State of the Art of Soil Research at International Agricultural Research Centres

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1. Introduction and scope

Agriculture is the main source of livelihood and income for 70 % of the world's poor who live in rural areas (World Bank 2015). Continuous cultivation without sufficient replenishment of extracted nutrients and associated soil erosion are the major drivers of soil fertility degradation. Limitations in organic matter and key nutrients greatly constrain agricultural production. Population pressure and climate change exacerbate the condition of soils in the region; soils in semi-arid zones are particularly vulnerable. Loss of soil fertility has caused average yields of grain crops in sub-Saharan Africa (SSA) to stagnate at about 1.5 tonne (t) per hectare since the 1960s, while fertilizer use has remained at about 10 kg per hectare of cultivated land over the past 40 years (Stocking 2003; Sommer et al. 2013). To keep pace with a growing population and increased food demand as well as dietary shifts, food production will have to increase by 70% by 2050 (Bruinsma 2009). Maintaining or rehabilitating soils to increase agricultural productivity is one of the key ways of tackling global hunger (Lal 2006; Gilbert 2012).

Linking crop productivity to soil health, soil research has a long tradition in international agricultural research centres (IARCs), i.e. the 15 centres aligned under the CGIAR[1] Consortium, as well as centres outside this Consortium, such as CATIE, CABI, IPNI or IFDC. CIAT and other institutes have developed significant knowhow in the area. Over the last decades, significant soils research has been conducted in Africa, Asia and Latin America in many eco-regions, including high potential semi-humid and humid areas and lower potential semi-arid areas and on many different soils of the tropics. Over the past decades, the Tropical Soil Biology and Fertility Institute (TSBF) of CIAT conducted research on soil fertility and soil processes in SSA and generated a wealth of knowledge, through the establishment of comprehensive data sets and publications of books, research articles, training manuals and handbooks.

The German Federal Ministry of Economic Cooperation and Development (BMZ) programmes have been focusing on sustainable soil management for many years. In 2014, BMZ/GIZ initiated a global programme on 'Soil Protection and Rehabilitation for Food Security'. This programme invests in rehabilitation of degraded soils and supports policy development for rehabilitation, soil information and extension systems in Benin, Burkina Faso, Ethiopia, Kenya and India.

To ensure that the current state-of-the-art of soil research is reflected in these new German development cooperation efforts, this state-of-the-art report summarises the major trends of the last two decades in soil research of the IARCs, with a focus on SSA.

[1] Consultative Group on International Agricultural Research http://www.cgiar.org/

2. History of soil research of IARCs

Over the past two decades, there has been substantial evolution in the paradigms underlying soil fertility management research and development efforts. On one hand, this is due to the progress of science and increased experience (what works and what does not) and on the other hand, because of changes in the overall social, economic and political environment.

During the 1960s and 1970s, the first paradigm – the 'external input' paradigm – in tropical soil fertility research evolved. It was based on a rather one-size-fits-all idea that external inputs – mineral fertilizers or irrigation – were sufficient to overcome soil fertility constraints present in SSA (Sanchez 1994), as successes in Asia applying this paradigm – later coined 'the Green Revolution' – were encouraging. As a consequence, many African Governments introduced subsidies on mineral fertilizers (Druilhe and Barreiro-Hurlé 2012).

However, as opposed to Asia and Latin America, successes in promoting the external input paradigm in SSA were limited for various reasons (IITA 1992). Features that set SSA apart include: (a) a higher diversity of crops are grown in Africa compared with Asia, which make it more challenging to apply a one-size-fits-all solution as is the basis of the Green Revolution; (b) Africa is a large continent with very different agro-ecological zones, so it requires a diversified range of management techniques; (c) similar applies to the soils of Africa, which are largely diverse, with highly weathered, inherently infertile soils covering vast areas (Sommer et al. 2013); and (d) most of African agriculture is rain-fed, contrary to Asia where irrigated agriculture is widespread (UNCTAD 2010). A lack of concerted effort and political willingness were additional reasons for the early failure of the Green Revolution in SSA (Verchot et al. 2007). This, together with environmental degradation resulting from massive applications of fertilizers and pesticides in Asia and Latin America between the mid-1980s and early 1990s (Theng 1991) and the abolishment of fertilizer subsidies in SSA imposed by structural adjustment programmes (Smaling 1993), led to an interest in organic resources as alternatives to mineral fertilizers.

Thus, to some extent, as a consequence or countermovement, starting in the mid-1980s, the organic input or low-input sustainable agriculture (LISA) paradigm evolved. This paradigm emphasised minimal use or total exclusion of external inputs that entailed research on developing technologies that prioritised biological techniques to replenish soil fertility. Mulching, rotational intercropping, agroforestry and composting are examples of such technology. Different low-input techniques were developed and tested on farmers' fields (Versteeg and Koudokpon 1993). Although it is undeniable that organic matter inputs are crucial for maintaining soil fertility, significant amounts are needed to balance the withdrawal of nutrients through harvesting of products and this is often not available to smallholders as its management is land and labour intensive.

Taking such constraints into account, Sanchez (1994) formulated a second paradigm that recognized the need to use mineral *and* organic fertilizers, together with improved germplasm. This paradigm recognized that organic and inorganic amendments have positive and complementary interactions and that one can rarely substitute one with the other (Buresh et al. 1997; Vanlauwe et al. 2001a, 2001b). This second paradigm was accompanied by a shift in approaches towards involvement of the various stakeholders in the research and development process (Swift and Seward 1994). One of the important lessons learned was that the farmers' decision-making process was not merely driven by the soil and climate, but by a whole set of factors cutting across the socio-economic and political domain (Bekunda et al. 2010).

At the same time, there has been increasing recognition that land degradation not only has on-site costs but generates off-site costs that affect the whole of society. Natural capital, such as soil, water, atmosphere or biota is not only the basis for producing goods with a market value (e.g. crops and livestock) but also generates further essential ecosystem services (e.g. climate regulation and clean water). The concept of integrated natural resource management (INRM) aimed to develop interventions targeted at restoring landscapes and a much wider range of ecosystem services (Izac 2000). At the same time, the concept of sustainable land management (SLM) was developed and encompasses a wide range of interventions, including those that fall under soil and water conservation (SWC), which are aimed at improving agricultural productivity, improving people's livelihoods and improving ecosystems.

In a strict sense, integrated soil fertility management (ISFM) is INRM with a focus on soil fertility and a field scale. ISFM also recognized the importance of social, cultural and economic aspects that shape soil fertility management practices. Current interest in ISFM results from widespread demonstration of the benefits of typical ISFM interventions (Zingore et al. 2007). ISFM had been identified by the Tropical Soil Biology and Fertility Programme (TSBF) quite early on as a key entry point for improving agronomic productivity and resource-use efficiency (TSBF 1984).

With the intention to rekindle the idea of boosting agronomic production in Africa through increased use of external inputs (mineral fertilizer, improved crops) and linking farmers better to markets (Gary et al. 2008) in 2006 The Bill & Melinda Gates Foundation in partnership with the Rockefeller Foundation established the Alliance for a Green Revolution in Africa (AGRA) with its headquarters in Nairobi. In 2013, AGRA gave US$ 52 million in grants to research and learning institutions, small- to medium-sized agribusinesses and various NGOs (AGRA 2014). AGRA pursues three goals: to reduce food insecurity (*by 50% in at least 20 countries by 2020*), to increase incomes (*double incomes of 20 million smallholder families by 2020*) and to put countries (*at least 15 countries by 2020*) on a pathway for attaining and sustaining a green revolution. AGRA's soil health programme promotes the use and adoption of ISFM practices.

First attempts to minimise the detrimental impact that soil disturbance and exposing bare soils can be dated back to the 1930s (Faulkner 1945). Conservation agriculture (CA) builds on these ideas of minimum tillage and residue retention. Initial trials in SSA were carried out in the 1970s in West Africa (Greenland 1975; Lal 1976a), though not yet coined CA then. Conservation agriculture kick-started in the Americas and (somewhat later) in Australia in the 1970s and 1980s and since the early 1990s it began to spread exponentially; at that time it also started to get the attention of some IARCs as well as FAO and CIRAD. Through consistent commitment and systematic research for development (R4D) by the IARCs that currently more than 100 million ha are under CA worldwide and are continuously increasing (Friedrich et al. 2012). However, CA does not yet have a notable foothold in place in SSA. The bulk of the land under CA is on larger farms in Argentina, Australia, Brazil, Canada, Paraguay and the United States of America. More recently, CA has been tested and adapted to the conditions of smallholder farmers in Africa and India.

Organic agriculture is not a new invention. However, it has gained tremendous significance over the last decade, not only in developed countries, but also in SSA. It is a system that – as well as ISFM – aims at promoting efficient nutrient use. The emphasis however lies in maximizing (whole farm/

system) nutrient and organic matter recycling and the exploitation of biological/agro-ecological mechanisms, employing crop rotations and leguminous species to maintain and build soil health. It deliberately renounces synthetic fertilizers, synthetic pesticides and performance stimulants (Meyer and Burger 2010). In 2011, 37 million ha were organic agricultural land, managed by 1.8 million farmers worldwide. Of this area, about one-third was located in developing and emerging countries (6.9 million ha in Latin America, 3.7 million ha in Asia, 1.1 million ha in Africa). Organic agriculture has the potential to develop natural resources, strengthen communities and improve human capacity, thus improving food security by addressing many different causal factors simultaneously (UNCTAD and UNEP 2008). However, there are limitations; it is only sustainable if nutrient losses (e.g. through exporting crops off-farm) are replenished by bringing back nutrients other than through synthetic fertilizers. This is a major challenge in SSA; addressing it, among others, would require building and closing rural-urban nutrient cycles. Organic agriculture has limitations with regard to addressing regional (micro-) nutrient deficiencies, i.e. “what is not there cannot be recycled.” It is also labour- and knowledge-intensive and the lack of the latter is often a limiting factor in the spread of organic production.

Since the 1960s, IARCs research has focused almost solely on agricultural productivity and efficiency. Although a reduction in environmental degradation was one aim of most of this research, it is only since the mid-1990s that IARCs shifted their research emphasis from increasing productivity to research that considered natural resources and environmental concerns. In 1998, the CGIAR embraced a new vision focused on alleviating poverty and conserving the environment. This was primarily driven by new global environmental agreements and the fact that many other organisations had increased their focus on plant breeding and crop protection that had been the mainstay of the CGIAR. This new vision was built on the concept of sustainability that had been developing in the CGIAR during the 1980s and 1990s. This shift has brought renewed focus and constantly evolving terminology, to research focused on the sustainability of agricultural systems. Below we focus on soil and water conservation (SWC), integrated natural resource management (INRM) and sustainable land management (SLM).

The more recent history of IARC’s soil research comprises the inclusion of remote sensing technologies for (digital) soil mapping, as well as proximal sensing (e.g. infrared spectroscopy) for rapid and cost-effective assessment of soil fertility at field level and for larger/regional-scale monitoring of soil and land degradation. The concept of Big Data is gaining momentum these days also in soil science. Together with constant progress in the field of computer-aided crop-soil simulation, these constitute powerful tools for analysing the impact of actual and potential soil conservation management practices, as well in targeting interventions for most effective impact.

Last but not least, climate smart agriculture (CSA) has gained tremendous momentum in the last 2-3 years, and there has been significant fund committed internationally to implement CSA large-scale around the globe. This trends and a few others will be describe in more detail in the following.

Major trends in soil research

2.1. Rationale

This chapter looks at the involvement of the CGIAR in soil research, particularly in relation to its comparative advantage to conduct and lead strategic scientific research directed towards the compelling problems of poverty, hunger and a healthy environment. Based on CGIAR centres’ case studies in literature, we provide major trends of soil research in SSA. The chapter also reviews positive outcomes from the best cases of soil research, as well as ongoing concerns and issues to consider in future planning.

The choice of major trends and findings is somewhat subjective and additional trends could be added. Here we focus on trends that were most successful to date or those we believe have the best potential to support the mission of soil protection and rehabilitation for food security.

2.2. Major trends and findings

There are eight major trends that we believe merit a closer look:

1. Green Revolution in Africa
2. Organic matter management, ISFM, soil biology
3. Conservation agriculture
4. Agroforestry
5. Soil water conservation, INRM and sustainable land management
6. Eco-efficiency
7. Soil organic carbon-sequestration, GHG emissions, climate-smart agriculture
8. Emerging trends and tools in soil science

Green Revolution (in Africa)

i. Science

Despite some criticism about its magnitude, sustainability and equity (Cullather 2010; Pingali 2012; *The Guardian* 2014), the Green Revolution in Asia by and large is seen as a tremendous success, tripling/quadrupling yields of staple crops such as wheat and rice, saving millions – some claim even billions – of people from starvation, providing food self-sufficiency and lifting people out of poverty. It thus seemed only logical to "recreate Borlaug's magic in Africa", as SSA is being struck by repeated food crises and chronic underperformance in terms of crop production and self-sufficiency.

At the centre of the Green Revolution in Asia was a specific package of technologies: nitrogen-responsive, new, higher-yielding varieties of wheat, maize and rice, chemical fertilizers and irrigation. This helped to create a "springboard" out of poverty in Asia and provided the foundation for the broader economic and industrial development that has occurred in the last 20 years (World Bank 2005; Huang et al. 2006). The Green Revolution in Asia and associated economic development alone, however, was not able to eliminate poverty in its entireness - which it actually never strived to achieve in the first place. Of the approximate 702 million people that live below the poverty line of US$ 1.90 per day in 2015, still 32 % are found in South Asia[2] (World Bank Group 2016).

Per hectare yield increases in Africa for maize, wheat and rice have failed to match the pace seen in other regions. Thus, production surpluses in Asia and Latin America are the result of productivity increases while Africa's production increases have been a result of increased land use. Intensification of production in current agricultural lands has been suggested as a key solution to the conflict between expanding agricultural production and conserving natural ecosystems (Smith et al. 2010; Phalan et al. 2011).

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[2] 45% of the world's poor are found in Sub-Saharan Africa, 19% in East Asia and Pacific, and 5% in the rest of the world.

The "one size fits all" approach that has worked well for the vast, irrigated regions of Asia is not appropriate for the highly diverse, rainfed farming systems of Africa. There is a multitude of reasons why Africa's agriculture is different from that of other regions of the world. Proponents of a Green Revolutions for Africa, above all, state that it is the lack of mineral fertilizer applied that hampers intensifying agriculture (AGRA 2013). Indeed, only very recently, there has been some humble success - in part through fertilizer subsidy programs - in increasing fertilizer consumption in some countries of SSA, such as Nigeria, Kenya, Malawi and Ethiopia. The majority of countries however consume far less than a mere 10 kg of mineral fertilizer per hectare and year, even though fertilizer has been promoted for some decades.

Therefore, to move beyond the one-size-fits-all solution of the 1960ths and 70ths, institutions supporting a Green Revolution for Africa suggested a greater emphasis on farmers' participation, local adaptation, strengthening national and local institutions and the building of agricultural value chains that enable farmers to generate profits from surplus production. Institutions for linking farmers to input and output markets should ensure that farmers have adequate, appropriate, affordable and timely inputs, as well as knowledge of appropriate agronomic practices and technology packages that enhance productivity in an environmentally sustainable way (AGRA 2013).

Practical relevance

The underlying rationale for a Green Revolution for Africa, is that the majority of SSA countries have agricultural-based economies; agriculture provides an effective means for both reducing poverty and accelerating economic growth. Evidence shows that agricultural growth reduces poverty by twice the rate of growth in non-agricultural sectors (Diao et al. 2007; World Bank 2007).

So far so good. However, the current vision of a "Green Revolution for Africa" in fact has long abandoned the simplicity of Green Revolution as it had been conveyed during its early days. In other words, simply to "recreate Borlaug's magic in Africa" has failed. Instead much more adaptive, complex and sustainable solutions have been brought forward. As Henao and Baanante (2006) and Bationo et al. (2006) noted: a Green Revolution for Africa should be one that "will exploit a mosaic of approaches and solutions, including conservation farming, minimum tillage, judicious use of inputs, with a goal to tap Africa's great diversity – human, cultural, dietary, biological, climatic and environmental – to ensure productive farming and livelihood systems". This can be done by focusing on overcoming nutrient mining and maintaining the physical, biological and chemical integrity of the soil. Global initiatives should enhance small-scale farmers' access to organic and inorganic fertilizer. Key to these actions is capacity building and training of farmers in the appropriate use of inorganic and organic fertilizers, with a focus on maximizing nutrient use efficiency while maintaining soil health. Data on soil health, crop nutrients, water management and reliable annual estimates of crop and animal production is required to substantiate these goals and progress with hard facts. It is somewhat a philosophical questions, if such comprehensive plan still should be called Green Revolution, if the latter actually implies a simplistic one-fits-all solution.

Organic matter management, soil biology, integrated nutrient and soil fertility management

i. Science

The majority of soils of the tropics are inherently infertile. Organic matter makes a vital contribution to soil fertility and system sustainability through regulation of numerous environmental constraints to crop productivity. Mineralisation of decomposing residues is a major source of plant nutrients in highly weathered soils with little inherent mineral fertility (Sanchez et al. 1989). Soil organic matter improves soil aggregation (Oades 1984; Bationo et al. 2008; Sahrawat et al. 2010), reduces erosion, enhances nutrient use efficiency (Woomer and Ingram 1990; Cassman 1999) and promotes rainwater infiltration and soil water-holding capacity (Lal 1986; Lavelle 1988; Bossio et al. 2007). However, inappropriate land use (Follett and Schimel 1989; Srivastava and Singh 1989; Den Biggelaar et al. 2004a, 2004b; Montgomery 2007; Sahrawat et al. 2010) has significantly contributed to soil degradation through soil organic matter loss in both temperate regions (Cole et al. 1987; Post and Mann 1990; Pathak et al. 2005; Poch and Martinez-Casanovas 2002; Sahrawat et al. 2010) and the tropics (Nye and Greenland 1960; Ayanaba et al. 1976; Ayodele 1986).

In the tropics, the availability of organic resources as nutrients sources is limited by their alternative uses as fuel, feed and fibre, especially in drier areas where overall biomass production is low, and the labour required to collect and process this materials. In addition, the rapid rate of decomposition in a moist, warm climate could create an asynchrony between nutrient release and crop demand (Myers et al. 1994), suggesting that the timing and placement of organic resources must be carefully elaborated. This, coupled with the low nutrient concentrations of available organic resources (Vanlauwe et al. 2006) limits their potential to improve crop yields when they are used as the sole source of nutrients.

To facilitate improved use of organic resources in tropical soil fertility management, the Tropical Soil Biology and Fertility (TSBF) Institute of CIAT characterized the nutrient contents of a wide range of farmer available organic resources and developed the organic resource database (ORD) and related decision-support system (DSS) for organic material (OM) management (Palm et al. 2001). This tool helps in making practical recommendations for appropriate use of OMs, based on their nitrogen (N), polyphenol and lignin contents. Materials with less N and higher lignin and polyphenol contents will release fewer nutrients due to microbial immobilisation and chemical binding. Systems relying on such organic resources thus require supplementary fertilizer or higher quality organic resources to release nutrients at levels to meet crop requirements. This diagnostic approach has been translated into a more farmer-friendly version by replacing chemical analysis with characteristics that include colours (green versus brown), taste (mild versus astringent) and physical integrity (crumbly versus fibrous or solid) (Palm et al. 2001). The decision support system (DSS) recognizes the need for certain organic resources to be applied together with mineral inputs consistent with the second paradigm. However, although this is a relevant tool in light of both second and ISFM paradigms, the tool is has not been updated for some time and currently is unavailable online.

The ISFM paradigm acknowledges the need for organic *and* mineral inputs to sustain soil health and crop production (Buresh et al. 1997; Nhamo 2001; Vanlauwe et al. 2002a, 2002b). One key complementarity is that organic resources enhance the soil organic matter status and the functions it supports, while mineral inputs are targeted to key limiting nutrients. By increasing the awareness of the variety of options available and how they may complement or substitute for one another, ISFM has gained rapid acceptance by development and extension programmes in SSA and, most importantly, by smallholder farmers. The combined application of fertilizer and organic resources also gained impetus (Vanlauwe et al. 2001c), because of (i) the failure of Green Revolution-like interventions in SSA; and (ii) the lack of adoption of low-external-input technologies by smallholder farmers.

Among the most promising organically based soil nutrient practices are: application of animal manure or compost, incorporation of crop residues, natural fallowing, improved fallows, relay or intercropping of legumes (and dual purpose legumes) and biomass transfer. Emerging evidence from across Africa points to widespread use of organic inputs, sometimes in conjunction with mineral fertilizers (Kelly et al. 2002; Mekuria and Waddington 2002; Place et al. 2002; Shapiro and Sanders 2002). However, the amounts of organic inputs produced and applied are limited due to high opportunity costs of labour and land. The availability of organic resources within farms (mainly as crop residues and/or farmyard manure) can be improved by diversifying farming systems (mainly with legumes). Under the biophysical and socio-economic conditions prevailing in SSA, the combined application of fertilizer and organic inputs is relevant because (i) both fertilizer and organic inputs are often in short supply in smallholder farming systems due to limited affordability and/or accessibility; (ii) both inputs contain varying combinations of nutrients and/or carbon, thus addressing different soil fertility-related constraints; and (iii) extra crop produce can often be observed due to positive interactions between fertilizer and organic inputs (Vanlauwe et al. 2001a, b, ; 2002a , b).

ISFM technologies capable of delivering rapid benefits to large number of farmers in SSA include: fertilizer micro-dosing, dual purpose grain legume-cereal rotations with fertilizer targeted at different phases of the rotation, improved cereal legume intercrops with adjustment in row arrangement and legume inoculation. The greatest strength of ISFM is its ability to integrate local suitability, economic profitability, adoptability and sustainability in developing improved land management recommendations.

Practical relevance

Current economic conditions such as subsidy removal, exchange rate devaluation and high inflation are not conducive to promoting the use of external inputs for smallholder farmers (Heisey and Mwangi 1996; Druilhe and Barreiro-Hurlé 2012). Adding organic fertilizer inputs, including animal manures, green manures, crop residues and agroforestry leguminous pruning, is an important way of improving soil fertility. The role of manures and plant residues in nutrient supply, promotion of soil aggregation and nutrient buffering capacity in highly weathered soils is well documented (Brown et al. 1994; Lal 2006; Batiano et al. 2007; Omotayo and Chukwuka 2009). However, the use of organic materials to increase the carbon reserves of soil under tropical conditions may require large amounts of annual additions. Janssen (1993), for instances, estimated that 7–10 t ha^{-1} yr^{-1} organic material would be required to maintain a 1.0% soil organic carbon level in the sub-humid tropics of Zimbabwe. However, typical biomass production from agroforestry species is only 2–4 t ha^{-1} yr^{-1}. Thus it is difficult to produce adequate organic material under smallholder farm conditions to build or maintain soil organic matter. Given the widespread demonstration of the benefits of ISFM interventions at plot scale, including the combined use of organic manure and mineral fertilizers (Zingore et al. 2007), dual purpose legume-cereal rotations (Sanginga et al. 2003), or micro-dosing of fertilizer and manure for cereals in semi-arid areas (Tabo et al. 2007), there is need to scale-out successful ISFM technologies to small-scale farmers in SSA.

Purely organic approaches are often not sufficient to address the SSA soil fertility problem due to lack of attractiveness and resources to sustain an “organic paradigm” especially on soils with inherently low fertility, although pockets of successful organic production with linkage to markets are emerging even in Africa. Often these markets are urban, such a for organic meat and vegetables in Nairobi, and export of organic vegetables to Europe. After abandoning the external input paradigm, significant experimentation shifted to low-input methods that prioritized biological techniques to replenish soil fertility, such as alley farming with leguminous trees whose cuttings were used to incorporate nitrogen into the system; improved fallows with leguminous trees; animal manure and composting; and biomass transfer. However, adoption rarely occurred after research interventions ended. This is because “low-input” methods are also characterized as “low output” systems due to the low quantity and quality of nutrient provision. In addition, these methods are labour and land intensive and require farmers to dedicate resources to producing and retaining biomass other than staple and cash crops. This has necessitated a change of focus to ISFM-based cropping practices, based on scientific evidence that fertilizers are most effective and efficient in the presence of soil organic matter.

Conservation agriculture

i. Science

Conservation agriculture (CA) intends to combine – as the name implies – conservation of the natural resource base and agriculture. It builds on three principles: minimum soil disturbance through zero tillage, crop residue management to retain as much residue on the soil surface as possible and crop rotation and diversification.

Currently, worldwide more than 100 million ha are under CA and this trend is increasing (Friedrich et al. 2012). However, CA is mainly been practiced on large farms. The bulk of land under CA is in Argentina, Australia, Brazil, Canada, Paraguay and the United States of America. More recently, CA has been tested and adapted to the conditions of smallholder farmers in Africa and India.

Searching available literature for the keywords ‘conservation agriculture and tropics’ yielded 334 hits.[3] About 90% of these studies were published after 2006 (Figure 1). Less than 13%, a total of 43 papers, explicitly addressed SSA, while a notable 11% (38) targeted India. This is in line with a recent review of CA carried out by Corbeels et al. (2014); they used 41 papers, representing 61 independent studies, in order to conduct a meta-analysis of the effectiveness of CA in SSA.

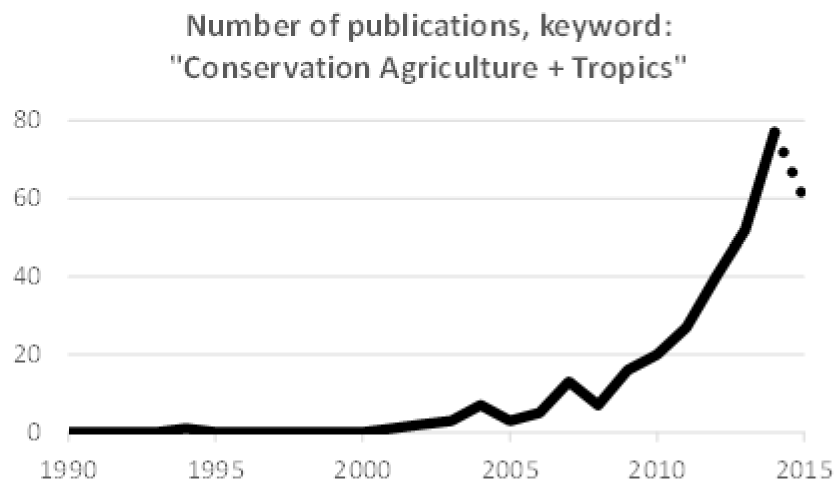

Figure 1. Judging from the number of scientific studies published, conservation agriculture in the tropics is a more recent trend.

[3] using ScienceDirect search engine (http://www.sciencedirect.com/science/search)

Major drivers for the adoption of CA on large farms are fuel reduction (Pratibha et al. 2015), labour/time saving and reduced soil erosion compared to conventional (tillage-based) agriculture (Merten and Minella 2013). The benefit of CA systems in terms of mitigating the impact of droughts by earlier sowing and better water use has been a reason for their adoption in the dry areas of Australia and more recently in West Asia (Sommer et al. 2012; Richards et al. 2014; Piggin et al. 2015).

Yield increases as well as increases in yield stability of CA in comparison to conventional systems have been observed in smallholder agricultural systems – e.g. in Southern Africa (Thierfelder et al. 2015) or SSA (Corbeels et al. 2014) – but challenges with CA have also been reported (Rusinamhodzi et al. 2011; Brouder and Gomez-Macpherson 2014; Homann-Kee Tui et al. 2014; Pittelkow et al. 2014; Rusinamhodzi 2015). Thus, yield increases in response to CA alone may not serve as the chief argument for promotion of its adoption.

The pronounced benefits in terms of conserving as well as physically protecting soils and enhancing soil fertility make CA a promising technology for sustainable agricultural intensification; this is documented by numerous publications worldwide (see e.g. Hobbs et al. 2008). These beneficial effects can largely be attributed to an increase in soil organic matter in the topsoil layer – often limited to the top 5 to 10 cm and accompanied by relative losses at deeper depths – in response to the retention of surface residues (Dalal et al. 2011, Valbuena et al. 2012), lower soil surface temperatures (Sommer et al. 2007) and as a consequence, improved soil health, water infiltration and reduced erosion (Thierfelder et al. 2012).

Whether CA systems contribute to mitigating climate change by sequestering carbon in the soil is currently the subject of debate (Paul et al. 2013; Powlson et al. 2014). If there is such net sequestration, the effect could be offset by an increase in nitrous oxide (N_2O) emissions – a very potent GHG (Li et al. 2005; Lenka and Lal 2013; Sommer et al. 2015).

ii. Practical relevance

CA is a knowledge-intensive system that includes the knowledge of how (and when) to plant seeds in an untilled soil and associated usage of suitable machinery, the appropriate application of chemical inputs and levels of surface residues, as well as how to address emerging problems such as potentially increased levels of weeds and new pathogens etc.

Additionally CA requires farmers to shift paradigms, especially when a neatly tilled soil traditionally plays a big role in "being a good farmer", or simply in maintaining/securing land rights.

As opposed to large, mechanized farms, the labour demand for non-mechanized smallholder farms could substantially increase under CA, especially when manual weeding and not herbicide application – very common in CA – is needed, or when residues to cover the soil surface are brought in from elsewhere (Ndlovu et al. 2014; Nyamangara et al. 2014).

Furthermore, for quite some time, CA has been advocated as a package that should be adopted all at once (Knowler and Bradshaw 2007), although crop rotation and residue retention certainly merit being tested and adopted one at a time. CA, however, seems doomed when minimum tillage is practiced without surface residue retention, resulting in soil surface crusting/sealing, soil compaction and subsequent poor soil water infiltration and increased surface water runoff. Such, however, unfortunately seems to be the most logical first choice of a farmer trying out CA components individually. Thus, the adoption of CA – as advocated by Sommer et al. (2013) in an attempt to unite ISFM and CA (then coined as ISFM+) – must not occur in an arbitrary fashion, but in steps, with minimum tillage at the end. Eventually, in order to achieve yield benefit, all three pillars should be implemented (Corbeels et al. 2014; Pittelkow et al. 2014).

Access to markets for selling surplus production or to purchase inputs such as seeds, herbicides and mineral fertilizers is a second obstacle to the successful adoption of CA. There is evidence that not disturbing the soil reduces the decomposition of organic matter and the release of crop nutrients. With the desired increase in biological activity and abundance of soil microbes, such nutrients could then also become temporarily unavailable to uptake by crops; this increases the need to apply (more) inorganic fertilizers, which smallholder farmers may not be in the financial position to do. There have also been cases reported where such type of agricultural intensification turned out to be financially unprofitable for poorer households (Ricker-Gilbert and Jayne 2012).

Eventually, probably the biggest challenge is the availability of plant residues for soil surface retention, especially in semi-arid regions where biomass production is low. Competition for and scarcity of, organic matter in resource-constrained smallholder farming systems has been somewhat overlooked in the early days of introduction of CA to SSA, but has gained significant attention more recently, documented by a number of studies tackling the issue (Lahmar et al. 2012; Jaleta et al. 2013; Baudron et al. 2014; Bhan and Behera 2014; Homann-Kee Tui et al. 2014). Studies on the benefits of investing in soil conservation and increasing soil fertility by retaining plant residues suggest that hoarding rather than using (soil) organic matter (Janzen 2006) is not a clear-cut, obvious decision; using organic matter e.g. for livestock feed may be more lucrative at least in the short-term and doing otherwise is effectively "burying resources in the ground".

Emerging from this debate is an emphasis on examining whole farm dynamics, e.g. by using simulation tools that allow for multi-criteria optimization (Groot et al. 2007), as well as testing CA practices in a participatory manner together with smallholders, among others, using a stepwise approach (CIMMYT 2013), which elsewhere had been termed "ISFM+". There is also a renewed debate about payment for environmental services (PES) and the value of ecosystem services that CA may support, maintain or generate (Palm et al. 2014).

In conclusion, CA has been proven as a smart way of sustaining intensified agricultural production in a multitude of studies and regions outside and inside SSA. It, to some extent, fulfils the criteria of eco-efficiency and climate-smart agriculture (see respective chapter for details). However, it has its bottlenecks and limitations and is far from constituting a "panacea for the problems of poor agricultural productivity and soil degradation in sub-Saharan Africa", as some scientists thought it was (Giller et al. 2009). To stimulate adoption of CA by farmers may require, at least initially, putting forward incentives (e.g. payment for environmental services [PES]) or facilitation of access to knowledge, credits, inputs, markets and, if applicable, machinery.

Agroforestry

i. Science

Globally, farmers have traditionally practiced agroforestry, the inclusion of woody perennials (trees, shrubs, palms, bamboos, etc.) within farming systems with some knowledge of its benefits. For example, in the Sahelian and Sudanese regions of Africa, *Faidherbia albida* has always been retained in crop fields in "parkland systems" in acknowledgement of the benefits it brings through "reverse leaf phenology" (Roupsard et al. 1999). This process forces the tree to go dormant and shed its nitrogen-rich leaves during the early rainy season, when seeds are being planted and need the nitrogen and then to regrow its leaves when the dry season begins and the crops are dormant. The scientific recognition of the benefits of trees in agricultural systems began in the late 1940s, while the dedicated study of agroforestry as a scientific discipline emerged in the 1970s (Young 1989). Two landmarks in the field include symposia (1979 and 1984) held by The World Agroforestry Centre (ICRAF), launching the agroforestry research and the study of soil productivity aspects of agroforestry we draw upon today (Young 1989). After 40 years of systematic study, agroforestry is also promoted as an important livelihood and sustainable land management option for smallholder farmers (Young 1989; Zomer et al. 2014).

Agroforestry systems are diverse and range widely from subsistence livestock and pastoral systems to home gardens and fertilizer tree systems (including alley cropping), all within a variety of social and agro-ecological contexts (Schroth and Sinclair 2003; Zomer et al. 2009; Zomer et al. 2014). Recent remote sensing studies show that from 2000 to 2010, agroforestry appears to increase in land area[4] and in the number of people involved and remains a significant feature of agriculture across the world (Zomer et al. 2014). Agroforestry currently represents over 1 billion ha of land and more than 900 million people (Zomer et al. 2014).

The fundamental assumption in agroforestry is that the integration of trees into farming systems and landscapes can increase soil fertility, productivity and sustainability (Schroth and Sinclair 2003; Van Noordwijk et al. 2015). Soil research has been a prominent part of the agroforestry research agenda from the start of ICRAF in 1978 (Van Noordwijk et al. 2015). Trees in agricultural systems can prevent soil erosion, improve soil biodiversity, suppress weeds, improve soil structure, increase soil carbon stocks and enhance soil fertility (Schroth and Sinclair 2003; Takimoto et al. 2008; Pumariño et al. 2015; Van Noordwijk et al. 2015) in addition to providing other ecosystem services (Jose 2009; Sinare and Gordon 2015). For example, farmers in Eastern and Southern Africa may use short-term planted fallows with leguminous trees (such as *Leucaena*, *Sesbania*, *Calliandra*, *Tephrosia*) to regenerate the fertility of their soils and to substitute mineral nitrogen fertilizer, with the added co-benefit that these trees may also produce valuable animal fodder, fuelwood, fruits and timber, often relieving pressure on natural forests (Schroth and Sinclair 2003; Minang et al. 2014).

The following three examples below illustrate trends in agroforestry systems and their impacts on soil health and fertility.

Alley cropping: During the 1980s and early 1990s, alley cropping was developed and tested as a method of restoring soil fertility (Steppler and Nair 1987). Under alley cropping, food crops are grown between hedges of trees (preferably nitrogen fixing) which are cut back regularly to minimise tree–crop competition, with the prunings added as green manure or mulch to crops to improve soil fertility. Nitrogen addition through the application of nutrient-rich organic mulch is the most important benefit in unfertilized alley cropping systems, but can vary widely depending on how much biomass trees yield and how fast this biomass decomposes, whether trees fix nitrogen and the management and site-specific factors (Nair 1993). Many studies demonstrate that alley cropping reduces erosion and has a positive impact on soil fertility, including soil carbon (Nair 1993; Kang and

[4] In sub-Saharan Africa, the study found an increase of 2% compared to 12.6% in South America, 6.7% in South Asia

Shannon 2001; Negash and Starr 2015). Early studies showed that alley cropping increased maize yields, in some cases by almost doubling them. Fertilizer has been shown to increase yields further and alley cropping with fertilizer is the most economically viable option compared to alley cropping alone or conventional (non-alley cropping) systems (Aihou et al. 1998).

However, alley cropping can also result in yields that are the same or less than crops under no alley cropping (Nair 1993). This unpromising result has been attributed to shading, root competition, immobilization of nutrients due to decomposing mulch and the mulch impeding the emergence of crop seedlings (Gutteridge and Shelton 1994; Ong and Leakey 1999). Benefits can also take some time to accrue (Akyeampong and Hitimana 1996). In moisture-stressed environments, alley cropping has also been shown to have negative impacts because trees grow faster than crops using available water and reducing crop yields (Ong and Leakey 1999). A number of studies conducted in the 1990s revealed that choosing appropriate alley crop species and spacing ratios was critically important. In general, alley cropping is likely to be less suitable for drier areas compared to humid and sub-humid areas. The quantity, quality and timing of application of the mulch is key to success. Other issues that have been raised include labour requirements (for planting, pruning and mulching), the loss of cropping area given over to trees and pest management problems.

Slash-and-mulch agroforestry systems (SMAS): Alternatives to slash-and-burn[5] agriculture systems cultivation and the use of fire to prepare land for planting have been developed and adapted throughout the world. One particularly exciting example is the Quesungual slash-and-mulch agroforestry system (QSMAS), originally promoted in the early 1990s by the Food and Agriculture Organization of the United Nations (FAO) with community-based organizations in Lempira department, Honduras as an alternative to slash-and-burn agriculture that was particularly suited to hillsides and steep slopes. The system includes various species of trees, many of them legumes, scattered across cropland at a density of up to 1,000 trees per hectare. The roots of the trees stabilized the hillsides, minimized soil erosion and improved nutrient uptake from deeper soil layers. Farmers regularly prune a majority of the trees and leave the cuttings on the field as mulch to provide nutrients, increase soil organic matter, improve soil structure and retain moisture (Fonte et al. 2010). This provides crops within these fields some protection from drought spells and heavy rains. These key principles are: (i) no slash and burn, by management (partial, selective and progressive slash-and-prune) of the natural vegetation; (ii) permanent soil cover by continual deposition of biomass from trees, shrubs and weeds and crop residues; (iii) minimal disturbance of soil by not tilling the soil, direct seeding and reduced soil disturbance during agronomic practices; and (iv) efficient use of fertilizer by appropriate application (timing, type, amount and location) of fertilizers (CIAT 2009b).

Agro-silvo-pastoral systems (ASPS): Many agroforestry systems in the tropics have been adapted to include livestock and grazing and are known as agro-silvo–pastoral-based systems. Russo (1996) describes an agro-silvo-pastoral system as a land-use system with deliberate combination of trees or shrubs with cattle in the same site with the potential to be a model of production and conservation. CIAT has implemented these systems in Latin America to integrate improved crops, forages, multipurpose trees and management options for improved productivity, profitability and resilience.

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[5] shifting cultivation and the use of fire to prepare land for planting

ii. Practical relevance

Agroforestry will continue to be a widespread land use globally as it provides many benefits to farmers. The practical use and recommendations depend on the context for each farmer and land manager. Consequently, improved agroforestry techniques must be matched with the fertility problems in context; for example, if a farm is deficient in nitrogen and phosphorous, leguminous trees can increase the availability of nitrogen through fixation, but phosphorous may have to be added from external sources (Schroth and Sinclair 2003).

When considering adoption (or non-adoption) issues of access and rights to land, inputs and capital for long-term investments that may require several years for benefits or returns on investment, such as trees, must be understood and addressed (Akyeampong and Hitimana 1996; Mbow et al. 2014). An agroforestry technique not only has to be matched to the biophysical context of a farm, but also has to be compatible with the views, experiences, traditions and economic capacities of the farmers. Progress in agroforestry depends on an understanding of both the biophysical and socio-economic context of farming systems at a range of scales.

Alley cropping: Although the promise of multiple benefits (i.e. improved soil fertility, food, fodder, timber etc.) makes alley cropping an attractive option, achieving all of these benefits without trade-offs is a technical challenge and numerous factors need to be considered (Nair 1993). Alley cropping is not a substitute for fertilizer and high yields may only be achieved with fertilizer addition. Much of the debate surrounding alley cropping has come about because alley cropping is only suitable under certain conditions; there are a number of factors that hinder its adoption and to date; and there is a wide body of evidence on only a limited number of appropriate species, despite the large number of potential agroforestry species within SSA. The subject of alley cropping became so polarised in the 1990s that research on the topic began to decline or was labelled under a different name – research on fertiliser trees still continues today (Ajayi et al. 2011). The practice has experienced a recent surge (2009–2010) in research because of the implications of alley cropping for increasing carbon in agricultural systems, as well as for intercropping biofuels with food crops.

Slash and mulch agroforestry systems: Research indicates that SMAS technologies contribute to improving biodiversity and soil functioning by enhancing the cover of native vegetation (Ordonez Barragan 2004), increases in soil biological activity (Pauli et al. 2009; Fonte et al. 2010) and much more balanced nutrient flows compared to slash-and-burn systems (Sommer et al. 2004). The inclusion of trees and the maintenance of soil cover (by mulching of tree prunings and crop residues) has been shown to reduce erosion and increase water infiltration, storage and subsequent availability to crops (Rivera 2008). Furthermore, large-scale dissemination of SMAS and improved integration of alternative pest control options is likely to promote regional biodiversity due to increases in both on-farm diversity as well as enhanced connectivity between natural areas (Perfecto and Vandermeer 2010).

Soil and water conservation, integrated natural resource management and sustainable land management

i. Science

Research on Soil Water Conservation (SWC) has been conducted since the early 20th century, but it was only in the 1980s that the CGIAR started investing in this research. Defined as "activities at the local level that maintain or enhance the productive capacity of the land in areas affected by, or prone to, degradation" (WOCAT 2007), SWC practices cover a wide range of activities including soil fertility and crop management, soil erosion control measures and water harvesting. WOCAT categorise SWC practices into four types: (i) agronomic e.g. mulching, manure (ii) vegetative e.g. grass strips, agroforestry (iii) structural e.g. terraces or (iv) management e.g. leaving land fallow. These categories helped to identify the level of investment that a practice might require and the way in which it might help maintain soil properties or restore degraded land. According to Pagiola (1999), in 1996 about 17% of the CGIAR research budget was spent on soil and water conservation research. Of this research, 70% was focused on on-site impacts of SWC and the rest looked at community and watershed level impacts.

The new emphasis on natural resources and the environment led to a new focus on INRM, which operated on the premise that farmers lives do not only take place within the boundaries of their farms and that they both rely on and impact the environment and natural resources around them. The INRM research and development approach aimed to combine the interconnected goals of poverty reduction, food security and environmental sustainability, requiring a shift in emphasis from the impact of on-farm management to management at watershed, landscape and regional levels. The definition of INRM has changed over time, as the approach has embraced new concepts such as those of ecosystem services and SLM. INRM has been defined as: "An approach that integrates research of different types of natural resources into stakeholder-driven processes of adaptive management and innovation to improve livelihoods, agro-ecosystems resilience, agriculture productivity and environmental services at community, eco-regional and global scales of intervention and impact" (Thomas 2002). INRM may incorporate SLM which are practices relating to management of soil, water, vegetation and land systems – this includes many SWC practices. SLM has enlarged the focus of SWC – from a major focus on the biophysical benefits of practices on soil and water to "a form of land management that is targeted towards improving or stabilising agricultural productivity, improving people's livelihoods and improving ecosystems" (Schwilch et al. 2012). Many of the practices involved are still the same. SLM interventions "seek to combine and optimise the ecological, technical, institutional, socio-cultural, economic and scientific aspects of land management in response to land degradation" (Schwilch et al. 2012).

Since the 1980s, research in SSA has and continues to demonstrate that numerous SWC and SLM practices increase yields in the major staple crops in SSA, such as maize (Meliyo et al. 2007, Mtambanengwe et al. 2007), beans (Akyeampong and Hitimana 1996, Gichangi et al. 2007), millet (Sangaré et al. 2002, Fatondji et al. 2006), sorghum (Mando et al. 2005, Kabanza and Rwehumbiza 2007) and sweet potato (Chuma et al. 2006). There have also been limited studies on the impact of certain SLM practices on soil erosion and run-off, where it has been demonstrated that SLM can reduce the impact of both (Lal 1976b, Kiepe 1996). Much research has assumed that improvements in soil properties are reflected in yields and so can be derived by measuring yields. However in the 1990s, there was a shift in focus on solely measuring yields to also measuring the impacts of practices on soil properties (Nziguheba et al. 2005). This shift was important for increasing our understanding of the extent to which different practices can rehabilitate soil – i.e. the sustainability of practices (Zingore et al. 2007, Erkossa 2011). Long-term trials across SSA have also been invaluable in providing robust evidence on the benefits of different SLM practices on soil properties and yield (Kibunja et al. 2011, Bationo et al. 2012). Since fertilizers became widely available, there have also been numerous studies comparing the impacts of SLM practices implemented with and without fertilizer. Often, a combination of organic amendments and fertilizer show a greater increase in yields versus using either alone. However, mineral fertilizer used without addition of organic amendments has been shown to negatively impact soil properties over time (Kapkiyai et al. 1999). Meta-analyses have been useful in determining common patterns (Sileshi et al. 2008). For example, using data from across West Africa, Bayala et al. (2012) showed positive benefits on crop yield (maize, millet and sorghum) for six SLM practices. They also demonstrated that different practices were most beneficial under different rainfall regimes.

There is now a wide body of evidence on the biophysical on-site impacts of SWC and SLM, but this evidence is scattered throughout the literature, making it difficult to assess the true extent of the evidence base. In general, there is far more data on yield and soil properties available for agronomic and vegetative SLM practices from research and farmer trials compared to structural and management SLM practices.

Recognition that ecosystems provide benefits (ecosystem services) that contribute to human well-being has allowed for the incorporation of a much wider range of benefits, such as carbon sequestration, water quality regulation, etc. into assessments of SLM (including SWC) and INRM. The ecosystem services concept aims to support the development of INRM and SLM (Balvanera et al. 2012). Quantifying and valuing off-site and on-site benefits of SLM not only increases the measured value of SLM, but can be used to identify where to invest to reduce off-site costs of land degradation, as well as highlight who benefits from SLM and who bears the financial costs of implementation. Over the past 20 years, a number of SLM programmes have started to embrace these research themes within CGIAR. Most notably, the global CGIAR Challenge Program on Water and Food (CPWF) and subsequent Water, Land and Ecosystems Program (WLE) incorporated these themes into their research. Within their Nile River Basin site, CPWF developed tools to help plan and target INRM interventions based on ecological principles as well as human needs. This approach should lead to a more comprehensive understanding of the trade-offs involved in managing land sustainably, providing more concrete evidence to inform decision-making (although Laurans et al. (2013) make the point that currently many ecosystem service assessments are supply driven with little evidence of how they have influenced management and policy). It may also be crucial to garner higher level support for cost-effective SLM design and sustain momentum for SLM incentive programmes (Branca et al. 2011, Fremier et al. 2013).

Application of the ecosystem services concept into INRM and SLM programmes was accompanied by a shift in thinking that if land management initiatives were to ultimately result in sustainable farming systems, managing food, water and energy at the landscape level is key (Sayer et al. 2013). Landscapes contain many different resource niches, resource users and institutions. They are connected to other landscapes through both biophysical and social dynamics. These multiple scales of connectivity (between institutions and social processes) have an impact on individual land users' decisions regarding SWC. Additionally, depending on their position within a landscape, households will have access to different areas and resources that will in turn impact their on-site management decisions (Snyder and Cullen 2014). Further, through social networks, land users can access resources (land, labour, livestock, inputs) from others within and outside of their landscape, which shapes the choices they make and the opportunities available to them. Planning and managing at a landscape scale presents additional institutional and social challenges concerning governance and collective action, especially when addressing conflicts and trade-offs that may arise between different land users and land uses, as well as different government sectors across broader scales (Cordingley et al. 2015). For this reason, the emphasis of SLM research within CGIAR still appears to be focused on identifying the on-site costs and benefits of SLM and SWC practices.

Many SWC programmes are not leading to widespread adoption of SLM and the area of degraded land is increasing. Pretty and Shah (1997) provide a detailed account of the history of SWC in the USA, SSA and Asia. The overarching premise behind many SLM programmes has been that farmers should adapt to practices rather than the other way around (Cordingley et al. 2015). Evidence suggests that adoption of SWC by smallholder farmers in SSA is constrained by an array of ecological, social, economic and political factors specific to the context within which they are farming (Bisaro et al. 2011). A focus on the biophysical problems associated with land degradation and a lack of emphasis on context in the past has meant innovations in SLM have often failed because farmers did not adopt them (Snyder and Cullen 2014). Often the very same factors that drive land degradation prohibit the uptake of SLM practices (Shiferaw et al. 2009). Poverty, resulting in lack of capital for investment, insecure land tenure, limited extension services and infrastructure, volatile or unreliable market prices for agricultural products and inputs, lack of access to credit and labour, are all social factors that can inhibit SLM adoption. Biophysical factors such as poor soil fertility, pests and erratic rainfall (Ajayi et al. 2007, Adimassu et al. 2012, Teklewold et al. 2013, Kassie et al. 2015) also play a part in its adoption. For some SLM practices, there is now a much wider body of evidence on the drivers of adoption and non-adoption, than on the biophysical impacts they have on factors such as yield and soil properties.

ii. Practical relevance

One reason for low adoption in the past has been the focus, until recently, on short-term responses aimed at reversing the observable problems of land degradation, such as soil erosion, rather than responses aimed at addressing both the observable problems and the underlying range of social, economic and political factors that drive land degradation (Andersson et al. 2011, Cordingley et al. 2015). Designing SLM practices that are adaptable to the context is key, as is addressing the drivers of degradation. Clearly, SLM practices that do not require considerable resources, are relatively easy to implement and are suited to local conditions are more likely to be adopted (Snapp et al. 2013). Incentives to encourage adoption should be considered for SLM practices that are resource demanding, difficult to implement and whose costs are high. Evidence suggests there is little spillover of resource demanding SLM practices from areas where SLM initiatives have made considerable investments to promote them. Across SSA, spontaneous adoption of SLM practices has been shown to occur for those practices that result in the most economic gains – in other words, for farmers the benefits of SLM must outweigh the costs of implementing it (Vanlauwe and Giller 2006, Requier-Desjardins et al. 2011). Equally important is the number, type and timing of benefits (McDonagh et al. 2014). However, benefits need to be defined quite broadly and as more than simply monetary income (Emerton 2014). Farmers consider many other factors, for example food security, timing of cash earnings to meet peak demands and trade-offs involved in the allocation of on-farm resources (Vanlauwe and Giller 2006, Shiferaw et al. 2009). Labour availability is a major concern and depends on the health of people and competition with other income generating activities. Conflicts with off-farm work including the seasonal migration of labour force (often men) can be a major constraint for SLM. A recent study revealed that jointly managed plots are more likely to adopt SLM-related interventions than male-managed plots (Ndiritu et al. 2014).

Different groups of land users across a landscape, such as men, women and youth, resource-poor versus resource-rich farmers, or farmers versus pastoralists, will have different needs, interests and challenges. Therefore, blanket recommendations are unlikely to serve this diversity well (Snyder and Cullen 2014). Numerous examples of local adaptations to adverse conditions support the need to promote the design of differentiated practices (Milgroom and Giller 2013, McDonagh et al. 2014). Essentially, farmers' motivations, goals and constraints must be well understood before rolling out any SLM intervention, to avoid it being rejected. Whilst individual recommendations for farmers are impractical (Tittonell et al. 2011), identifying methods to categorise patterns of agro-ecological and socio-economic variability for which certain SLM options will be suitable, or could be adapted, can be developed (Reece et al. 2004, Giller et al. 2011, Getnet and MacAlister 2012).

Strengthening institutions within agencies tasked with land management and agricultural development has been called for repeatedly over the last 20 years and remains one of the biggest challenges. Planning and implementing agencies often lack a multisectoral approach, which is particularly important in SLM where water, forests, livestock and agriculture and infrastructure such as roads all converge in the landscape. Institutional change also concerns issues related to markets (tariffs, taxes, licensing, etc.) and governance (devolving decision-making to lower levels, by-law development and enforcement, land tenure). In Ethiopia, research found considerable institutional challenges to SLM. Planning and implementation at district level, under pressure to meet national targets, deployed a top-down, often blanket approach to restoring landscapes that neither took into account the biophysical or social context. The emphasis was often more on quantity rather than the quality of the SLM interventions (Snyder et al. 2014). Institutional change requires not only identifying constraints, such as conflicting policies or lack of coordination in planning and implementation, but also identifying and strategically trying to change interactions among key actors, many of whom have vested interests in keeping these institutional constraints in place (Hounkonnou et al. 2012). Removing institutional barriers is likely to be much more cost-effective in addressing land degradation as opposed to focusing on individual SLM interventions (Shepherd et al. 2015). However, there is little consensus on how this could be achieved. One of the biggest barriers to increasing SLM adoption is the longevity of SLM programmes. Often, successful programmes run over long time periods (10 years or more) which allows time (i) to properly identify the context; (ii) to develop, trial, test and adapt SLM practices; and (iii) for trust to develop between stakeholders.

The evolution of terminology from SWC to INRM and SLM is only useful if it leads to changes in action on the ground. In general, research has shifted in the last 20 years to a much wider focus on the social and economic considerations that impact the adoption of SLM practices. A much wider number of participatory approaches are now available and employed in on-going programmes so that farmers, land users, researchers and decision makers can work together to find solutions to land degradation. Participatory processes, such as multi-stakeholder platforms, have also been useful for finding solutions amongst multiple stakeholders with different agendas. Consideration of ecosystem services provided within farms and the surrounding landscapes are facilitating planning aimed at more sustainable landscapes. One problem with all these approaches is how the outcome is monitored and evaluated, as the impact they have on the ground is often very difficult to quantify.

In conclusion, whilst there is increasing evidence that SWC, SLM and INRM provide a wide range of benefits both on and off farm, low adoption of practices continues to be a major challenge. In fact, the discourse on low adoption of SLM has remained unchanged for over 20 years. It seems that whilst there is a wealth of knowledge on what needs to happen for SLM adoption to increase, there is only limited uptake of these suggestions because (i) action is lagging behind the discourse or (ii) the barriers that need to be removed are often too big for single SLM programmes and should be addressed at higher levels. Having said this, the increased focus on INRM, landscape scale management and ecosystem services is encouraging a much broader perspective and bringing ecological management principles into management of agricultural land. This is likely to lead to greater resilience and sustainability in agricultural systems if it results in action on the ground.

Eco-efficiency

i. Science

To keep pace with population growth and dietary change, food production will have to increase by 70% by 2050 (Bruinsma 2009). Without doubt, potentials to increase crop production are high in Africa. But, even though 2001-2010 was perceived as a “decade of growth” in Africa, the agricultural sector’s growth has lagged behind national economic growth. This slow growth is an obstacle to regional poverty reduction, as agriculture underpins the livelihoods of over two-thirds of Africa’s poor (Diao et al. 2012). Sustainable intensification by eco-efficient agriculture is one of the major issues to be addressed (Pretty et al. 2011).

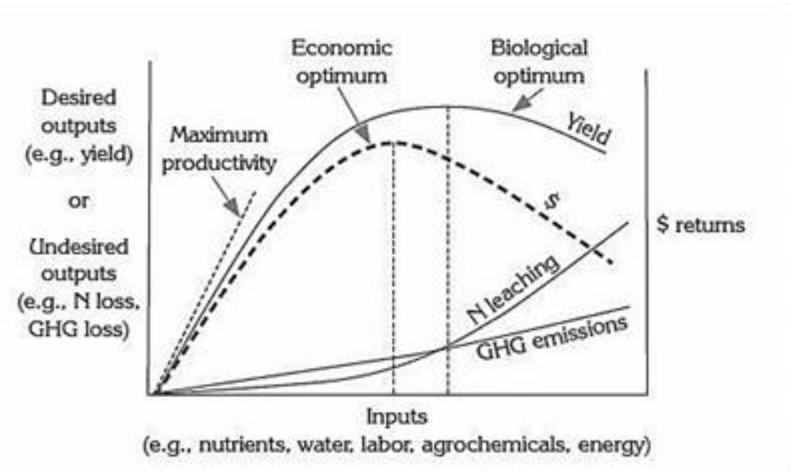

Figure 2. Output–input relationships relating desired and undesired agricultural outputs to the level of resource supply of soil nitrogen (N).

Source: Keating et al. (2011)

Agricultural eco-efficiency is a rather new concept that focuses on increasing productivity while decreasing negative impacts on natural resources (CIAT 2009a). Similar to the World Commission on Environment and Development (WCED), delineation of the concept of sustainability (WCED 1987), approaches that merit the term *eco-efficient* must meet the economic, social and environmental needs of the rural poor. Eco-efficiency seeks to strive toward solutions that are competitive, profitable, sustainable and resilient in the face of a changing climate (Cassman and Daugherty 2012).

In other words, an eco-efficient farmer would (have to) sacrifice crop as well as economic productivity, if this came at a significant increase of undesirable outputs, such as environmental pollution through increased nitrogen leaching into the groundwater and GHG emissions into the atmosphere (Figure 2).

Currently, it is unlikely that crop production can be intensified in SSA without creating some damage to the environment. However, for SSA (and many other regions of the world), environmental standards and binding pollution thresholds for the agricultural sector – which would also apply to the concept of an eco-efficient agriculture – still largely remain to be formulated and agreed upon. As long as these are absent, trade-offs between productivity, social equity and the environmental footprint have to be analysed and balanced against each other. As a consequence, rather than passing (or failing) a standardized eco-efficiency test, judging a considered agronomic practice eco-efficient is within the discretion of the observer. Similar conditions apply to benefits to the environment, such as clean drinking water and mitigation of climate change and other ecosystem services that adoption of an eco-efficient land use could bring.

ii. Practical relevance

Without doubt, the concept of eco-efficiency is a noble, holistic approach that intends to address the entire set of pressing issues around agricultural intensification. Unlike climate-smart agriculture (CSA), it lacks the focus on climate change and is not very explicit in relation to whether it constitutes a viable exit strategy of smallholders out of poverty.

As a relatively young approach, there have been just a few initiatives on the ground promoting and implementing eco-efficiency. Confusion over the various concepts and the notable overlap, such as eco-efficiency and climate smartness, or (though somewhat narrower in their goals) ISFM and CA, is also not conducive to inspiring larger initiatives. Furthermore, the eco-efficiency concept lacks the rigor, practical guidelines, concepts and recipes, like those produced for ISFM or CA.

Given SSAs wide range of agro-ecosystems, diversity of farming systems and livelihood strategies, pathways of eco-efficient agricultural intensification are likely to differ between regions. If sustainable, eco-efficient agricultural management is to be adopted on a large scale, assessments of land health and the agro-economic drivers of land degradation can provide information for regionally adapted, improved management techniques (Vågen et al. 2012).

Finally, it is unknown if eco-efficient production systems can meet the projected food production demands of the coming decades and if so, whether farmers are willing or could afford to “go eco-efficient”, if this entailed a considerable loss of income. In the latter case, it may be worth looking into related costs for payments for environmental services (PES) and whether these can be covered by for example Clean Development Mechanisms (CDMs) or similar concepts.

Soil organic carbon sequestration, GHG emissions and climate-smart agriculture (CSA)

i. Science

Maintaining soil organic carbon (SOC) content is seen as an important strategy for a well-functioning soil ecosystem (Schlesinger 1991; Palm et al. 2007; Lal 2010, Victoria et al. 2012). The UN Convention to Combat Desertification (UNCCD) and the UN Framework Convention on Climate Change (UNFCCC) both recognize that reduced SOC content can lead to land degradation and ultimately low land and agricultural productivity. While 70% of Africa’s population lives in rural areas and depends almost solely on agriculture, over half of Africa’s land is unsuitable for agriculture (Swift and Shepherd 2007). Degradation of soil and water resources further exacerbates the situation (Verchot et al. 2005; Vågen et al. 2012; Vågen et al. 2013). While studies that highlight management options for restoring SOC in agricultural soils exist (Lal 2004, 2007), restorations rates and potentials for specific land-cover types are still poorly understood.

Pressing socio-ecological challenges facing society call for increased food production, more efficient use of resources and reduced land degradation. As agriculture is the mainstay of the global economy, there has been a rethinking of agronomic practices in the light of climate change. The concept of CSA is being readily embraced by scientists (Harvey et al. 2013) and funding agencies

(Grainger-Jones 2011) alike. FAO (2013) outlined three pillars of CSA: (i) sustainably increasing agricultural productivity and incomes; (ii) adapting and building resilience to climate change; and (iii) reducing and/or removing GHG emissions, where possible. In fact, FAO (2010) highlights that climate-smart practices already exist and could be implemented in developing country agricultural systems and that an ecosystem, landscape-scale approach is needed. An important component of CSA technologies include maintaining soil health and reducing land degradation, including increasing soil organic carbon stocks.

In response, several initiatives have formed to support and promote the adoption of CSA technologies. For example the Global Alliance for CSA (GACSA) was launched in September 2014 at the UN Climate Summit.[6] Currently, over 74 stakeholders have joined GACSA. The Africa CSA Alliance[7] was formed in order to empower 6 million smallholder farmers across SSA by 2021. In West Africa, the West African Alliance for Climate-Smart Agriculture was launched in June 2015, which aims to support implementation of CSA across West Africa.

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is actively promoting CSA[8] and has started to test CSA in so-called "climate-smart villages", globally. In addition, new tools have been developed to assess CSA potential across landscapes (Mwongera et al. 2014; Corner-Dolloff et al. 2015).

ii. Practical relevance

Currently, some SSA countries are developing CSA plans within their agriculture and climate change strategies, led by the Common Market for Eastern and Southern Africa (COMESA) in collaboration with CCAFS. For example, recent efforts in Kenya have brought together various stakeholders to identify opportunities for out-scaling CSA in smallholder systems (Chesterman and Neely 2015). Thus, there is a tremendous momentum and notable commitment of African Governments towards CSA.

Turning soils into carbon sinks (carbon sequestration) is seen as a promising way of mitigating climate change. The only viable way of storing carbon in soils in notable quantities is by increasing the organic matter content.[9] For the highly weathered and depleted soils of Africa, this means an increase in soil fertility as it is closely linked to the soil organic matter content. Thus, mitigating climate change through soil organic carbon sequestration – one of the pillars of CSA – (Sommer and Bossio 2014) is a win-win situation. However, as mentioned earlier, carbon sequestered in soils has to be seen as an investment, as the basis of carbon – organic matter – is often a scarce resource. Not using it, e.g. as livestock feed, but burying it, constitutes a real loss of a valuable resource and income, if it is not compensated for.

[6] http://www.fao.org/climate-smart-agriculture/en/
[7] http://africacsa.org/
[8] http://ccafs.cgiar.org/climate-smart-agriculture#.VSzw0WYz5pw
[9] Biochar, i.e. an inorganic form of carbon, has been suggested as a soil amendment to increase soil fertility (and soil C levels), but production costs and/or lack of availability of starting materials seem prohibitive.

Emerging trends and tools in soil science

Big data and open data

> # big da·ta
>
> *noun* COMPUTING
>
> extremely large data sets that may be analyzed computationally to reveal patterns, trends, and associations, especially relating to human behavior and interactions.
> "much IT investment is going towards managing and maintaining big data"

Source: Google

The science of big data has stimulated a discussion about whether this concept could also be used to address agricultural, social and economic challenges facing developing countries, as well as the cautions around using such data (Simons Institute 2013). While the definition of big data can still be debated and discussed, it is less about how big the data is and more about the ability to search, access, aggregate and analyse these often disparate data sets in order to identify patterns and engage in scientific discovery (Boyd and Crawford 2012; Cukier and Mayer-Schönberger 2013).

CGIAR has also engaged in the big data discussion and believes that making data open access is a critical step in developing big data to achieve impact which will improve the livelihoods of smallholder farmers. Further to sharing open access articles, CGIAR recognizes the importance of developing, organizing and sharing data sets (Gassner et al. 2013).

CIAT has been proactive in the big data movement, particularly with the WorldClim spatial data set, which has global coverage (Hijmans et al. 2005). The wide availability of this data set has allowed for its inclusion into spatially explicit crop models such as EcoCrop (Ramirez et al. 2013) and DSSAT, among others. In essence, it is not just about creating big data, but about increasing its accessibility through the open access movement.

In addition, CIAT has been working with site-specific agriculture in Latin America to combine agricultural production with digital soil mapping to better understand farming system productivity across various scales and agro-ecosystems.[10]

This application of big data shows its use in addressing agricultural and food security issues facing smallholder farmers. Application of big data can also be used to inform GIZ projects and interventions, particularly for country practitioners.

Digital soil mapping

Traditionally, soil data is hard to collect, time-consuming and resource demanding. This situation leads to a lack of soil information, making it difficult to understand soil-human-environment relationships and to generate applicable solutions whether local, national, continental, or global scale (e.g. suitable land use, carbon cycling, nutrient status). Innovations and access to technology in

[10] https://ccafs.cgiar.org/bigdata#.ViSRNCsbG19

the past few decades have allowed soil scientists to integrate most recent technologies (e.g. satellite images, digital elevation models and climate data) with soil data to provide detailed spatial soil information.

This new paradigm drove the field of soil science through profound changes moving away from traditional, tacit knowledge based soil survey methods to new, digital soil mapping (DSM) approaches (Ashtekar and Owen 2013). Until a few years ago, most of soil sampling strategies and mapping worldwide were based only on manual methods centred on the relationships between soils and landscape. Using aerial photographs and soil-landscape relationships guided by forming factors (Jenny 1941), soil specialists used to determine soil variability and their boundaries and then to define sampling locations and map soil units. Both processes of sampling and mapping are time-consuming, resource demanding and rely on the experience and ability of soil scientists to define the soil boundaries. Moreover, the maps produced are based on polygons that consider that spatial variation of soils only occurs at the boundaries of delineated polygons, thus, soil properties have uniform values within each soil polygon (Zhu et al. 1997). Although field experience shows us that abrupt changes of soils over space exist, more often this is gradual and continuous, unlike polygon-based mapping (Zhu et al. 2001).

DSM follows the same soil-forming relationships and introduces modern computational tools to process large data sets to better develop the relationships between soil attributes and legacy and environmental variables (Moore et al. 1993; McBratney et al. 2003). This paradigm shift has allowed soil scientists to work in areas as expansive as entire a countries or even global level as well as changing the characterization of soils from their traditional description/classification towards their functions (Pásztor 2007). Also, the maps produced are not polygon based anymore and a raster concept emerges, representing soil as continuum, as a more realistic way to determine soil variability in the landscape.

A variety of mapping approaches can be used to generate accurate maps at high resolution depending on the availability of existing soil surveys, environmental data and point observations (Arrouays et al. 2014). The approaches range from linear regressions, geo-statistical analyses and kriging interpolation, hybrid methods (combining one or more approaches), knowledge-based and fuzzy logic and regression tree, among others (Moore et al. 1993; Odeh et al. 1995; Zhu et al. 2001; McBratney et al. 2003; Ashtekar et al. 2014). Although the main advantage of DSM compared with traditional soil mapping is the ability to capture soil variability as a continuum, other advantages such as: (i) quick map updates when new data is acquired; (ii) the inclusion of co-variables that drive soil differentiation such as soil forming factors (climate, organisms, relief, parent material and time); and (iii) the ability to determine uncertainties, make DSM even more attractive.

Global initiatives such as GlobalSoilMap and Global Soil Partnership (GSP) have engaged in DSM to provide soil data and information responding to various users' needs at global, regional, national and local scales. CIAT has contributed to these initiatives and in partnership with GSP/FAO, Brazilian Agricultural Research Corporation (EMBRAPA) and national institutions in Latin American countries (LAC) have developed the Soil Information System for Latin America – SISLAC (www.sislac.org). The first phase of SISLAC, led by CIAT, collected, standardized and stored soil profiles/point data and national polygon maps at scale of 1:1 million to be used to develop digital soil maps as well as support decision making at the region. CIAT scientists have tested the conditioned Latin Hypercube Sampling strategy (Minasny and McBratney 2006) that consider the spatial variability of environmental variables to define sampling locations for DSM as well as developed knowledge-based models to map soils with high spatial variability and limited resources/data and its uncertainties at Latin America (Ashtekar et al. 2014) to better target land management decisions.

Infrared spectroscopy

Infrared spectroscopy (IR) is a rapid and cost-efficient technology that is transforming soil analytics, as biophysical field surveys are no longer subjected to economic constraints incurred by traditional analytical methods (Aynekulu et al. 2011; Nocita et al. 2015). IR, specifically is the interaction of infrared light with matter and is sensitive to functional groups, which have specific chemical properties and bond types. An IR spectrum is a plot of measured infrared intensity versus wavelength of light. Therefore, an IR spectrum for a soil sample is a complex assessment of the various chemical and physical properties exhibited by the soil. In order to understand and predict specific soil properties, robust calibration models must be developed, using a large data set of samples that have IR spectra and associated wet chemistry data.

CGIAR has been using IR in soil science since the mid 1990s. IR is a well-established methodology for predicting important soil properties, with the most success in predicting soil organic carbon (Shepherd and Walsh 2002; Madari et al. 2006; Reeves et al. 2006; Vågen et al. 2006; Brown 2007; Terhoeven-Urselmans et al. 2010; Nocita et al. 2015). More specifically, through large-scale projects, such as the CGIAR-led Africa Soil Information Service (AfSIS), large databases of both mid-infrared (MIR) and near-infrared (NIR) spectroscopy and reference data sets using rigorous standard operating procedures were created (Vågen et al. 2013). These systematic data sets allow for robust predictions of soil properties and the development of continental-scale maps of dynamic soil parameters (Vågen et al. 2015). Due to the high accuracy of the prediction models, the use of IR is becoming common practice and is now mainstreamed both within CGIAR and globally (Nocita et al. 2015). However, not all soil chemical and physical properties can yet be predicted with the same level of accuracy. Especially rather dynamic soil chemical properties, such as the mineral nitrogen content of the soil,[11] or the plant-extractable amount of phosphate – the exact amounts of which have a strong effect on crop growth and yield, are still a challenge to be detected with sufficient accuracy by IR and there have not been any convincing solutions published and well defended in this domain.

Systematic field surveys

In light of the big data movement and the need for whole-systems and landscape-scale approaches, new surveys methods are needed to holistically assess key land and soil health metrics. One such method that has been applied across CGIAR Research Programs over the last 10 years is the Land Degradation Surveillance Framework (LDSF), first developed at the World Agroforestry Centre.[12]

This biophysical field methodology is designed to provide a biophysical baseline at landscape level and a monitoring and evaluation framework for assessing the processes of land degradation and the effectiveness of rehabilitation measures over time (Vågen et al. 2013). Since its initial development in 2005, CIAT scientists have contributed to further development of the LDSF by incorporating

[11] ...not to be confounded with the total nitrogen content of the soil. Mineral N, i.e. mainly nitrate and ammonium, does only constitute a minor fraction of the total nitrogen in the soil. It is a product of microbially mediated decomposition of (N-containing) organic matter.

[12] http://landscapeportal.org/blog/2015/03/25/the-land-degradation-surveillance-framework-ldsf/

modules on SOC stocks methodologies, among others. The LDSF was the mainstay of the Africa Soil Information Service (AfSIS) project, led by CIAT (2009–2013) and is currently being used by the CGIAR Research Programs on Forest, Trees and Agroforestry and Climate Change, Agriculture and Food Security (CCAFS), as well as projects funded by USAID, IFAD, BMZ, among others. Using the LDSF, along with IR allows for landscape-scale assessments of SOC and land degradation risk factors (Vågen et al. 2013; Vågen et al. 2015; Winowiecki et al. 2015) in order to target land management interventions.

3. Synthesis

The trends in soil science described above are not necessarily listed in chronological order, but represent an element of learning and building upon the ideas, concepts, frameworks of one another in a general trajectory over the past 20 to 40 years (Figure 3).

To briefly summarize the main points of each of these trends, we start with the Green Revolution in Africa, where the main emphasis was on inputs such as mineral fertilizer, improved varieties and irrigation. Integrated soil fertility management (ISFM) added a focus on organic and mineral soil amendments alongside intercropping and crop rotation. The idea of stepwise adoption of elements of the management approach is key to the philosophy of ISFM. Conservation agriculture builds on some of the previous elements, but adds a focus on the three pillars: (i) minimum soil disturbance; (ii) constant surface residue and (iii) crop rotation. Integrated natural resource management starts to take analysis and recommendations beyond the field level to the landscape level to include ecosystem service management and environmental impact and interactions with farming systems. INRM brings in multidisciplinary approaches and a focus on gender, social and political dynamics. Agroforestry incorporates a focus on woody perennials within the farming system, again beyond the field level and a focus on a range/diversity of integrated systems as well as the erosion prevention and enhanced fertility benefits from trees in agricultural landscapes. Eco-efficiency means to decrease the negative environmental impacts and address economic social, environmental sustainability and needs of the rural poor. Climate-smart agriculture views many issues through a lens of climate change and understanding the contribution of practices and approaches to the three pillars of: (i) food security, (ii) climate change adaptation and (iii) climate change mitigation. What this means for soils is a focus on agricultural productivity and incomes, as well as reducing GHG emissions and restoring soil carbon.

The general trajectory of these trends is a move from research station and plot-level research and focus of the Green Revolution to embracing the complexities of conducting research on farmers' fields, within diverse farming systems and exploring the community and landscape levels. The movement of soil research is toward addressing the farms and farmers within their broader biophysical, social and political landscape. Simultaneously, the research approaches are evolving beyond top-down dissemination of technologies of the Green Revolution in Africa and ISFM, for example, towards a focus on understanding farmer's constraints and willingness to invest and innovation to adapt technologies as a core part of research questions. As the paradigms of research and development evolve, so do the tools to better understand the complex array of factors driving farmers' land and soil management decisions. Participatory tools such as *Evaluating Land Management Options* (Emerton et al. 2015) are designed to better understand farmers' preferences for different practices using participatory rapid assessment techniques to assess the economic costs, benefits, motivations and enabling conditions that influence farmers' uptake (or rejection) of land management practices.

As new approaches became popularised and mainstreamed in the soil research community, they drew on various lessons learned from other established approaches. In a process of some evolution (not necessarily in chronological order or ranking) we distilled some of the challenges and lessons along the path outlined in Figure 4.

Figure 3. Trends in soil research with main thrusts of and key components of each trend.

The trends are not in chronological order, but do show some elements of building upon, learning from or expanding upon in an upward direction (direction of the arrow).

Figure 4. Lessons learned across trends in soil research over time.

The Green Revolution in Africa focused heavily on farm inputs, but did not necessarily address individual farmers' access or understanding of how to best use those inputs. In many ways, this led to for example, negative environmental impacts of overuse of mineral fertilizers or a decrease in agro-biodiversity due to inappropriate and excessive herbicide and pesticide use. Some governments tried to address the issue of access to fertilizers by putting subsidies in place, which increased access for some individuals, but also had serious repercussions on agricultural budgets and ability to invest in other agricultural services (see Chapter 3 in Sommer et al. 2013 for further details). The top-down nature of the Green Revolution in Africa so far did not result in the widespread increases in yields as seen with the Green Revolution in Asia, as it was not adapted to local (social, political, economic) conditions and infrastructure.

ISFM adapted the focus on mineral fertilizers to include balanced management of both organic and mineral inputs. However, the limitations of availability of and access to both organic (manure, compost, crop residue) and mineral inputs similarly affected the adoption of ISFM. Questions of input-use efficiency were also not necessarily addressed by ISFM techniques. The idea of a stepwise approach puts more control and focus on the farmer and his or her needs, but some top-down research and results remain part of the ISFM legacy. There is also limited data on the long-term impacts and sustainability of ISFM practices such as ensuring practices are not mining nutrients from the soil or contributing excess GHGs, as reported by Sommer et al. (2015). Issues of local suitability and adaptation were not necessarily incorporated into ISFM research and recommendations, which also affected the (non-) adoption we see today.

Conservation agriculture (CA) faced a similar challenge to ISFM in the competition for organic matter (crop residues). It is also a system that is knowledge intensive, requiring a change in management of fields and initial investment of time and money that may not pay off in the short term. The package approach of simultaneously implementing all three principles (minimum soil disturbance, crop residue management and crop rotation and diversification) is not necessarily appealing to farmers as it often represents a large shift in practices and potential risk. We recommend a potential step-wise approach to CA that allows farmers to slowly add new practices or in combination with ISFM (what we term ISFM+). Conservation agriculture also lacks an element of whole farm dynamics and farmer co-design and adaptation for locally appropriate practices. It does not always address the environmental or off-farm impacts of increased herbicide use, which is becoming part of the research and discussion of INRM.

Agroforestry addresses an element of the complexity at the farm level through a focus on integrated tree, crop and/or livestock systems and provides opportunities for soil erosion protection and fertility enhancement. It also provides feasible alternatives to practices such as slash-and-burn that are no longer sustainable under current population and land availability constraints. However, land access and land tenure are often constraints to adoption of some agroforestry species and practices that reap long-term benefits and require upfront capital investments. Additionally, access to seeds, seedlings and nursery infrastructure and training are a vital component that is not always addressed in agroforestry interventions. We can also understand the trade-offs for managing technical and numerous factors and the need for locally appropriate species from the long-term research investment in the alley cropping initiative.

INRM and SLM incorporate a perspective beyond the farm environment to include an understanding of off-farm impacts and interactions that many of other approaches do not. INRM research incorporates participatory approaches to better understand the underlying social, political and economic constraints to adoption. Additionally, expanded temporal scales are incorporated into the research including long-term versus short-term benefits. These multiple scales and participatory approaches add increased complexity; there are challenges in selecting and monitoring appropriate indicators to measure long-term benefits within short project cycles.

Eco-efficiency attempts to address some of these complexities through analyzing trade-offs of whole farm dynamics. However, the challenge lies in the affordability and incentives for the rural poor to transition to eco-efficient practices that may come at a cost to their yields and income. Eco-efficiency research also provides an opportunity for soil researchers to ask the breeding community to breed for eco-efficient varieties (tolerant to droughts, nutrient loss and other stresses). Undefined thresholds and definitions make eco-efficiency a difficult concept to study and promote and thus it has lost some momentum. Additionally, it is unknown if farmers are willing or could afford “going eco-efficient”, if this entailed a considerable loss of income. It may be worth looking into related costs for PES and other investment scenarios. Finally, eco-efficiency lacks a focus on climate change and is not clear about whether it constitutes a viable exit strategy out of poverty for smallholders.

Climate-smart agriculture (CSA) has gained momentum globally and offers an opportunity to feed many of the strongest concepts and lessons learned from the previous trends into regional, national and subnational planning with a climate focus. However, CSA initiatives have not given due attention to soil protection and rehabilitation, despite the apparently strong potential to increase climate smartness. Turning soils into carbon sinks (carbon sequestration) is seen as a promising way of mitigating climate change. With the addition of organic matter needed to do this, farmers could also reap more immediate productivity and soil health benefits, which is an easier entry point than sequestration or mitigation alone. CSA also addresses resilience under climate variability, where investment in soil protection will likely be key. CSA faces similar challenges to eco-efficiency with undefined thresholds of what qualifies as climate-smart and the fact that climate-smart practices should align with all three pillars. This provides a challenge in SSA where mitigation is not a priority or a likely entry point. CSA does, however, place an important focus on understanding the gender impacts of climate change and adaptive agricultural practices and the resilience of the rural poor under climate variability.

Emerging trends and tools in soil research rely on technological advancements and availability to generate, store, share and analyze more data quickly. With these emerging tools we can monitor and target applicable solutions at a local to global scale and find patterns might not have been able to see without the technology (e.g. big data).

The overall lessons from these trends in soils research tell us that farmers have to be at the centre of research questions from the very beginning; they should provide input and guide research questions and directions. This farmer-centred or participatory approach helps to ensure locally appropriate options and higher potential for adoption. To enhance farmer interest, it is also important to include economic, social and environmental sustainability.

The research should span from farm to landscape to best inform and target interventions. Trade-offs as well as costs and benefits have to be included in understanding complex, whole-farm systems that reflect farmers' reality. For example, many of the practices or interventions stemming from the above research trends require additional input of crop residues (for increased organic matter and soil cover), but do not address the high competition for residues and organic matter (livestock, field, burning, etc.) within the farm.

This review couples with the best bets compendium (https://ciat.cgiar.org/compendium-of-soil-practices) to identify potential practices. Many of the research trends have given rise to technologies that in the right context, can provide soil protection, rehabilitation, increased productivity and improved livelihood options. The compendium of best bets showcases a selection of these technologies – showing what is context appropriate and what puts farmers at the centre of the approach.

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