012). CA has the potential for managing decreasing soil productivity and for improving the resource-use efficiency and the natural resources base. Hence, it adapts to and mitigates climate change and leads to a more efficient use of inputs to reduce production costs. Integrated farming systems based on CA, irrespective of the location, management and socioeconomic conditions, must produce more for less to improve profitability and livelihood security for farmers.

In short, the globally-shared challenge is to ensure a more efficient use of available land and water resources as well as purchased production inputs. Thus, improving agricultural productivity is essential to increase global food supplies on a sustainable basis (OECD, 2011). Standard agronomic land, water and crop management practices supporting the intensification of sustainable crop production include: selection of crops and cultivars, efficient farming systems for crop establishment, plant protection, fertilizer and nutrient management, and sustainable crop rotations. When applied together, these practices collaborate to improve factor and overall productivity (FAO, 2011).

What is needed to support sustainable crop production systems?

Investments in knowledge – especially in the form of science and technology – have featured prominently and consistently in most strategies to promote sustainable and equitable agricultural development at the national level. In the long run, productivity growth requires innovation, *i.e.* a process of transforming knowledge into money

Figure 1. World population 1965-2050. Source: Population division of the Department of Economic and Social Affairs of the United Nations Secretariat (2007).

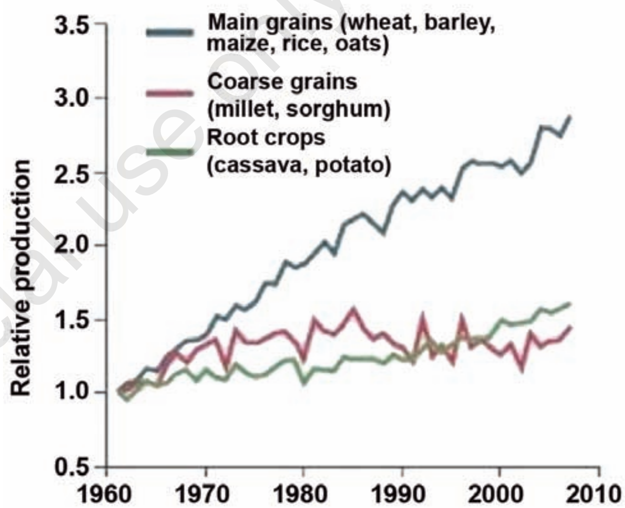

Figure 2. Changes in the relative global production of crops since 1961 (when relative production scaled to 1 in 1961). Source: FAOSTAT (2009). Available from: http://faostat.fao.org/default.aspx

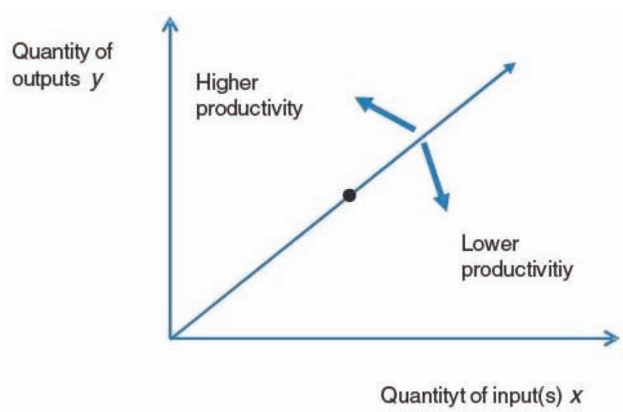

Figure 3. Graphical illustration of productivity growth. Source: OECD (2011).

(whereas research is to transform money into knowledge) (Figure 4).

Agriculture should innovate to increase competiveness by providing advantages in the market, but also to offer more cost-effective public goods. Innovation can be based on the result of scientific research about processes or the attributes of a product, the introduction of new or significantly improved goods or services, or the use of new inputs, processes, organizational or marketing methods (OECD and Eurostat, 2005). Scientific and technological knowledge and information add value to existing resources, skills, knowledge, and processes, leading to innovative or novel products, processes and strategies. These innovations can be simple, like changing the crops that are produced, or more complex, like developing a new business model with entirely different production technologies to satisfy different needs (*e.g.* from better production and productivity to more quality such as flavour, fragrance, or colour). Innovation produces better packaging that protects the nutritional content and also a cost system of *more for less* that allows establishment of more attractive prices. Economies of scale are also a component of productivity growth for individual firms (Latruffe, 2010).

The ability to innovate and to become more productive is partly affected by the farm itself and the farmer's engagement, but it can also be affected by the economic and political environment where the farm is operating (Porter *et al*., 2007). Innovation is therefore central to development, and effective innovation systems include all the relevant stakeholders who can contribute to the discovery of underlying processes and principles, transforming the principles into technologies and practices and further adapting these to improve efficiency and performance. Governments have recognized that much of a firm's ability to innovate can be driven by public research, infrastructure, regulations, taxation, and other public policies that have both direct and indirect effects on the operating environment of firms (OECD, 2011). An examination of the agronomic innovations (crops and cultivars; farming systems for crop which take a predominantly ecosystem approach; management of pest and weed populations; fertilizer and nutrient management and irrigation technologies) over the past four decades and the impacts that they have had on crop productivity and the environment can help identify those areas where sustainable intensification of agri-

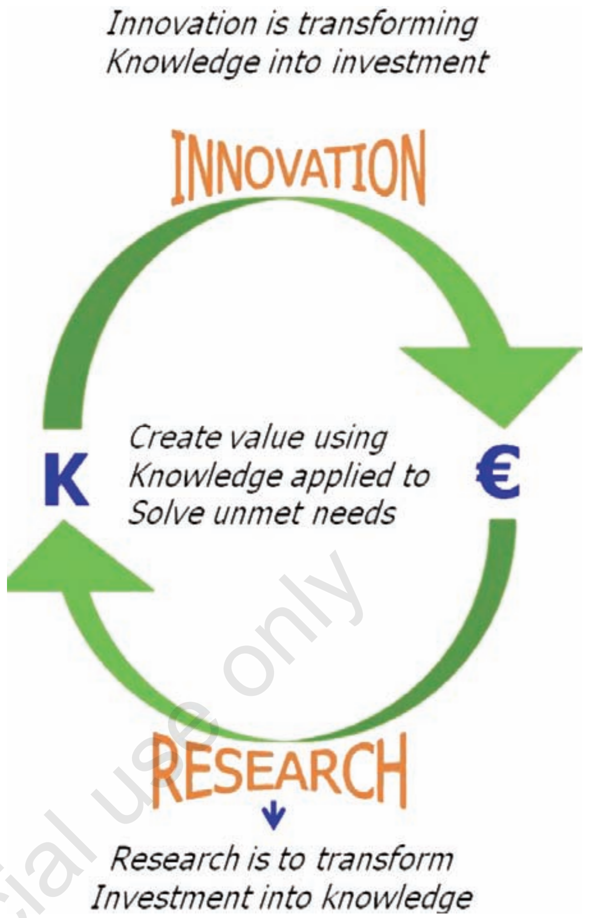

Figure 4. Raffler's circle explaining the difference between research and innovation. Adapted from H. Raffler (VP Innovation of Siemens, unpublished).

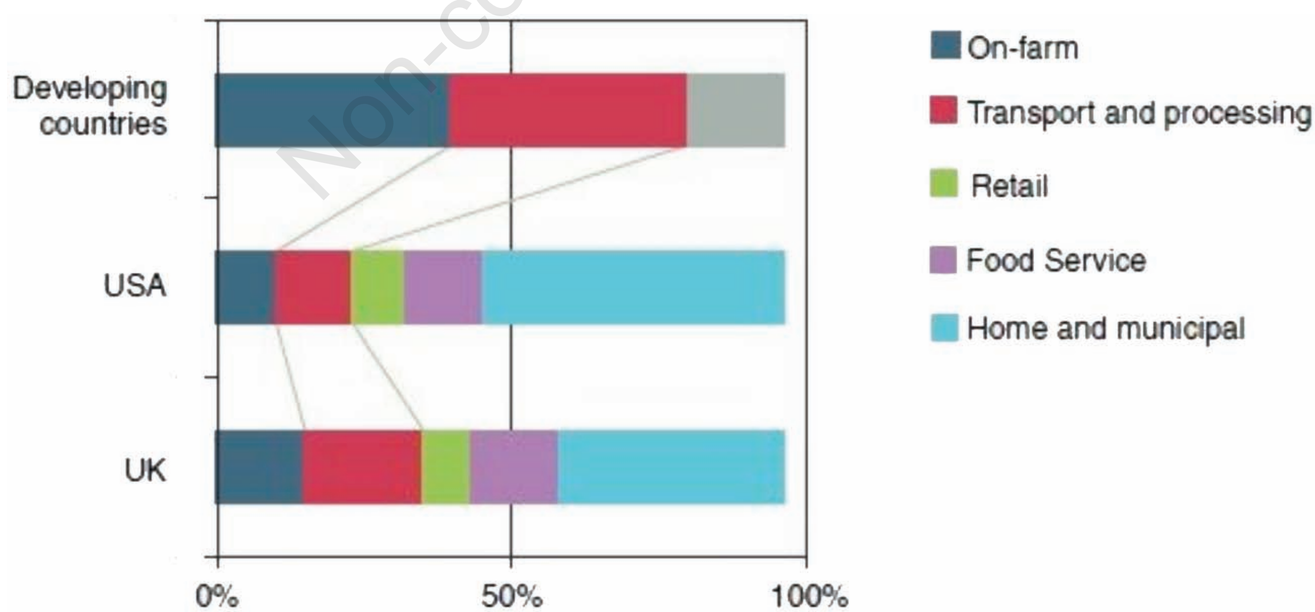

Figure 5. Makeup of total food waste in developed and developing countries. Retail, food service, and home and municipal categories are grouped together for developing countries. Source: Godfray *et al.* (2010).

cultural systems may be done in the future.

The importance of innovations along the food chain and post-harvest handling and processing is also growing to meet consumers' demand for food quality, storability and convenience. Although data are scarce (Figure 5), roughly 30% to 40% of food in both developed and developing countries is doomed to be wasted mainly because of the lack of food-chain infrastructures and the lack of knowledge or investment in storage technologies in farms. In the developed countries, stricter food quality regulations, consumer preferences and food processing and packaging as well as modern urban life style are additional factors that contribute to food being wasted. Thus, there is a need for continuing research in post-harvest storage technologies (WRAP, 2008).

Crops and cultivars

Farmers will need a genetically diverse portfolio of improved crop varieties that are suited to a range of agro-ecosystems and farming practices, and are resilient to climate change. The Green Revolution succeeded in improving productivity by using conventional breeding to develop F1 hybrid varieties of maize and semi-dwarf, disease-resistant varieties of wheat and rice. These varieties could be provided with more irrigation and fertilizer (Evenson and Gollin, 2003) without the risk of major crop losses due to lodging (falling over) or severe rust epidemics. Increased yield is still a major goal, but the importance of greater water- and nutrient-use efficiency, as well as tolerance of abiotic stress, is also likely to increase (Godfray *et al.*, 2010). However, the heavy reliance on irrigation and intensive crop inputs, as well as the reduction in biodiversity associated with the replacement of local and varied landraces with cultivars that are released and grown over a wide geographical area, may lead to a reduction in the sustainability of crop production in the future. The high-yielding cultivars may also contain lower levels of trace elements than traditional crops or than lower yielding cultivars, due to their high carbohydrate production. Currently, the major commercialized genetically modified (GMO) crops involve relatively simple manipulations, such as the insertion of a gene for herbicide resistance or another for a pest-insect toxin. The next decade will see the development of combinations of desirable traits and the introduction of new traits such as drought tolerance. By mid-century, much more radical options involving highly polygenic traits may be feasible. Production of cloned animals with engineered innate immunity to diseases that reduce production efficiency may reduce substantial losses coming from mortality and sub clinical infections. Biotechnology could also produce plants for animal feed with modified composition that increase the efficiency of meat production and lower methane emissions (Godfray *et al*., 2010). The issue of trust and public acceptance of biotechnology has been highlighted by the debate over the acceptance of GMO technologies. As genetic modification involves germline modification of an organism and its introduction in the environment and food chain, a number of particular environmental and food safety issues need to be assessed. Despite the introduction of rigorous science-based risk assessment, this discussion has become highly politicized and polarized in some countries, particularly in Europe. Our view is that genetic modification is a potentially valuable technology whose advantages and disadvantages need to be considered rigorously on an evidential, inclusive, case-by-case basis: Genetic modification should neither be privileged nor automatically dismissed (Godfray *et al*., 2010).

Table 1. Effects on sustainability and ecosystem services of production system components applied simultaneously.

System component ▶	Mulch cover	Minimum or no-tillage	Legumes (to supply plant nutrients)	Crop rotation
Simulate optimum *forest-floor* conditions	√	√		
Reduce evaporative loss of moisture from soil surface	√			
Reduce evaporative loss from soil upper soil layers	√	√		
Minimize oxidation of soil organic matter, CO_2 loss		√		
Minimize compactive impacts by intense rainfall, passage of feet, machinery	√	√		
Minimize temperature fluctuations at soil surface	√			
Provide regular supply of organic matter as substrate for soil organisms' activity	√			
Increase, maintain N levels in root-zone	√	√	√	√
Increase CEC of root-zone	√	√	√	√
Maximize rain infiltration, minimize run-off	√	√		
Minimize soil loss in run-off, wind	√	√		
Permit, maintain natural layering of soil horizons by actions of soil biota	√	√		
Minimize weeds	√	√		√
Increase rate of biomass production	√	√	√	√
Speed the recuperation of soil-porosity by soil biota	√	√	√	√
Reduce labour input		√		
Reduce fuel-energy input		√	√	√
Recycle nutrients	√	√	√	√
Reduce pest-pressure of pathogens				√
Re-build damaged soil conditions and dynamics	√	√	√	√
Pollination services	√	√	√	√

N, nitrogen; CEC, cation exchange capacity. Source: Friedrich *et al.*, 2009.

Production systems for better productivity

Current crop production systems vary widely. There are many production systems which take a predominantly ecosystem approach and which are not only productive, but also more sustainable than traditional production practices in terms of environmental impacts.

Conservation agriculture

Conservation agriculture (CA) is a method designed for resource-saving agricultural crop production whose aim is to achieve acceptable profits together with high and sustained production levels while simultaneously preserving the environment. Interventions such as mechanical soil tillage are reduced to an absolute minimum and external inputs, such as agrochemicals and nutrients of mineral or organic origins, are applied at the optimum level and in a way and quantity that does not interfere with, or disrupt, the biological processes (FAO, 2012). Healthy soils underpin CA, which in turn is characterized by three intertwined principles, namely: i) continuous minimum mechanical soil disturbance and no-till direct seeding; ii) permanent organic soil cover with crop residues and cover crops; iii) crop diversification with crop rotations and associations in case of annual crops or plant associations in case of perennial crops. CA facilitates good agronomy, such as timely operations, and improves overall land husbandry for rain fed and irrigated production and is complemented by other good practices, such as the use of quality seeds and integrated pest management. Benefits of CA, shown in Table 1, include improved moisture conservation and water infiltration, reduced run-off of pesticides and fertilizers, reduced consumption of fuel, improved organic matter content with associated carbon sequestration, improved diversity of soil, flora, and fauna, better wildlife habitat, better soil structure, reduced wind and water erosion, less labour and less investment in equipment (Cook, 2006; Huggins and Reganold, 2008; Stagnari *et al.*, 2009; Kassam *et al.*, 2012). CA has also proved to contribute to significant increases of crop production (40-100%) in many regions with decreasing needs for farm inputs, in particular power and energy (50-70%), time and labour (50%), fertilizer and agrochemicals (20-50%) and water (30-50%). Furthermore, in many environments soil erosion is reduced to a level below the soil regeneration one or it is avoided altogether, and water resources are restored in quality and quantity to levels recorded before the land was put under intensive agriculture (Montgomery, 2007; FAO, 2011).

A summary of numerous published studies comparing no-till to conventional tillage under natural rainfall conditions showed that, on average, no-till reduced soil erosion, water runoff and herbicide runoff by 92%, 69% and 70%, respectively (Royal Society of London, 2009). After an intense rainfall of 100 mm in 24 h, Chaves (1997) found that direct drilling reduced the peak flow by 86% and the weight of sediment leaving the catchment by 98%, compared to conventional till (Table 2). Improved planters and better herbicides led to the widespread adoption of CA in many parts of the world over the past 40 years. Conservation agriculture is now practiced on some 125 million ha worldwide, or about 10% of the total crop land. Highest adoption levels (more than 50% of crop land) are found in Australia, Canada and the southern cone of South America. Its adoption is increasing in Africa, Central Asia and China (Pisante *et al.*, 2010; Friedrich *et al.*, 2012).

Such sustainable production systems are knowledge-intensive and relatively complex to learn and implement. They are dynamic systems, offering farmers many possible combinations of practices to choose from and adapt according to their local production conditions and constraints (Pretty, 2008; Kassam *et al*., 2009, 2010; Godfray *et al.*, 2010; Pretty *et al*., 2011). Modernization and transformation based on CA principles and practices (as well as on existing, though in transition, practices) require affordable sources of adapted good-quality seeds, affordable mineral fertilizer, as well as farm power, equipment and machinery, and pesticides (herbicides, insecticides, fungicides, *etc*.).

Field operations required by each system are summarized in Table 3, together with the outcome of calculations on fuel energy requirement. Fuel energy requirement includes an appropriate allowance for the *overhead* energy used in equipment manufacture and maintenance.

Policy planning and investment are required to establish/strengthen the seed, fertilizer, pesticide, and farm equipment machinery sectors. In particular, national action plans for input supplies and services consistent with national crop sector strategies would be essential to ensure the delivery of sector development strategy, projects and campaigns (FAO, 2010). Limitations associated with CA are elaborated in (Shaxson *et al*., 2008) and can include increased crop diseases and insect pests (Cook, 2006), development of herbicide-tolerant weeds, reliance on agrichemicals, excess moisture, cooler soils, initial increase in nutrient requirements, and requirement for specialized nutrient management to avoid immobilization and volatilization (Malhi *et al*., 2001). Where livestock is part of the farming system, switching to CA from tillage agriculture requires a different way of

Table 2. Parameters of the MUSLE model, values of run-off and sediment load from conventional tillage and no-tillage.

Parameter	Description	CT	NT
CN	Runoff-generation factor	70	45
R (mm/24h)	Rainfall amount	100	100
K	Soil erodibility	0.0013	0.013
L	Slope-length factor	4	4
S	Slope-steepness factor	0.5	0.5
C	Factor for use/management of soil	0.3	0.05
P	Factor for mechanical practices	0.5	0.5
Q (m^3)	Runoff volume	326,000	45,000
Q (m^3/s)	Peak flow	36.3	5
Y (t)	Sediment load	3198	58

CT, conventional tillage; NT, no-tillage. Adapted from Chaves (1997).

Table 3. Machinery operations and energy requirements for three tillage systems.

Operations	Residue management	Tillage frequency, operations/crop			Herbicide spraying	Planting	Σ fuel energy MJ/ha
Representative systems		Primary	Secondary	Seedbed			
TA conventional tillage, no herbicide		1	2	2	0	1	1941
CA reduced/zero, <1 tillage/crop	1	0.6	0	0	4	1	1116
CA permanent bed, minimum tillage		0.25	0	0	3	1	397

TA, tillage agriculture; CA, conservation agriculture. Source: Tullberg (2005).

managing the available functional biomass. This different management implies that the needs of both soil health and livestock feed requirement should be met, and that over time more residues should be allocated to cover the soil. This can be a challenge in certain dryland situations (Kassam *et al*., 2012), but not in others (Landers, 2007; Owenya *et al.*, 2011).

Development of precision agriculture

Conventional crop management presumes uniformity. In order to manage spatial variability, it is necessary to adopt management practices that allow for the precise management of soils, crops, pests according to localized differences within a field. Innovative agricultural techniques, known as Precision Agriculture, Site-Specific Management, Precision Farming, refer to innovative agricultural techniques aiming at improving production and reducing environmental pollution through a more accurate management related to field variability (Basso *et al.*, 2005).

The site-specificity of precision agriculture is intuitively appealing and represents a means of improving the economic and environmental performance of the cropping system. Precision agriculture encompasses a broad array of topics ranging from variability of the soil resource base, weather, plant genetics, crop diversity, machinery performance, most physical, chemical, biological inputs used in crop production, and socio-economic aspects. A successful precision agriculture system depends on how well it can be applied to manage spatial and temporal variability in crop production and on what benefits it could bring. Before this system can be adopted effectively, it is fundamental to have a clear understanding of the in-field variability, which is not an easy task. For example, rather than nitrogen (N) applications based on yield goals and an estimation of N supply using soil tests and a uniform rate within a field unit, precision management applies variable rates across the field, according to the projected difference between N supply from the soil and N demand by the crop. The rate calculations were initially based on intensive soil sampling and analysis, using grids, soil types, landscape position, or some other method to divide the field into application units (Schlegel *et al*., 2005). The development of continuous yield-sensor and differential GPS (DGPS) has been perhaps the most important and influential development in precision agriculture data collection. Yield rates vary spatially and maps produced by the yield monitors systems demonstrate the degree of within-field variability (Batchelor *et al.*, 2002; Basso *et al.*, 2007, 2011). The magnitude of this variability is a good indicator of how suitable it is to implement a spatially variable management plan. Technological improvements will follow an evolutionary process and new developments will continue to be adapted for making agricultural decisions. It is anticipated that investments in the development and diffusion of precision agriculture by the private sector will continue at a fast pace.

Organic farming

When practised in combination with CA, organic farming can lead to improved soil health and productivity, increased efficiency in the use of organic matter and energy savings. However, tillage-based organic production restricts the management options available to producers, often resulting in lower crop productivity due to excessive mechanical soil disturbance, nutrient deficiencies and weed, insect or disease problems where the cropping system is not adequately diversified and soil mulch cover is inadequate. Organic CA farming serves mainly niche markets and it is practised in parts of Brazil, Germany and the USA, and by some small-holder farmers in Sub-Saharan Africa (Badgley *et al.*, 2007).

Improvements in plant protection

Insect pest and disease control

Improvements in agro-ecosystem management can help avoid indigenous insect pest outbreaks, respond better to pest invasions and reduce risks posed from pesticides to both human health and the environment.

Integrated pest management (IPM) is an example of an ecosystem-based production practice involving the scientific application of ecosystem principles for the management of pest populations and aiming at avoiding their build up to damaging levels. IPM is based on understanding the way local agro-ecosystem works, the relationship between insect pests and their natural enemies, and the mechanisms regulating the balance between pest and predators (FAO, 2011).

Weed control

Before World War II, weed control relied primarily on non-chemical control mechanisms such as mechanical tillage, crop rotation, mowing, use of clean seed, field sanitation, delayed seeding, and the growth of highly competitive crops. Some selective broad-leaf herbicides were developed from the 1930s to the beginning of World War II, but the development and the widespread adoption of 2,4-Dichlorophenoxyacetic acid (2,4-D) in the mid- to late-1940s represented the beginning of the modern era of chemical weed control. Use of herbicides became a significant factor in crop production in the 1950s, with intense activity in herbicide development during the 1960s and 1970s. In Canada, herbicides account for approximately 80% of total pesticide sales (Holm and Johnson, 2009). Development of effective herbicides was one of the driving factors which guaranteed the development of reduced tillage and no-till production systems and contributed to the dramatic increase in agricultural productivity over the past 40 years. The requirements of herbicide manufacturing energy set out in Table 4 for herbicides commonly used in fallow situations are based on data from Zentner and colleagues' (2004) and Green's (1987) studies.

Table 4. Energy requirements of herbicide manufacture.

Commercial product	Herbicide/s	Manufacturing energy MJ/kg	Application rate kg/ha (label)	Manufacturing energy MJ/l/ha
2,4-D Amine	2,4-D	98	0.500	49
Atrazine	Atrazine	190	0.500	95
Spray Seed 250	Diquat	400	0.115	108.1
	Paraquat	460	0.135	
Round-up CT	Glyphosate	511	0.450	229.95

2,4-D, 2,4-Dichlorophenoxyacetic acid; CT, conventional tillage. Adapted from Zentner *et al.* (2004) and Green (1987).