CHAPTER 7

Climate-Smart Agriculture Practices Based on Precision Agriculture: The Case of Maize in Western Congo

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Precision agriculture (PA) is an appealing concept, referring to a package of technologies that can reduce input costs by providing the farmer with the detailed information necessary to optimize field management practices, resulting in improvements in yields and profits as well as environmentally less burdensome production (National Research Council 1997; Schimmelpfennig 2016). For small farmers in developing countries in particular, PA holds the assurance of substantial yield improvement with minimal external input use (Florax, Voortman, and Brouwer 2002).

Although the US Department of Agriculture (USDA) reported that PA technologies were used on roughly 30 to 50 percent of US corn and soybean acres during the period 2010–2012 (Schimmelpfennig 2016), it appears that adoption of PA technologies is limited in Africa and Asia (Swinton and Lowenberg-DeBoer 2001). One reason for the low adoption rates may be that, as some studies reveal, increased input efficiencies result in rather modest profitability increases (Kilian 2000; Cook, Adams, and Bramley 2000). Although precision farming can include simple practices, it does imply complex and intensely managed production systems, such as the use of Global Positioning System (GPS) technology to spatially reference soil, water, and yield (NRCS 2007). The human capacity required to master the use of these technologies is not yet readily available in Africa.

In the Democratic Republic of the Congo (DRC), agriculture is the most important economic sector, accounting for 44.9 percent of the gross domestic product and employing more than 70 percent of the population (62 percent of males and 84 percent of females). Undoubtedly, the agricultural sector remains the largest sector in terms of employment and thus constitutes the most promising foundation for achieving food security as well as overall economic development. However, this huge agricultural potential remains largely unexploited, with only about 10 percent of arable land being cultivated (Herdeschee, Kaiser, and Samba 2012).

Although food security is at the heart of economic and social development priorities in the DRC, and despite the country's great agricultural potential combined with government efforts to alleviate poverty, the threat of food insecurity is still present. The country has been ranked first on the Global Hunger Index for several years; average daily food consumption is estimated at less than 1,500 kilocalories per person, well below the minimum of 1,800 per person required to maintain good health (USAID 2012, 2014). Food insecurity has been exacerbated by decades of conflict, reduced agricultural productivity, and migration out of rural areas.

The growing population constitutes an additional constraint to achieving food security in the DRC. In 2017, the United Nations estimated a population of 82 million, with a growth rate of 3 percent per year (World Population Review 2017). The increasing competition for land by multiple users suggests that available land suitable for agriculture is likely to decrease. In order to meet the food demand of a growing population, efficient and sustainable cropland management is therefore crucial to increase crop productivity without further degrading the soil and depleting resources.

The vast majority (70 percent) of the rural population that depends on agriculture for its livelihood relies mainly on rainfall. Indeed, agriculture is primarily rainfed in the DRC and also characterized by crop rotation and slash-and-burn farming that leaves land fallow for up to five years and typically managed to only a very low output per hectare (World Bank 2010). Maize, for instance—crucial to food security because it is the most frequently eaten cereal in the country (World Food Programme 2014)—is grown by small-scale farmers, typically under rainfed conditions with low or no inputs. As a result, yields are very low and at risk to changes in weather patterns.

In general, extreme weather events and increasing unpredictability in African weather patterns are already having serious consequences on crop yields for farmers who rely on rainfall. Though the western part of the DRC has good rainfall compared with the southern part, the area is still vulnerable to climate change as a result of changes in rainfall and temperature patterns, as well as extreme weather events. Climate predictions suggest that some areas will get warmer and others wetter by 2050 (Harvey et al. 2014).

In addition to changes in weather patterns, the agricultural sector faces other serious challenges that will require Congolese farmers to monitor and manage their farming operations more effectively using climate-smart agriculture (CSA) practices. There have been proposals to address concerns of food security and climate change using an integrated framework (FAO 2013a; Harvey et al. 2014). According to the Food and Agriculture Organization of the United Nations (FAO), CSA refers to land management practices that increase food security, boost the resilience and adaptive capacity of farmer households to climate variability, and mitigate climate change (FAO 2013a). Conservation agriculture, a combination of soil management practices including minimal soil disturbance, permanent soil cover, and crop rotation, is promoted across Africa south of the Sahara (SSA) and often labeled as "climate smart" (FAO 2013a). In fact, conservation agriculture practices have been found to address some of CSA's goals under certain conditions (Sithole, Magwaza, and Mafongoya 2016). In short, CSA practices seek to increase agricultural production and incomes by adapting and building resilience to climate change.

Similarly, the implementation of PA practices in farming operations has the potential to provide solutions to climate-related challenges and promote sustainable farming operations. For example, variable-rate application of seeds and nutrients based on inherent soil properties can increase yield in high-producing areas, maintain yield in low-producing areas, and reduce the use of costly inputs. Likewise, precision nitrogen (N) management can balance soil nutrient content, preventing unwanted nitrate leaching that can impair surface water and groundwater quality (Colorado State University Extension 2012). Indeed, established advantages of implementing improved cropland management practices include not only higher and more stable yields but also increased resilience, which will further improve food security (Abberton, Conant, and Batello 2010; Vallis et al. 1996; Pan et al. 2006; Woodfine 2009; Thomas 2008).

Although there is a great potential to increase agricultural production in the DRC, it is crucial for farmers to adopt these PA practices in order to increase their productivity while managing climate risks, thus improving their livelihoods. In order to achieve and maintain food security, agricultural systems need to be transformed to increase the efficiency and capacity of agricultural production. Though the realization of this potential requires high levels of commitment, resources, and consideration of climate risks, it is crucial to answer the question of which technologies and practices are the most appropriate to reach these objectives. Special funding mechanisms are needed to improve smallholders' access to PA. Moreover, PA practices should be included as a requirement for every new agriculture agricultural development project.

For this purpose, the government of the DRC has taken some steps toward developing a complete agricultural transformation strategy through agricultural special economic zones (ASEZs) that take the form of agricultural business parks (ABPs). The ABPs are perceived as the foundation for sustainable and inclusive development in the DRC. As Ulimwengu (2017) pointed out, the development of spatially targeted ASEZs has the highest potential among strategies being considered to induce a higher level of innovation and its fundamentals (human, social, manufactured, and knowledge capital). The pilot ABP, created in 2014 and called Bukanga Lonzo Agricultural Business Park, is located 250 kilometers from Kinshasa (the capital city of the DRC). It stretches over more than 80,000 ha, between two major rivers (the Kwango and the Lonzo) in the western part of the country.

The purpose of this study is to examine the effects of PA on maize yields in western DRC by comparing input application with and without PA recommendations. We argue that PA recommendations are the core of CSA practices. This study will focus on maize because of its extended upstream and downstream value chains and because in the DRC, maize production serves both animal and human consumption.

While estimating the impacts of PA-induced CSA practices on maize yields, this study is an attempt to explicitly analyze the use of soil knowledge to guide optimal input use and cultivation methods in order to improve yields and farmers' income. The study also examines how such knowledge can reinforce sustainable farming activities with respect to climate change. The goal is not only to report on changes in PA-induced maize yield but also to provide a better understanding of how PA helps determine the optimal cultivation method and the most efficient crop management practices to adopt in an area, given its specific soil conditions. The study uses georeferenced data on soil characteristics, inputs, and yield to assess the effects of CSA practices on a 10,000-ha plot in western DRC.

The sections that follow give an overview of CSA and PA; describe the application of PA for agricultural development; discuss the implications of PA results for site-specific CSA practices; and look at expected benefits from implementing CSA practices. Policy implications are laid out in the concluding section.

Climate-Smart and Precision Agriculture

Previous work on climate change impacts conducted in Africa suggests that maize, sorghum, and millet production is expected to decline significantly (by -5 percent, -14.5 percent, and -9.6 percent, respectively) (Knox et al. 2012). A recent study (Ramirez-Villegas and Thornton 2015) has indicated that during the 21st century, maize output is projected to decrease at a rate of 3–5 tons[35] per decade from historical levels as a result of climate change. The authors add that if no adaptation occurs, in the best scenario, total maize production in Africa will have decreased by 12 percent per year by the end of the century, whereas in the worst-case scenario it could be as low as 25 million tons per year, a 40 percent reduction. Considering all these challenges, countries such as the DRC should invest in technologies that promote sustainable intensification and adaptation to emerging climatic variability while also mitigating greenhouse gas (GHG) emissions.

CSA has been promoted as a way to overcome the challenge of increasing food supply and improving food security in an environmentally sustainable way. The FAO describes CSA technologies, practices, and services as options that sustainably increase productivity, enhance resilience to climatic stresses, and reduce GHG emissions (FAO 2010). In the DRC,

35 Throughout the chapter, *tons* refers to metric tons.

enhancing food security will require agricultural production systems to move toward higher productivity and lower output variability due to climate factors. The goals are to make production systems resilient and to assure good management of natural resources.

One study (Porter et al. 2014) pointed out that the most cost-effective CSA options have been assumed to be cropland management, grazing land management, and restoration of organic soils. Several regions in Africa are experiencing degraded and poor soils, which cause a decline in productivity. Using a probabilistic cost-benefit analysis, Sain and colleagues (2017) assessed the introduction of CSA options in Guatemala and found that all examined practices except one were profitable over their life cycles, but those that were expected to be ideal for drought-prone areas presented higher risks for adoption.

One example of an agricultural method for restoring organic soils and improving fertility is conservation agriculture (CA), with the following key characteristics: (1) minimal mechanical soil disturbance (that is, no tillage and direct seeding), (2) maintenance of much of the farm's carbon-rich organic matter (that is, use of cover crops), and (3) rotations or sequences and associations of crops including trees. CA thus augments climate change adaptation and mitigation solutions while improving food security through sustainable production, intensification, and enhanced productivity of resource use (FAO 2010).

Several meta-studies have attempted to quantify the average benefits of CA practices. Lal (2009), for instance, concluded that mulching and no-till farming clearly improved soil health, sometimes improved yields, and usually improved profits due to lower inputs. Pretty and others (2006) gathered evidence on the effect of CA from 286 developing-country case studies of "best-practice" sustainable agriculture interventions, finding the average yield improvement to be more than 100 percent. Branca and colleagues (2011) undertook a comprehensive, empirical meta-analysis of 217 individual studies on CA from around the globe and showed that reduced tillage and crop residue management was associated with a 106 percent increase in yield. A study conducted in southern Africa using the Agricultural Production Systems Simulator concluded that in semiarid environments, CA can improve yields in drier seasons and thus improve climate change resilience (FAO 2011). In subhumid environments, on the other hand, the same study found that CA offered little yield benefit, at least in the short term, due to the wet-season danger of waterlogging (FAO 2011), also mentioned by Thierfelder and Wall (2009, 2010). Other evidence of increased productivity with reduced- and no-tillage practices under rainfed agriculture is mixed. Meta-analyses show higher yields under CA than under conventional practices in a few cases, but benefits have varied based on soil type, precipitation, and application of N fertilizer (Rusinamhodzi et al. 2011; Farooq et al. 2011). Although the literature offers some evidence that CA has a positive effect on yields, the magnitude of this effect and how it interacts with climatic variables are still unclear.

Another example of a soil-restoring and fertility-improving method is PA, encompassing a series of technologies for applying water, nutrients, and pesticides only where and when they are required, thus optimizing the use of inputs (Day, Audsley, and Frost 2008). Farmers using PA manage their crops based on the site-specific conditions in variable fields (Seelan et al. 2003). PA provides the data necessary for farmers to make guided decisions about fertilizer and pesticide applications, seed distribution densities, irrigation metrics, and tillage patterns (Daberkow and McBride 1998).

Researchers have studied several aspects of PA, including technologies, environmental effects, economic outcomes, adoption rates, and drivers of adoption (Tey and Brindal 2012). Although many have acknowledged the method's environmental and economic benefits, a low rate of PA adoption is still reported, especially in developing countries (adoption efforts have been initiated in Brazil, China, India, and Uruguay in recent years), and adoption has focused on cash crops.

Indeed, research has revealed that increased input efficiencies result in rather modest profitability increases (Kilian 2000), which could explain the rather low adoption rates (Cook, Adams, and Bramley 2000). Another obstacle could be the failure to apply fertilizers that appropriately match individual site characteristics (Florax, Voortman, and Brouwer 2002; Stewart and McBratney 2002; Bullock et al. 2009).

Regarding profitability, Tey and Brindal (2012) noted that for farmers who have access to accurate information about the nutrient needs on their land, the precise application of fertilizer could reduce input costs. This conclusion is based on the assumption that the net savings from precise fertilizer application more than offset the cost of additional labor or the use of specialized equipment.

Studies on the profitability of PA application have led to mixed results. In contrast to the studies mentioned above, showing that information-led application of pesticides would result in input cost savings, others (Carr et al. 1991; Biermacher et al. 2009) have found no significant difference in returns. Some studies also show that soil sampling tests for fertility do not lead to profitability (Lowenberg-DeBoer and Aghib 1999; Swinton and Lowenberg-DeBoer 1998). In an attempt to explain the mixed results, some authors have suggested that PA application may involve too high a level of complex data management and interpretation (Robertson et al. 2012).

Research has shown that PA has the potential to reduce environmental impacts caused by agricultural activities (Fuglie and Bosch 1995; Khanna and Zilberman 1997; Hudson and Hite 2003). Consistent with one of the CSA objectives, improving the match of fertilizer application with crop needs prevents excess application (Reichardt and Jurgens 2009). Indeed, a study by Biermacher and colleagues (2009) demonstrated that applying the necessary amount of N needed for crops to reach their maximum potential yield could reduce nitrate contamination in groundwater and the pollution of downstream water.

Tey and Brindal (2012) noted that a number of studies have demonstrated the economic and ecological superiority of PA over conventional approaches (Tey and Brindal 2012; Silva et al. 2007; Sylvester-Bradley et al. 1999; Takacs-Gyorgy 2008).

Precision Agriculture in Practice

The Case for Precision Agriculture

The use of PA in BL was aimed at improving farmers' understanding of the variability of soil properties and crop requirements, which we expected to allow more informed decision making (Maohua 2001). We argue that decisions made by farmers under PA are better than those that would be made with conventional agricultural practices (that is, the national recommendations), and therefore that PA has the potential to promote efficient use of resources (through site-specific information), reduce input (fertilizer and pesticide) costs, and minimize environmental degradation caused by agricultural activities (by preventing excess application). In addition, we expected PA to improve soil condition and crop quality, and increase crop yield.

Data Collection Methods

The ASEZ of Bukanga Lonzo (BL) spans more than 80,000 ha. The South African agricultural company Agri Xcellence[36] was engaged to perform soil analysis and classification at BL to identify land suitable for crop cultivation (mainly maize for the first year) and provide a better understanding of maize yield response to fertilizers. Based on topography limitations and physical aspects of the soil, the land identified as suitable for cultivation was about 56,000 ha, and this arable land was later arranged into 9 parcels.

The government started its first phase of PA implementation in BL with parcel 1 (10,575 ha). First, Agri Xcellence conducted complete soil chemistry and classification on 1,500 soil samples—2 samples per 20–50 ha grid—to establish the presence of the major elements, such as calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), and sodium (Na). Soil chemical characteristics were also determined by measuring cation exchange capacity and pH. Researchers used technology such as GPS to map topography as well as soil and plant deficiency or excess characteristics, indicated by chemical and physical attributes. Rainfall patterns, temperatures, and evaporation tendencies were also studied to determine the best times to plant and harvest maize. The rainy season starts around September and lasts until around March, and the dry season runs approximately from June to August. September was therefore targeted as the ideal planting date to allow the maize plants to be developed enough to withstand the heavy showers that usually fall in November. Similarly, March, which usually marks the end of the short dry season (February-March), was determined to be the ideal time to commence harvesting.

The soil analysis was followed by yield simulations, which determined that a portion of the parcel (3,742.7 ha) presented very low productivity prospects (less than 2 tons/ha); it was therefore deemed not profitable and excluded from the planting area. The remaining part of the parcel (6,832.6 ha) was then divided into two areas: 1a (1111.1 ha) and 1b (5721.5 ha).

In BL, the government opted to use precision farming to optimize the use of required nutrients based on good knowledge of crop requirements and local soil, terrain, and climatic conditions. We argue that PA provides farmers with spatial information that reduces uncertainty and improves decision making. Cook and others likewise indicated that site-specific information—"for example, the knowledge that fertilizer should be applied to one location but not another; the decision that a cropping system variety is suitable for one area, but not another" (2003, n.p.)—reduces the chance of both type I and type II errors.

Physical Properties of the Soil

The soil survey conducted by Agri Xcellence assessed the physical properties (texture, structure, water-holding capacity, and dispersion) and chemical properties (potential in hydrogen, or pH, as well as nutrients and salinity). The planting area is composed of only four types of soil, making it quite homogenous considering its size. Each soil type represented (Cartref, Clovelly, Constantia, and Fernwood) presents a different depth and clay

36 https://www.triomfsa.co.za/index.php/home/agri-xcellence

content, both of which play an important role in water storage capacity.[37]

Both areas 1a and 1b were dominated by the Constantia soil type, which consists of an orthic A horizon followed by an E horizon and then a third horizon consisting of a yellow-brown apedal soil. The soil analysis also indicated a high organic material content in the form of carbon, which helps in the retention of nutrients. The E horizon is formed by water that drains laterally out of this horizon and is an indication of a highly leached horizon. Thus, the high carbon content is perceived as a positive factor because it counters the effects of highly leached soils. The USDA reported that soil organic matter serves as a reservoir of nutrients for crops, provides soil aggregation, increases nutrient exchange, and increases water infiltration into soil (NRCS n.d.). The Constantia soil type is also considered a sandy soil because of the sandy nature of its E horizon. The remaining soil types found in the area suitable for cultivation were far less represented (Summary of Soil Analysis, Parc Agro Industriel de Bukanga-Lonzo, Part 1. n.d.).

Characteristics of the Soil

The soil analysis performed in BL on parcel 1 (10,575 ha) indicated a wide variation in soil characteristics. It also identified areas of nutrient deficiency, suggesting the need for nutrient adjustment over time to reach the optimal levels required for efficient farming in terms of both environmental sustainability and profitability (Table 7.1).

TABLE 7.1—SOIL CHARACTERISTICS

Parameter	Soil in sampled area	Normal range	Recommendations
pH (potential in hydrogen)	4.4 KCl (low)	5.5–6.5 KCl	Indication of highly leached soil. Dolomitic lime should be used to correct the pH in the soil.
Exchangeable acids	≥ 2.33 cmol/kg in 1a (very high) ≥ 0.30 cmol/kg in 1b (very high)	0.00 cmol+/kg	The high level of exchangeable acids is very toxic to plants and plant roots.
Magnesium (Mg)	8 mg/kg in 1a 6 mg/kg in 1b	100–120 mg/kg	Highly leached soils cannot physically retain enough Mg in the clay complex. The deficiency in Mg can be corrected by using dolomitic lime.
Acid saturation	42% in 1a 51% in 1b	0%–7%	This very high level may result in poor root development and stunted growth.
Potassium (K)	12 mg/kg	70–90 mg/kg	Deficiency can be corrected by using a K source such as KCl 50 fertilizer. Or it can be corrected over time by applying a higher rate of a fertilizer blend high in K.
Calcium (Ca)	51 mg/kg in 1a 39 mg/kg in 1b	200–220 mg/kg	If the physical amount of Ca in the soil is corrected, the pH will also start to stabilize at greater than 5 Kcl. Deficiency in Ca can be corrected by using either dolomitic or calcitic lime.

Source: Agri Xcellence
Note: cmol = centimole (1 cmole = 10^{-2} moles); KCl = potassium chloride.

[37] Soil texture varies by depth, and so does water-holding capacity. To determine water-holding capacity for the soil profile, the depth of each horizon is multiplied by the available water for that soil texture, and then the values for the different horizons are summed (Plant & Soil Sciences eLibrary 2017).

The first 30 cm of the topsoil was high in organic carbon, which has positive effects by reducing the leaching of cations. Nevertheless, the report suggested the importance of building up organic matter in the soil by using a no-till or strip-till system of cultivation. Indeed, organic matter production is affected radically by conventional tillage, which decreases soil organic matter and increases the potential for erosion by wind and water (FAO 2005).

Overall, the soil analysis results suggested the following:

- Low pH and high levels of exchangeable acidity were the most yield-limiting factors in the first year of cultivation and were expected to especially hamper production in the first year.
- The soils were highly leached, making it important to reach adequate levels of Ca, Mg, P, and K over time.
- The first 30 cm of the topsoil was high in organic matter, which creates more negatively charged sites to which cations can bind, potentially lowering the amount of leaching. Therefore, it was important to build up even more organic matter in the soils by using a no-till or strip-till system of cultivation.
- The soils were prone to compaction, so care had to be taken not to compact the soil with traffic on the fields. The soils would need to be monitored for compaction every year.
- As the production of grain crops continues, the soil chemical balances should start stabilizing and crops should start producing higher yields over time.
- The split application of fertilizer, especially N and K, over the growing season was expected to have a positive effect on yield.
- The use of foliar feeding during the growing season should also have a positive effect on yields in the first year, when the soil does not have enough nutrients to produce very high yields.

Fertilizer Application in Precision Farming

Based on the soil analysis described above, we then derived georeferenced, PA-based recommendations for nutrient application, presented in Table 7.2, which allow for optimal use of fertilizer for maize cultivation in BL.

In general, Table 7.2 depicts a greater need for Ca, monoammonium phosphate (MAP) 33, and potassium chloride (KCl) 50 than for other nutrients.[38] As Table 7.2, panel A, shows, soil types determine the level and nature of required nutrients. Systematically, Fernwood requires the most attention across all nutrients and Cartref requires the least. It follows that any homogenous application is not only against recommendations but also likely to lead to inefficient farming.

The thickness of the white E horizon (Table 7.2, panel B) appears to have relatively little impact on the amount of recommended nutrients of all types. Harris and others (2010) pointed out that the water table depth in relation to the E horizon thickness affects the availability to crops of applied P as well as the potential for lateral transport of P through subsurface flow. In addition, when determining N fertilizer rates, it is important to keep in mind that poorly drained soils can lose N via denitrification. Thus, as recommended for BL (panel B), the thicker the white E horizon, the fewer

38 MAP 33 contains around 11 percent N and 22 percent P. It is widely used as a source of P and N, and has the highest P content of any common solid fertilizer (IPNI n.d.-b). KCl 50 is the most widely used K fertilizer due to its relatively low cost and inclusion of more K (50–52 percent) than most other sources (IPNI n.d.-a).

TABLE 7.2—FERTILIZER APPLICATION RECOMMENDATIONS

A. Average recommended fertilizer (kg/ha) by soil type						
Soil type	Calcium	MAP 33	Phosphate	Magnesium	Potassium	KCl 50
Cartref	88.1	48.9	20.6	17.3	10.9	40.0
Clovelly	926.2	490.5	236.8	184.9	109.9	491.8
Constantia	1,103.4	620.4	264.9	218.8	136.7	531.8
Fernwood	1,263.9	679.5	299.6	245.0	149.2	597.6
B. Average recommended fertilizer (kg/ha) by thickness of white E horizon						
Thickness (cm)	Calcium	MAP 33	Phosphate	Magnesium	Potassium	KCl 50
0	1,263.9	679.5	299.6	245.0	149.2	597.6
≥ 7	1,038.1	598.1	250.7	205.8	132.2	504.8
≥ 8 and ≤ 9	1,072.8	621.8	258.0	212.0	136.7	520.1
≥ 10	1,177.5	608.8	282.0	234.6	134.3	563.0
C. Average recommended fertilizer (kg/ha) by level of nitrogenous loss due to leaching						
Level of nitrogenous loss	Calcium	MAP 33	Phosphate	Magnesium	Potassium	KCl 50
Very high	1,260.6	686.5	302.4	249.0	151.1	602.5
High	1,086.4	609.2	257.8	211.0	133.9	520.1
Average	942.0	534.6	224.2	185.5	117.9	450.9
Low	926.2	490.5	236.8	184.9	109.9	491.8
D. Average recommended fertilizer (kg/ha) by frequency for top dressing						
Frequency	Calcium	MAP 33	Phosphate	Magnesium	Potassium	KCl 50
1 time	926.2	490.5	236.8	184.9	109.9	491.8
2 times	1,037.6	584.0	246.4	202.4	128.5	496.7
3 times	1,260.6	686.5	302.4	249.0	151.1	602.5
E. Average recommended fertilizer (kg/ha) by risk of waterlogging						
Waterlogging risk	Calcium	MAP 33	Phosphate	Magnesium	Potassium	KCl 50
Yes	1,217.7	654.6	290.1	238.2	144.0	579.3
No	1,122.5	636.9	275.7	224.5	140.5	557.7
Avg.	1,013.1	589.4	241.4	199.7	129.8	485.4

Source: Authors' calculations using data from Agri Xcellence.
Note: KCl = potassium chloride; MAP = monoammonium phosphate.

nutrients are required. Nevertheless, Ca is recommended at a higher amount than KCl 50, MAP 33, and the other nutrients.

Similarly, nitrate loss through leaching (Table 7.2, panel C) appears to have little relative impact on nutrient needs. Still, appropriate nutrient management can greatly reduce the risk of nitrate loss through leaching. In addition, highly leached soils (those whose loss is considered "high" or "very high") cannot retain enough Mg in the clay complex, and thus it is important to increase the soil organic matter and reach the appropriate fertilizer mix (with the proper proportions of Ca, Mg, K, and P) to satisfy the plants' needs for Mg. Thus, more nutrients should be applied to highly and very highly leached soils than to soils with average and low levels of leaching. Soils experiencing very high nitrate loss would need about 22–40 percent more of each nutrient in comparison to soils experiencing low nitrate loss (Table 7.2, panel C).

At the time of maize planting in BL, farmers applied diammonium phosphate (DAP), which contains 18 percent N and 46 percent phosphate, making it an excellent source of N and P, in addition to KCl 0-0-60, which contains 60 percent K fertilizer (as potassium oxide, or K2O, also known as potash, yielding 50 percent K). For top dressing (Table 7.2, panel D), N-supplying fertilizers (urea) and other nutrients (Ca, Mg, P, KCl 50, and MAP 33) were applied. In a very wet season, when heavy rain may leach away some of the fertilizer, top dressing should be split (one application at two to three weeks and the second before tasseling), for a total of three applications, consistent with the soil analysis report's recommendation to split the application of fertilizer, especially N and K, over the growing season. Thus, the amount of nutrients applied should be slightly higher in the second and third applications than in the first.

Maize is frequently subjected to waterlogging (Table 7.2, panel E), especially in poorly drained soils, where standing water can cause a rapid depletion of the oxygen required for plant growth and development (Geigenberger et al. 2000). In addition, waterlogging can leach out or change the availability of nutrients to the plant (Palapala and Nyamolo 2016). Thus, for BL, it was recommended that an average of 1,217.7kg/ha of Ca, 654.6 kg/ha of MAP 33, 290.1 kg/ha of phosphate, 238.2 kg/ha of Mg, 144.0 kg/ha of K, and 579.3 kg/ha of KCl 50 be applied when there is a risk of waterlogging (Table 7.2, panel E).

Table 7.3 displays descriptive statistics for all of the fertilizer recommendations. The mean and median values for each input are close to each other and the skew values are relatively low, indicating that the data are normally distributed.

TABLE 7.3—DESCRIPTIVE STATISTICS, FERTILIZER RECOMMENDATIONS, KG/HA

Statistic	*Ca*	*MAP 33*	*K*	*Mg*	*P*	*KCl 50*
Mean	665.91	373.28	158.94	131.73	82.07	318.10
Median	664.81	400.00	160.25	132.40	85.71	300.00
Mode	698.84	400.00	164.59	135.40	80.91	300.00
Min.	466.12	0.00	87.81	99.17	0.00	150.00
Max.	1,036.54	600.00	200.16	156.64	134.03	400.00

Source: Authors' calculations using data from Agri Xcellence.

There were 6,135 ha requiring Ca in the range of 500–1,000 kg/ha and 6,130 ha requiring Mg in the range of 90–150 kg/ha, suggesting that the entire land area required Ca and Mg. In addition, most of the land required more than 250 kg/ha of KCl 50 (that is, 56 percent of the land required between 250 and 300 kg/ha and 44 percent required more than 300 kg/ha—which is close to the mean value of 373 kg/ha). As for K, approximately 99 percent (6,112 ha) of the land required this nutrient in amounts greater than 120 kg/ha.

Fertilizer Application: National Recommendations in the Democratic Republic of the Congo

We use national recommendations for fertilizer as an example of non-CSA practices based on PA. Because BL is in the western part of the country, we use recommendations for the provinces of Kongo Central (formerly called Bas-Congo) and Kinshasa, and the former province of Bandundu, as opposed to nationwide recommendations.

In Kongo Central and Bandundu, maize is produced by smallholder farmers, cultivating 1 ha or less per household and using no external inputs. In Kinshasa Province, there are some large (100- to 1,000-ha) commercial, tractor-mechanized farms on the Batéké plateau, which usually use some chemical fertilizers (urea and N-P-K). In smallholder agriculture, yields are very low, less than 1,000 kg/ha (± 800 kg/ha) (USAID 2015b).

Farmers have only limited access to fertilizers because of their high cost. Maize always tends to be grown on the more fertile soils in the valley bottoms. Because no chemical fertilizers are used on maize or cassava, except on large commercial farms on the Batéké plateau near Kinshasa, and because organic fertilizers (manure and compost) are usually in very short supply, soil fertility is not restored after harvest. Furthermore, fallows tend to disappear completely due to population and marketing pressure. Thus, yields tend to decrease over time, and poor soil fertility becomes a major production constraint (USAID 2015b).

Overall, fertilizer application is based on national recommendations from the Ministry of Agriculture, which call for specific amounts for small, medium, and large farms. For example, the recommendation for large farms is that the first application be done following the formula NPK 17-17-17[39] (300 kg for N, P and K), in addition to 200 kg of urea. In Kongo Central Province, for example, the amount of fertilizer recommended for maize is 200 kg/ha, at a unit cost of US$1.60/kg.

These recommendations assume homogeneity across space and time, prescribing the same quantities of nutrients regardless of the soil and spatial heterogeneity. However, as the soil analysis performed in BL shows, there is wide variation in the soils' chemical and physical properties. Therefore, the optimal amount of fertilizer is specific to the region, soil type, and predicted rainfall. Thus the agricultural sector in the DRC would greatly benefit from precision farming practices, which facilitate the optimal use of fertilizers and other resources.

Benefits from Implementing Climate-Smart Agricultural Practices

Expected Long-Term Yield

Based on PA recommendations for nutrient application, the expected long-term maize yield is much higher than under national recommendations without PA—one more reason that the DRC agricultural sector would largely benefit from PA and CSA management practices in the medium and long run. As shown in Table 7.4, 49.1 percent of the land is expected to yield between 4 and 8 tons/ha, 30 percent to yield at least 9 tons/ha, and 20 percent to produce 2 to 3 tons/ha", compared with 0.8 tons/ha when PA is not applied.[40] Yield distribution is not uniform across the field (Table 7.4) due to the spatial heterogeneity of available soil nutrients.

TABLE 7.4—DISTRIBUTION OF EXPECTED LONG-TERM YIELD UNDER PRECISION AGRICULTURE PRACTICES

Yield (tons/ha)	Area (ha)	Area (% of total)
≤ 2	57.3	0.5
2–3	2,101.1	19.9
3–5	237.2	2.2
5–7	4,865.8	46.0
7–8	7.6	0.1
8–9	86.3	0.8
> 9	3,220.2	30.4
Total	10,575.5	100.0

Source: Authors' calculations using data from Agri Xcellence.

If provided with the information in Table 7.4, what would a smart farmer do? Because fertilizer cost per hectare is the same regardless of expected yield, a smart farmer would avoid planting in areas with at most 2 tons/ha of expected yield and maximize planting of areas with 5–7 tons/ha and more than 9 tons/ha. Such optimization thinking, which leads to smart farming, is possible only when knowledge is available to farmers.

39 Fertilizer grade refers to a legal guarantee of the content of available plant nutrients, expressed as a percentage by weight in the fertilizer. For example, the 12-32-16 grade of NPK complex fertilizers has 12 percent N, 32 percent P (in the form of P2O5), and 16 percent potash (K2O).

40 The average yield under national recommendations in the DRC is only 0.8 tons/ha (Ministry of Agriculture, DRC).

In addition, an analysis of first-year and long-term expected yields indicates that the total production from the entire parcel of land will be 50,360.6 tons of maize during the first year but will grow over the long term to 64,284.6 tons, an increase of 27.6 percent. These predictions are consistent with the BL progress report (Africom Commodities 2016), which predicted, based on the current condition of the crop, that a yield of 4–5 tons/ha can indeed be achieved.

Cultivation Method: Tillage versus No Tillage

In general, no-till agriculture is considered good for soil fertility, with benefits in terms of adaptive capacity and food security because it contributes to increased yields. Kassam and colleagues (2009) indicated that minimal soil disturbance through no tillage or reduced tillage ensures a favorable proportion of gases for root respiration, moderate organic matter oxidation, good porosity for water movement, and limited re-exposure to weed seeds and their germination—all of which may enhance crop growth and final grain yield.

In addition, research shows evidence of yield and soil improvements in humid tropical and temperate ecosystems where minimal and no-tillage practices are applied (Rasmussen 1999, Diaz-Zorita, Duarte, and Grove 2002; Bronick and Lal 2005). Consistent with previous research, Hine and Pretty (2008) suggested positive effects on maize yields compared with traditional tillage management.

The BL soil analysis revealed that the first 30 cm of the topsoil was high in organic carbon. Such organic matter creates negatively charged sites to which cations can bind, reducing the leaching of cations. Therefore, recommendations called for building more organic matter by using a no-till or strip-till system of cultivation, which can contribute toward improved water retention, rain use efficiency, soil improvement, and increased yields. In addition, farmers in the DRC practicing no tillage are likely to save on plowing costs, estimated at US$200–US$300 per hectare.

Optimal Soil and Crop Management

Research has shown that the greatest benefits of implementing improved cropland management practices under CSA are higher and more stable yields, increased system resilience, enhanced livelihoods, greater food security, and reduced uncertainty (Conant 2010; Woodfine 2009; Thomas 2008).

In BL, the application of inorganic fertilizer was based on the soil analysis with the objective of improving the proportion of nutrients retained in the soil while reducing both waste and GHGs. Given their low agricultural productivity, food insecurity, poverty, and additional constraints because of climate change, countries such as the DRC need to increase their food production. This process of agricultural intensification requires the use of inorganic fertilizer. Indeed, increases in fertilizer use have driven a rapid expansion in agricultural productivity in the post-World War II era (FAO 2015).

Optimal Soil Management: Cover Crops

As part of PA-driven soil management practices, BL farmers used cover crops, first planting them so that trial runs could be conducted. Thus, soil analysis as well as cover crop tests provided valuable insights into the best-suited applications of lime, humates, nutrients, and fertilizer in order to ensure the expected optimal yields (Africom Commodities 2016). The

BL experiment is in line with previous studies (Pretty 2000; Altieri 1999) showing that farmers benefited through increased yields of maize following the use of cover crops. In addition, mixing no-till farming and cover crop usage with herbicides has been found to reduce leaching and improve yields (FAO 2010).

The use of improved crop varieties in BL is also expected to increase average yields over time. Though the gains may vary across countries and crops, the International Centre for Tropical Agriculture (CIAT 2008) found a yield increase following the introduction of new bean varieties in some African countries. Thus, the use of improved crop varieties in BL is also expected to improve average yields.

Profitability: Fertilizer Costs

Table 7.5 compares first-year fertilizer costs between DRC farmers under precision farming, which requires location-specific fertilizer application, and those using homogenous fertilizer application as recommended by the DRC Ministry of Agriculture.

TABLE 7.5—FIRST-YEAR INPUT COSTS WITH AND WITHOUT PRECISION AGRICULTURE

Variables	PA	No PA
Average area planted (ha)	5,721.5	5,721.5
Application rate (kg/ha)	296.6	200.0
Fertilizer cost ($US/kg)	1.60	1.60
Fertilizer cost ($US/ha)	474.60	320.00
Total fertilizer cost ($US)	2,715,195.00	1,830,880.00

Source: Authors' calculations.

Note: "No PA" application rate is based on national recommendations of an average of 200 kg/ha of fertilizer for maize. "PA" application rate is a weighted average. PA = precision agriculture.

Agricultural practices involving efficient use and application of fertilizers (i.e., PA) lead to higher initial costs. We use an average unit fertilizer cost of $US1.60/kg and an area planted of 5,721.5 ha (the area of BL parcel 1), which leads to a total cost of $1,830,880 when fertilizers are applied per national recommendations, compared with $2,715,195 under PA. Therefore, precision farming, entailing an increase of 48 percent in fertilizer costs for the first year, does not allow immediate savings for farmers. However, this comparison paints an incomplete picture until we take into account the following factors:

- First, the need for fertilizer during the first year, following the soil analysis, will be higher than in subsequent years. The soil condition and nutrient balance are expected to improve over time, leading to lower fertilizer requirements in the future (Africom Commodities 2016).
- Second, the combined effect of inorganic fertilizer and organic fertilizer (compost and animal manure) use in the subsequent years in BL, as recommended by CSA practices, is likely to boost yields, leading to higher incomes that offset the fertilizer costs. Indeed, research has shown that maize yields increased by 100 percent in Kenya (Pretty et al. 2006), and maize and wheat yields increased by between 198 and 250 percent (Altieri 1999) following the adoption of organic fertilization. In addition, following PA recommendations is expected to improve soil conditions, reducing future fertilizer costs (as mentioned above) while having a positive effect on the environment.
- As pointed out above, the no-tillage practice offers an immediate savings on input costs (plowing).

- Some costs are not included in this analysis (cost of pesticides, operating expenses, transportation costs)[41] and could alter the results.

Table 7.6 shows a significant yield increase when PA practices are implemented. The total production with PA is 22,886 tons, representing an increase of a little more than 400 percent over conventional practices.

TABLE 7.6—MAIZE YIELD WITH AND WITHOUT PRECISION AGRICULTURE

Variables	PA	No PA
Hectares planted	5,721.50	5,721.50
Average yield (tons/ha)	4.00	0.78[a]
Total production (tons)	22,886.00	4,462.77

Source: Authors' calculations.
Note: [a]Average yield under no PA for maize in DRC between 2000 and 2014 from FAO (2013b). PA = precision agriculture.

As reported in Table 7.7, the level of income under PA is significantly higher than under the national recommendation (about four times as high). Given the higher yield that is expected to be sustained over time when PA practices are implemented, there is a very high potential for the yield to remain at approximately 4 tons/ha or more. Our findings also suggest a positive profit under PA, compared with negative profit under the national recommendations, indicating that although implementing PA may result in higher costs (if all costs are included), the expected increase in yield will more than offset the additional costs. In addition, a portion of the costs is expected to be lowered over time for reasons described above.

[41] An estimate of these costs (which will further increase the input costs) is available for BL but not for farms under national recommendations, so no comparison is currently possible.

TABLE 7.7—INCOME WITH AND WITHOUT PRECISION AGRICULTURE

Variables	PA	No PA
Input costs (US$/ha)	474.56	320.00
Plowing (US$/ha)	0.00	250.00
Total planted area (ha)	5,721.50	5,721.50
Total input costs for 5,721.5 ha	2,715,195.04	1,830,880.00
Average yield (tons/ha)	4.00	380.00
Sales price ($US/ton)	380.00	4,462.77
Total production	22,886.00	1,695,852.60
Total revenue ($US)	8,696,680.00	265,477.60
Profit (including plowing costs)	8,696,680.00	

Source: Authors' calculations.
Note: For simplicity, we assume that all costs are the same except the ones whose application requires fine-tuned knowledge, such as fertilizer and cultivation methods. PA = precision agriculture.

Concluding Remarks and Policy Implications

Similar to that of most countries in SSA, the agricultural sector in the DRC has been characterized by low productivity. The effects of climate change constitute an additional challenge to food security; rising temperatures and increased frequency of extreme weather events (floods, droughts, and so on) have already started having negative effects on crop yields.

For these reasons, the DRC needs to revisit and improve on its current agricultural methods and management of natural resources to achieve food security while also preserving natural resources and the environment, and reducing the effects of climate change.

The government of the DRC recently initiated efforts to transform the agricultural sector; feed the growing population; and provide a basis for inclusive economic growth, food security, and poverty reduction. In 2014, it created the BL ASEZ, making investments in crop production, agroprocessing, and marketing following CSA practices induced by PA. PA methods help farmers optimize inputs for agricultural production in accordance with the capability of the land. Thus, some of the practices analyzed here fall into the category of conservation agriculture and PA, whose impacts on production have been extensively researched (FAO 2011; Umar et al. 2011). Specifically, the following practices were implemented: efficient and georeferenced application of inorganic fertilizer, use of selected seeds, use of cover crops, and minimal or no tillage.

This study aimed at examining the effects of PA-induced CSA practices on maize yields in BL by comparing input application with and without PA recommendations. In addition, it was an attempt to explicitly analyze the use of soil knowledge to guide optimal input use and cultivation methods to improve yields and farmers' income. The first step was an extensive soil analysis and data mapping of BL, which was crucial in that it provided a better understanding of the soil condition, texture, and nutrient deficiencies. Using the knowledge gained from the soil analysis, some recommendations were made to guide the timely application of nutrients in precise and targeted areas.

Overall, the findings suggest that climate-smart practices offer to countries such as the DRC a sustainable way to boost productivity through improved crop yields and increased input efficiencies. We compared the expected average long-term yield under PA with the average yield obtained under national recommendations (as formulated by the Ministry of Agriculture) and found that yield under PA was about four times higher than under national recommendations, indicating that farmers could largely benefit from increased crop yields under PA. Specifically, the average yield under national recommendations in the DRC is only 0.8 tons/ha, whereas the yield under PA was 4.0 tons/ha.

Under national recommendations, the average fertilizer application rate is 200 kg/ha, whereas under PA it is about 296 kg/ha. Though farmers may have to spend a little more at first on fertilizers under PA, the significantly large increase in crop yield more than offsets the cost of fertilizer. In addition, total fertilizer cost is expected to decrease over time because the CSA practices should enhance soil conditions and preserve the environment.

Moreover, market information suggests that the price of maize flour in the DRC decreased by 30 percent when BL began providing an additional maize supply for the country. Given that consumers allocate a high proportion of their income to food, a 30 percent reduction in the price of maize flour would make a significant and positive impact on consumers' budgets.

Consistent with previous studies, the use of cover crops, combined with mulching and no tillage, are expected to improve crop yield over time. Thus, the yield expected in the future could be even higher than that reported in this study. No-tillage practices are expected to cut farmers' costs as well, with plowing costs estimated at US$250 per hectare.

Overall, then, farmers' revenue under PA is significantly higher than that under the national recommendations. Though fertilizer costs are higher (due to a higher application rate in the first year), the savings on plowing and the increase in crop yield largely compensate for this cost, and yields are expected to increase over time.

It goes without saying that “blind farming,” that is, farming without PA, is highly inefficient and exacerbates the challenges of addressing climate change. As in the case of the DRC, other African governments should promote PA as a way of optimizing the use of limited resources while mitigating the effects of climate change. For example, it should be mandatory to include results of soil analysis in farming loan and crop insurance applications. Similarly, under the National Agricultural Investment Plans, ministries of agriculture should require detailed soil analysis prior to every new land development for farming purposes. However, because of the high cost associated with PA technology, millions of smallholders, who make up more than 70 percent of the African agricultural production system, will likely be left out. Therefore, we propose that a special fund be set up to make PA accessible to these smallholders.

Smallholder farmers’ access to PA is still very limited for two main reasons: affordability and understanding. Indeed, in the DRC, soil analysis costs US$74/ha—too expensive for smallholder farmers. The ideal would be the creation of a special-purpose funding vehicle as a platform for the corporate sector to work in partnership with the government, multilateral development banks, development organizations, donor agencies, foundations, nongovernmental and civil society organizations, small farmers, and local community organizations. With respect to understanding, it is important that national education and research systems be reorganized to upgrade smallholder farmers’ skills to properly use PA tools. As the FAO stated, “this requires strategic interministerial planning involving the ministries of agriculture, education, and trade, along with representatives of tertiary and secondary institutes, farmer organizations, and agro-industry” (2015, 4).

Finally, to promote and expand the use of PA, given its benefits beyond targeted farmers, we propose that (1) PA practices be included as a requirement for every new agricultural development project and (2) soil analysis be made part of applications for agricultural loans and crop insurance.