ECOLOGICAL INTENSIFICATION: TECHNICAL BRIEF

FOREWORD

"In a world where natural resources are in short supply at the same time as almost one in four people in Africa suffer from chronic hunger, the Montpellier Panel believes that a new paradigm to tackle food insecurity is urgently needed."

In 2013, the Montpellier Panel, a group of African and European experts from the fields of agriculture, trade, ecology and global development, released a report, "Sustainable Intensification: A new paradigm for African agriculture." This report examined and redefined the concept of Sustainable Intensification (SI) and its potential to increase food production whilst ensuring the natural resource base on which agriculture depends is sustained and improved. "*Sustainable Intensification can be relevant as a new paradigm for African smallholder farmers as long as suitable, sufficient resources and practices are supported and delivered at scale."*

Conceptualising SI is relatively straightforward. Sustainable intensification is about producing more, be it yields, incomes or nutrients, with the same amount or less of inputs be they land, costs, labour, chemicals or other resources. The difficulty lies in achieving SI in its entirety. To this end the Montpellier Panel divided the concept of SI into three pillars: ecological intensification, genetic intensification and socio-economic intensification. Together these pillars provide a framework for conceptualising and implementing SI in a comprehensive and structured way. Although divided into 3 pillars, SI interventions seek to achieve multiple benefits within and across the pillars. Indeed SI is dependent upon all three pillars and it is important, therefore, that they work together in order to maximise the goals of SI, productivity and environmental protection and resilience.

Agriculture for Impact (A4I), an independent advocacy initiative and convenor of the Montpellier Panel, aims to enable better European government support for productive, sustainable, equitable and resilient agricultural development in sub-Saharan Africa. Towards this aim, A4I launched **The Sustainable Intensification**

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Database [www.ag4impact.org/database] to bring together the latest research and examples of SI under the three pillars. Each pillar is broken into three approaches, with 27 sub-sections and 81 accompanying case studies to illustrate the pros and cons of each method. The explanations and case studies are intended to serve as a resource for donors, practitioners and policy-makers alike, offering insights on defining SI, innovating within SI and facilitating open sharing of knowledge on these subjects, Additionally, three technical briefs focusing on Ecological Intensification, Genetic Intensification and Socio-economic Intensification delve deeper into the science and economics underpinning each pillar, expanding on the information provided in the database.

The focus of this brief is Ecological Intensification. In terms of the physical scale, ecological intensification sits between genetic intensification, at the level of a gene, and socio-economic intensification, at the scale of markets and political systems. The attention of ecological intensification is the farm itself and the relationships between the physical structures, biotic communities and individual species that occur there as well the relationship between farming systems and the wider environment. This brief aims to illuminate how some of these relationships can be used to improve the environmental performance of farming while at the same time enhancing productivity and improving well-being.

Contents

Introduction

Ecology (the processes that influence the distribution, abundance and interactions of organisms) and ecosystems (the interaction of a community of organisms with their environment) have underpinned agriculture since the beginnings of domestication and cultivation, some 12,000 years ago (Cary Institute of Ecosystem Studies, 2015; Random House, Inc, 2015). Our food comes principally from managed agricultural ecosystems or agroecosystems as well as from marine and freshwater systems or forests (TEEB, 2010). Agroecosystems are natural ecosystems modified to produce one or several products whether plant or animal-based. Within the boundaries of a farm the diversity of the original wildlife is reduced to a limited set of crop, pest and weed species, but many of the basic ecological processes remain the same and can be used intensively to create sustainable forms of crop and livestock production. These include the processes of competition between crop plants and between crops and weeds, herbivory of crops by pests, predation of pests by their natural enemies and the decay of organic matter.

Figure 1: Barn swallows rest on a bamboo stake that supports string bean and bitter gourd, growing on a rice bund in an ecologically engineered field. Credit F. Horgan/IRRI.

The focus of ecological intensification is to better understand these processes so as to utilise nature's resources without exploiting them unsustainably (CIRAD, 2014). The aim is to create multifunctional agroecosystems that are sensitive to their landscape, highly productive and that "*are both sustained by nature and sustainable in their nature*" (Tittonell, 2014).

The United Nations Food and Agriculture Organisation (FAO) and several other reviews (The Royal Society 2009; Clay 2011; Foley et al. 2011) have highlighted that it is highly advantageous to address future needs by transitioning to systems of food production that are based on ecological intensification—using land, water, biodiversity and nutrients efficiently and in ways that are regenerative and minimise negative impacts, a key tenet of sustainable intensification.

The following brief discusses in more detail what ecological intensification is and how it works in practice, in particular focussing on preserving natural capital on farms; precision farming and diversification. The information is not comprehensive, but aims to provide an overview of methods of ecological intensification and how they form an essential component of sustainable intensification in particular by seeking multiple benefits across all three pillars.

Building Natural Capital

Natural capital is defined as the physical assets within the natural environment that deliver economic value through ecosystem services, and upon which we rely for our survival and well-being (Voora & Venema, 2008). Soil, air, water and living organisms provide us with ecosystem goods and services, such as the food we eat, the water we drink and the plant materials we use for fuel, building materials and medicines. There are also many less visible ecosystem services, for example climate regulation and natural flood defences provided by forests; carbon stored by soil and peatlands; and the pollination of crops by insects (TEEB, 2010). The Millennium Ecosystem Assessment (MA), in 2005, estimated that two thirds of ecosystem services on the earth have degraded or are in decline due to the unprecedented scale of human activities during recent decades (Millennium Ecosystem Assessment, 2005).

Energy- and resource-intensive or unsustainable farming systems generally deplete natural capital by degrading and changing the chemical composition of soils, polluting and depleting water resources, reducing species and genetic diversity, and producing large quantities of global greenhouse gases (GHGs), the effects of which disproportionately affect the poor (UNEP, 2011; Lott, 2011; WWF, 2015). Poor communities are often more dependent on ecosystem goods and services and are less able to employ substitutes when they are depleted or lost, for example, the use of irrigation when rains are unreliable or the use of fertiliser when soils lose fertility (MA 2005; Yang et al, 2013). Rural and isolated communities also do not exhibit sufficient financial and technical capacities to manage the risks associated with climate change and loss of natural capital (Skoufias, 2012).

Although disproportionately felt in the developing world, declining ecosystem goods and services can impact the health and well-being of everyone. As such, there is a need to halt the loss of natural capital by using resources such as water, soil, land and biodiversity more efficiently. Conservation agriculture and organic agriculture are two systems of farming that aim to holistically conserve and utilise natural capital in order to improve the quality and quantity of production. Water conservation on farms, through a variety of techniques, can also be part of broader ecological farming methods or used alone to reduce water loss and increase the efficiency of its use. While central to SI, natural capital cannot be regarded in isolation. For example, complementing natural capital with social capital greatly increases its productive capacity, or the maximum possible agricultural output of an area (FAO, No date), while ecological processes can be enhanced through plant breeding (World Bank, 2012).

Conservation Agriculture

Conservation Agriculture (CA) is an integrated system of soil, water and biological resource management combined with external inputs. Its objective is to improve agricultural production by adopting economically, ecologically and socially sustainable farming methods (FAO, 2015).

Particularly in temperate climates, it is common practice for farmers to till the soil before sowing seeds to loosen and aerate the soil and destroy weeds. Tillage helps to break up heavy clay soils, however for many soils prone to erosion or drought as are common in sub-Saharan Africa, tilling can harm soil structure and increase water loss (Montpellier Panel, 2013). Whilst soil tillage has in the past been associated with increased fertility – which originated from the mineralization of soil nutrients as a consequence of soil tillage – this process leads, in the long term, to a reduction of soil organic matter (SOM). SOM not only provides nutrients for the crop, but is above all else, a crucial element for the stabilization of soil structure. Therefore, many soils degrade under prolonged intensive arable agriculture, leading to soil erosion and a drop in productivity. The process is dramatic under tropical climatic situations but can be noticed all over the world (Kasam & Pretty, 2006). Indeed in the Great Plains of the US around the 1930s, the dust bowl winds eroded top soil from 65 million hectares of land and led to an unprecedented environmental disaster, motivating the development of no-till farming.

Figure 2: Farmer spreading mulch on his conservation agriculture plot, Zimbabwe. Credit M. Sawatzky/MCC.

CA involves abandoning ploughing or soil tillage in order to build up soil quality, nutrients and water. Phillips & Young (1973) describe no-till agriculture as "a defined system of planting crops into untilled soil by opening a narrow slot, trench or band only of sufficient width and depth to obtain proper seed coverage. No other soil tilling is done." No-till farming is reported to conserve and enhance the quality of the soil, leading to higher yields and the protection of the local environment and ecosystem services (Friedrich et al., 2008).

Figure 3 Mulch covers the ground in this maize plot, Mozambique.

CA is a combination of techniques characterised by three linked principles:

- <u>Zero/minimal till</u>: Minimal soil disturbance requires that farmers use hoes to make planting holes or ox-drawn or tractor-drawn drills to plant seeds directly into the soil. The disturbed area must be less than 15 cm wide or 25% of the cropped area (whichever is lower).
- <u>Mulch cover</u>: Crop residues or cover crops are left on fields to provide permanent organic soil cover. Three categories are distinguished: 30–60%, 61–90% and 91%

ground cover, measured immediately after the planting operation. Ground cover of less than 30% does not qualify as CA.
- Crop rotation: Crops have root structures reaching a variety of depths. By rotating crops of different root depths, organic matter is placed in different soil strata through complex root systems, thereby making the soil more fertile. To improve crop rotation, nitrogen-fixing legumes (crops that allow the conversion of atmospheric nitrogen into growth stimulating nitrogen compounds in the soil) may be grown to help the succeeding crops (FAO, 2007).

There are an estimated 106 million ha of arable and permanent crops grown without tillage in CA systems (primarily in Argentina, Brazil and North America), corresponding to a global annual rate of increase since 1990 of 5.3 million hectares (Kassam et al., 2009). CA has now spread to approximately 25,000ha in Lesotho, Kenya, Tanzania and Zimbabwe, and resulted in increased and more stable yields (Marongwe et al., 2011; Owenya et al., 2011). A number of emergency rehabilitation projects promote CA in several countries, such as Zambia, Zimbabwe and Swaziland. CA has also been incorporated into the regional agricultural policies by NEPAD (New Partnership for Africa's Development) and more recently by AGRA (Alliance for a Green Revolution in Africa) (Derpsch et al, 2010). However, at present Africa only accounts for an estimated 0.3% of the total amount of land under no-tillage farming (Friedrich et al, 2012).

Contribution to Sustainable Intensification

CA simultaneously promotes environmental conservation and increases agricultural production by improving the growth conditions for crops (FAO, 2007). CA can improve input use efficiency, increase farm income and protect the natural resource base (FAO 2007), especially when complemented with the use of quality or improved seeds, water conservation, fertiliser microdosing and Integrated Pest Management (FAO, 2015). Agroforestry (discussed in more detail below) can be a core aspect of CA, which when combined with other sectors, such as crop-livestock integration, has the potential for improved productivity and sustainability (FAO 2010; ICRAF, 2014).

Figure 4: Field under conservation agriculture in Malawi. Credit T. Samson/CIMMYT

Benefits & Limitations

Soil structure and content

Figure 5 Tanzanian soil. Credit, G. Smith, CIAT.

Control of soil erosion is thought to be the most significant benefit of CA, as there is a clear relationship between the retention of mulch and a reduction of soil lost through erosion, especially on steep slopes and on highly eroded soils (Roose and Barthes, 2001; Erenstein, 2002) (Box 1). However, when mulching alone, other measures such as contour bunds may be needed (Giller et al, 2009).

No-till farming is reported to improve soil and deep root structures facilitating better infiltration of rainwater deep into the soil where moisture is limited. In arid or semi-arid regions, this enables the recharge of groundwater resources and decreases water pollution through reduced erosion and leaching (Friedrich and Kassam 2011). No-tillage combined with mulching is also thought to lead to the accumulation of soil organic matter (SOM), which can hold many times its weight in water, resulting in greater capacity for water retention. This reduces labour and fuel use as well as wastage of irrigation water (FAO, no date) and is particularly advantageous in finer-textured soils, due to a lack of protection of SOM in sandy soils (Giller et al, 2009). One farmer practicing CA in KwaZulu Natal, South Africa found that his field could withstand irrigation at up to 20mm per hour, whereas soil in fields under conventional tillage could only absorb 4-5 mm per hour before run-off occurred (FAO, No date). This is of great benefit in arid or semi-arid regions but on humid or poorly drained soils or heavy clay soils, CA can cause waterlogging, resulting in a loss of yields (Giller et al, 2009).

Higher levels of SOM also allow the soils to retain nutrients – improving the effectiveness of applied fertilisers – and improve the micro-flora in the soil, a vital component of living soil. It is difficult, however, to separate these effects and it appears that reported increases in SOM are mainly due to increased biomass production rather than reduced or no tillage (Corbeels et al., 2006).

Conservation Agriculture in Tanzania: the case of Mwangaza B Conservation Agriculture Farmer Field School, Rhotia Village, Karatu District, Arusha, Tanzania

In 2006, the farmers of Rhotia village in the Karatu district of Tanzania made the switch from conventional tillage farming to conservation agriculture. Similar to other smallholder farmers in Tanzania, these farmers suffered from low yields due to soil erosion, a common practice of grazing and removing all crop residues from their fields leaving them bare and vulnerable to the elements, and low use of organic or inorganic fertiliser.

Figure 6: Banana FFS and extension in Tanzania. Credit, FAO

In 2004, the Conservation Agriculture for sustainable agriculture and rural development (CA SARD) project began to teach the farmers of Rhotia conservation agriculture (CA), a sustainable way of growing crops and managing soil health. The first phase of the project from 2004-2006 used the farmer field school (FFS) approach as a means of teaching CA to 765 farmers in 31 groups across 3 districts (Arumeru, Karatu and Bukoba). The second phase, from 2007-2010, expanded to include another 4 districts, 86 FFS groups reaching more than 3,500 farmers. To start, CA SARD provided training on CA to extension workers, who then facilitated FFS and trained the participating farmers in how to apply CA practices. CA SARD provided start-up assistance to the FFS in the form of field equipment, 10kg of maize seed, and 8kg of hyacinth bean seed and a 1-litre bottle of glyphosate herbicide. Each group tested several CA options depending on their priority problems using different combinations of tillage and multiple cropping of pigeon pea, hyacinth bean, beans or pumpkins.


Figure 7: Maize with hyacinth beans CA SARD FFS Tanzania. Credit, CA SARD

The preferred option of the Mwangaza B FFS group was maize intercropped with hyacinth bean because it generated the highest maize yields (3.75 t/ha), conserved moisture, and controlled soil erosion. The second most preferred option was maize intercropped with pigeon pea which also produced high maize yields, controlled erosion, high levels of leave droppings used for cover crops and improved soil fertility. Overall, yields under CA increased from 1.25 t/ha in 2004 to 7 t/ha by 2009. Labour requirements declined, and farmers also benefited from selling hyacinth bean and pigeon pea at a favourable rate of TSH 1,100 per kilogram (approximately US$1).

Although the introduction of CA produced significant benefits, these were met with many challenges. The use of crop residue for mulching directly competed with animal feed. With the adoption of CA, farmers stopped selling their crop residues to farmers with livestock and began to prohibit free grazing on their lands. Pastoralists who acquire 80% of their livestock feed from crop residue, especially during the dry season, suffered resulting in conflicts between the farming and pastoralist communities. Additionally, tractor and oxen providers lost significant business when farmers no longer tilled. (Mariki et al, 2011).

Yields

In Zimbabwe, 8,000 farmers have adopted CA methods, resulting in maize yields growing by 67%. In Lesotho, the numbers are smaller (5,000 farmers), but the productivity increases are vital for the very small farms (Silici et al., 2011) (Box 2).

A meta-analysis by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) found that reduced or no-tillage without mulch or crop rotation leads to lower yields compared to conventional agriculture. In contrast, yields were higher overall in no-tillage treatments compared to conventional tillage-based practices, when mulch was applied. For farmers to gain the maximum benefit from CA, crop rotation should be an integral component of their farming practice, which implies a change from monocropping systems towards systems that encompass a variety of crops, preferably legumes. Growing legumes and rotating crops may prove challenging for some smallholder farmers in sub-Saharan Africa where legumes or other non-cereal crops lack ready markets but for others intercropping beans or peas is commonly practiced (CCAFS, 2014).

Conservation Agriculture in Zimbabwe, Concern Worldwide.

From 2005-2006, Concern Worldwide found that 133 farmers practicing conservation agriculture (CA) achieved an average maize yield of 2.8 tonnes per hectare (ranging from 1.03-4.71 tonnes per hectare) whilst conventional farmers in the same area averaged yields of just 0.8 tonnes per hectare. Other reported benefits included reduced labour time and fewer requirements for farm power that lowered input costs, leading to higher profits. Farmers who were previously receiving food aid improved their productivity so much so that they were able to sell grain to neighbouring villages. Farmers also benefited from increased incomes that allowed them to send their children to school, cover medical expenses, and rebuild their assets, such as cattle. In addition to Zimbabwe, Concern Worldwide has introduced CA—targeting mostly women farmers—in Tanzania, Zambia, and Malawi (Harty et al, 2010).

Figure 8: Conservation Agriculture in Zimbabwe. Credit, FAO

Figure 9: Hand dug planting pits. Credit, Harty et al 2010

In the Matopo area of Zimbabwe, Christian Aid also found that conservation agriculture (CA) techniques are helping farmers to increase their yields and conserve natural resources. Many farmers are single mothers or from families affected by HIV/AIDS, with small farms of 0.5ha-1ha. Trained in CA, farmers use a variety of practices and technologies such as digging **planting pits**, improving soil fertility with manure, mulch or legumes, and precise planting operations. By **multiple cropping** and rotating maize with indigenous nutrient-rich crops, the soil quality builds up over time. Crop residues are used as mulch to trap moisture in the soil, control weeds, and maintain cooler soil temperatures. Despite challenging climatic conditions over a period of 3 years, farmers reported increases in yields of sorghum, millet and maize, from an average of about 0.5 tonnes to between 3-4 tonnes per hectare (ASFG, No date). Another survey in Zimbabwe compared CA with conventional farming practices under low, normal and high rainfall situations. Regardless of the level of rainfall, farmers achieved yields between 2 and 6 times of those under conventional agricultural practices whilst also benefitting from reduced labour and costs because of the lower levels of inputs required (Hobbs and Powell, 2011).

Apart from a few recent articles (Erenstein, 2002, 2003; Bolliger et al., 2006; Knowler and Bradshaw, 2007; Affholder et al., 2008; Lahmar, 2009), it appears that CA has escaped significant critical analysis. There is, however, a well-reported short-term reduction in yields at first. Proponents of CA claim that it results in higher and more stable crop yields (African Conservation Tillage Network, 2008), although there also are numerous examples of no yield benefits and even yield reductions. Short-term yield effects have been found to be variable (positive, neutral or negative yield responses (Giller, 2009).

It is also noted that the potential risks of CA include an increased use of herbicides and their contamination of water resources; and the exacerbation of crop pests and diseases (Gianessi, 2014). Additional decomposable organic matter can stimulate populations of white grubs or cutworms that cut roots of cereals, eliminating growth and, if severe, result in a complete loss of crop (See Chikowo et al, 2004 for an example from Mozambique). The use of crop rotation in CA is a well-recognised approach to reduce the build-up of pests and disease that may proliferate in the presence of crop residues (University of Sydney, 2003; Nunez, 2010). However, crop rotation is unlikely to have an effect against bacteria that survives in the soil for a long time (Abawi & Widmer, 2000). Improved crop varieties that are resistant to weeds and pests could also form a strategy for CA to sustainably intensify production.

Climate change

CA methods can help boost the role of soils as a carbon sink. Soils contain twice as much carbon as found in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC,1996) estimated in its Second Assessment Report that it may be possible during the next 50 to 100 years to sequester 40 to 80Gt of carbon in global cropland soils (Cole et al., 1996; Paustian et al., 1998; Rosenberg et al., 1998). There is thus considerable scope to reduce emissions and increase the capacity of agricultural soils to absorb carbon. Agricultural systems that result in increased carbon sequestration can also contribute to farmers' incomes through natural capital accumulation on the farm, improved soil biodiversity and energy efficiency, but particularly because of their reduced reliance on purchased inputs that are energy-intensive to manufacture. The amounts of carbon sequestered, although large in some situations, however, can be small in others. There is no simple rule of thumb, but in general conventional conservation farming systems tend to sequester a maximum of 0.1 to 0.4 tonnes/ha of carbon per year (FAO 2005).

Labour-saving

CA eliminates the power-intensive work of soil tillage, reducing the labour for crop production by more than 50%. Also for mechanized farms it reduces the need for machinery by about 50% and fuel requirements by about 70% (Friedrich and Kassam, 2011). Where CA has been adopted, farmers have more time to start processing produce or taking part in other value adding activities, enhancing their farm income (Friedrich and Kassam, 2011).

Figure 10 Farmers prepare their field. Credit, T. del Río, Wageningen University.

Despite reduced labour due to no tillage some of this time saved is actually transferred to activities for weed control which is laborious and costly, with a greater requirement for herbicides than conventional tillage in the first five years (Wall, 2007). The increased amount of labour required for weeding may outweigh the labour saving gained by not ploughing, unless herbicides are used. A case study in Zimbabwe (Siziba, 2008) clearly shows the change in labour use profiles from planting to weeding; resulting in a shift of labour from tasks normally performed by men such as hand tillage, to hand weeding that is performed mainly by women (Giller et al., 2009). Timely weeding ensures weeds are destroyed before any seeds are produced, reducing the amount of weeds that appear the following season. As such, weeding becomes less of a burden under CA with time (Zimbabwe Conservation Agriculture Task Force, 2009).

Adoption

Despite sound, long-term research showing positive results for no-tillage and CA, this technology has experienced only small rates of adoption (Derpsch and Friedrich 2009). The lack of uptake is thought to occur because farmers are constrained in their resources, such that investment in a new technology not only influences what must be done in one field, but involves trade-offs with other activities from which the farmers generate their livelihood (Giller et al., 2006). Crop residues, for example, provide highly valued fodder for livestock in smallholder farming systems in sub-Saharan Africa. Given the cultural and economic value of livestock (Dugue et al., 2004), livestock feeding takes precedence and as a result, mulching materials are often in low supply making the recommended application rates of 0.5-2 t/ha unrealistic (Wezel and Rath, 2002). In some parts of sub-Saharan Africa, farmers cannot restrict grazing without challenging the traditional rights of the community. If farmers want to keep their residues as mulch, they would need to fence their field, requiring the re-negotiation of the traditional rules governing free-grazing (Martin et al., 2004; Mashingaidze et al., 2006), not to mention high costs for materials and construction.

The challenges of CA adoption are numerous, for example it requires a major transformation in land management and farming practices, and in the mind-set of farmers as well significant training and education (Erenstein, 2002). In general, farmers need to be more careful about the timing of agricultural operations under CA. Special attention has to be paid to weed control, either through hand weeding or by the careful use of herbicides. Methods have to be developed locally depending on the specific farming situation and agroecological conditions, making it difficult for extension workers to give specific advice in the early stages. As such there is a need for strong capacity in problem-solving around CA among development agents as well as in local research and extension systems. To help guide and introduce farmers to CA, particularly where tilling is common practice, community members may need to be identified and trained to act as locally trusted and recognised pioneers of the approach and organise participatory research and demonstrations. Extension services can support this, particularly in the initial few years when the benefits of CA are not as clear.

Also important for the successful implementation of CA is the application of fertiliser, using dung, organic matter or inorganic fertiliser. Where it can be hard to source or to afford adequate organic fertiliser, the use of targeted, non-organic fertiliser may be more accessible to smallholder farmers. The use of non-organic fertiliser may be preferable altogether as crops tend to respond well to CA with high nitrogen fertiliser application, and less so with low nitrogen fertilisation. The availability of fertiliser is thus a barrier to smallholder farmers engaging in CA. To reduce this, CA should be combined with the selective and targeted use of inputs as opposed to the more expensive and damaging broadcasting of inputs (see section on Precision Farming).

Organic Agriculture

Organic agriculture (OA) is a highly sustainable form of crop and livestock production (Montpellier Panel, 2013) defined as a "system of farm management production that combines best environmental practices, a high level of biodiversity, the preservation of natural resources, the application of high animal welfare standards, and a production method in line with the preference of certain consumer products using natural substances and processes" (European Commission, 2015). Typically, organic farming has strict regulations on the amount and nature of manure that can be applied and bans all synthetic fertiliser, herbicides and most insecticides and pesticides, with the exception of various "natural or simple" chemicals. Use of genetically modified organisms (GMO's) is prohibited and in livestock farming, there is a ban on the routine use of drugs, antibiotics and wormers, and livestock feed has to be organic.

Figure 11: Picking kale on an organic farm, Kenya. Credit, BBC World Service.

The land under certified organic production has grown steadily to 37 million hectares in 2011, representing about 1% of world farmland (Willer and Kilcher, 2012). However, this does not include the millions of smallholder farmers who by default do not use inorganic fertilisers or synthetic pesticides. Such non-certified "organic" agriculture may be practiced on another 10-20 million hectares in developing countries (Hine & Pretty, 2006). A lack of official and robust data in many African countries makes it hard to estimate the extent of certified organic production. Nevertheless, the availability and quality of information is improving in most countries and OA continues to grow across the continent. Africa accounts for 2.8% of total global certified organic land (Willer and Kilcher, 2012) and as of 2012 Africa had 30% of the world's organic producers (a total of 1.9 million) (IISD, 2008). This figure represents an increase of 7.7% between 2011 and 2012 whilst during the same period the amount of land under organic farming increased by 6.75%. The highest number of organic producers is in India, some 600,000, the second highest is Uganda at around 190,000, and Tanzania and Ethiopia qualify in the top 10 of countries (Willer and Lenoud, 2014).

Contribution to Sustainable Intensification

OA aims to 'mimic nature' by making use of natural ecological processes and resources to provide nutrients that sustain soil fertility, control pests, diseases and weeds. By building natural capital in this way, farms can be more resilient against shocks and stresses, and more productive. The potential of OA and agroecology to increase yields and farmers' incomes sustainably is considerable in developing countries and in those areas faced with degraded soils, lack of capital and or low product prices (Organic Research Centre, 2015). Thus in developing countries, OA can be a strategy for ecological intensification whilst in developed countries, low yields can motivate the extensification of agricultural land to meet demand, deeming such an approach unsustainable. As such care needs to be taken in determining where OA can contribute to sustainability and productivity and where it might have the reverse effect.

Benefits & Limitations

Soil

The IPCC found that OA, particularly intercropping and crop rotations, increases SOM content, increasing soil quality and allowing soils under OA to capture and store more water than soils under conventional cultivation. As such production in OA systems can be less prone to extreme weather conditions, such as drought, flooding, and waterlogging (IPCC, 2007a; UNEP-UNTCAD Task Force, 2008). Organic soil management is also reported to increase soil macrofauna and help build soil structure (FAO, 2005). Soil organic carbon is 14% higher in organic soils and the labile fraction (the fraction of the total carbon pool) is 30% to 40% higher, meaning the carbon breaks down relatively quickly, and is an active source of nutrition (Jakobsson, 2012). Increasing nitrogen levels in the soil through organic methods, however, is more challenging than with the help of targeted and prudent use of inputs (Montpellier Panel, 2013). Overall OA has been found to have the potential to increase the level of nutrients and biological activity in African soils compared to conventional farming systems (Stinner, 2007).

Organic agriculture has been proposed as a mitigation strategy against climate change, due to the increased capacity of soils to mitigate N_2O (Nitrous oxide) and CO_2 (Carbon dioxide) emissions through reduced soil erosion and thus a better ability to absorb greenhouse gas emissions (Niggli et al., 2007). CO_2 emissions may also be lower in OA systems as pesticides and fertilisers produced from fossil fuels are not used (FAO, 2015a). When plants photosynthesise, they integrate carbon into their tissue. When the plants die and decompose their tissues become part of the soil in the form of organic matter. Thus, healthy soils with a high proportion of organic matter sequester more carbon than degraded soils. Controversy around the effect of soil erosion on CO2 emissions remains, however, and there is a limited understanding of the fate of eroded SOM during transport and after deposition in landscape sinks (Lal, 2004). As a result, the IPCC considers lateral carbon movement as the greatest cause of uncertainty in the global carbon balance.

Reducing pesticide use

Organic agriculture minimises the risks that pesticides pose to farmers, to biodiversity and the wider environment by reducing the use of synthetic agrochemicals. There are negative impacts on health from handling agrochemicals that occur on a daily basis; globally, pesticides are estimated to cause more than 350,000 deaths every year (World Bank, 2007). A contributing factor is most likely the misapplication of pesticides, (for example, farmers sometimes apply banned pesticides or apply pesticides without due care) but the number still stands as an indicator of the potential dangers that can result from using agrochemicals (DeGregori, 2002). Synthetic pesticides may also kill natural enemies of pests and lead to pest outbreaks. Natural pesticides however, are not necessarily more environmentally friendly or less toxic than synthetic pesticides (Bahlai et al*.,* 2010), therefore choosing organic over synthetic may not under all circumstances be better for the environment.

Diversity

The Environment for Development initiative (a capacity building program in environmental economics focusing on research and policy interaction) (Muller, 2009) claims that organic farms are typically more diverse than conventional systems. Greater crop diversity encourages a wider range of species, including natural enemies that can help to control pests. By diversifying their crops, farmers can also diversity their income streams, leading to increased economic stability through risk-spreading. However, the FAO found that in developing countries, the costs to becoming certified are too high for most farmers. Some farms are also becoming less diversified to maximise production and produce a few high value organic commodities such as coffee and sugarcane. Where farms do diversify, there is a need to ensure the markets exist for the additional products.

Figure 12 A variety of crops. Credit, PaSu Farm.

Yields

It is widely believed that OA produces yields lower than conventional farming. One study, however, found that switching to OA resulted in increased yields of up to 180% in subsistence agriculture systems, maintaining yields comparable with conventional systems (92%). In drought affected areas and under subsistence conditions conversion to OA can improve yields, particularly where the soils have been degraded over time. The UN Environment Programme (UNEP) found that in developing countries, agricultural yields do not fall or at least stay the same when converting to organic from conventional farming. Over time, yields increase as natural capital increases. In their joint report on cases of OA in Africa, the United

Nations Environment Programme (UNEP) and the United Nations Conference on Trade and Development (UNCTAD) found that yields of crops and livestock productivity or total food produced increased on organic farms focused on food production and that agricultural yields in organic systems tend to be more stable when converting from other low input systems (UNEP-UNTCAD Task Force, 2008). Others have also found that organic conversion in tropical Africa is associated with yield increases rather than reductions (Gibbon and Bolwig, 2007)

Certified Organic cotton in Uganda
Cotton farming was introduced to Uganda in the 1940s, but slowed almost to a halt between 1972 and 1986 due to low prices and an unfavourable policy environment, attributed to armed rebellion and insecurity. Since the end of the civil war in 1986, peace allowed the new government to focus on the modernisation of agriculture (Kjær and Joughin, 2010). A revival in agriculture and cotton farming followed which opened the way for small-scale organic cotton farmers in certain regions of Uganda. Between 1994 and 2000, the number of cotton farmers in Uganda grew from just 200 to 24,000 (UNEP-UNCTAD, 2008).

Figure 13: Cotton family. Credit, Sara Delaney/A4I

The Export Promotion of Organic Products from Africa (EPOA) works with smallholder farmers – the majority of which are resource poor – through **cooperative** unions that provide technical advice on organic production methods and marketing. Soil fertility and pest management is maintained with traditional organic practices such as **crop rotations** and natural pest control, such as **push-pull**. Organic cotton production from this project achieves yields of 1,000–1,250kg per hectare of seed cotton, giving 300-320kg per hectare of lint.

Organic cotton receives premium prices compared to cotton produced through conventional methods, which translates to a 15-20% premium for farmers on farm gate prices. Finally, famers' **social capital** has improved through the formation of cooperatives and an increase in farmers' knowledge of organic methods from peer to peer training.

In general, however, wheat produced under OA yields 30%-40% less than with the use of inputs. This also seems to be the approximate ratio for other crops. If these results are consistent across multiple crops and environments, then the conversion to OA would require significant extra land to meet the same demand for food. Due to lower yields, more land is required to produce the same amount of crops that could otherwise be produced with the prudent use of inputs. Under these circumstances, deforestation may occur and other natural habitats lost to clear additional space for agricultural land. OA may, however, create local food systems where food is most needed, such as food insecure and market-marginalized remote areas of sub-Saharan Africa (Organic Research Centre, 2015).

Figure 14: Cotton harvest, Burkina Faso. Credit, Olivier Girard/CIFOR.

The question remains as to whether yields under OA are enough to ensure food security and at which price, given that organic product prices are higher on average. The FAO reports, for example, that in Uganda, farmers receive a 20% price premium for organic cotton (FAO, 2002). A 2005 study by the UN found that Ugandan organic farmers received premiums ranging from 10% - 100% for their products, which include pineapple, coffee, cocoa, and sesame (UNCTAD, 2005; Gro Intelligence, 2014). Although the higher price can be beneficial for the producer, it is also a consequence of the higher production costs, in part due to the longer value chain for organic products compared to conventional products. Considerable extra labour is needed, additional labelling and separate handling of organic products is required (Gibbon, 2007). Weeds have to be either manually removed (Niggli, 2007), and the production and application of compost and biological fertiliser adds to the labour time. In sub-Saharan Africa, the domestic market for certified organic produce is developing very slowly. This is partly due to low income levels and the low level of organisation of the organic movement in Africa. Nevertheless, several efforts are underway to establish organic markets in Uganda, Malawi, Kenya and South Africa (FAO, 2007).

Adoption

The cost of conversion from conventional to OA is one of the biggest hurdles to the adoption of OA practices, even in developing countries where traditional agricultural practices are nearly organic by default. In South Africa, certification can cost a farmer between R9000 (US$ 746) and R15000 (US$ 1244.5) per year (Thamaga-Chitja and Hendriks, 2008). Financial and logistical support with the certification process and linking farmers to both internal and external markets would enhance the benefits of OA for smallholder famers.

Payment for Ecosystem Services (PES) schemes, for example, may be used to support farmers in converting to OA. The agri-environmental policies of the European Union (EU) and the Organisation for Economic Co-operation and Development (OECD) countries support PES schemes for the development of OA, but potential problems arise where the agri-environmental incentives conflict with the marketplace. For example, schemes designed to encourage conversion to OA may result in an increased supply of organic products above current demand, resulting in falling prices, with all producers being worse off (OECD, 2013).

Similar care needs to be taken in transferring knowledge of OA from one place to another. There is a wealth of knowledge available on OA, especially in EU countries; however, this knowledge is specific to certain climatic circumstances and cannot be transferred to other regions such as sub-Saharan Africa without caution and modification. Additional attention is needed to build the capacity of farmers in sub-Saharan Africa, providing them with peer-to-peer training to ensure that the information is locally adapted to suit their land and needs. In Africa, the absence of secure land rights means that many poor farmers are unlikely to take on additional risks and efforts to gradually build up the "natural capital" of their farms beyond a one or two-year horizon (Muller, 2009; UNEP, 2011). To ensure that farmers invest in the transition to sustainable agriculture on a long-term basis, major efforts to secure land rights for smallholder farmers are needed, particularly in low income countries.

Water Conservation

Water conservation encompasses policies, strategies and activities to manage fresh water as a sustainable resource, to protect the water environment, and to meet current and future human demand (Defra, 2014). Approximately 70% of the world's poor live in rural areas with little option but to rely on rain-fed agriculture to sustain their livelihoods (Molden, 2007; Bulcock and Jewitt 2013). Without enough water crops are unable to use nutrients efficiently and yields suffer under conditions of drought (FAO, 2003).

Conserving water in agricultural systems includes a variety of technical approaches. Narayana and Ram Babu (1985) propose classifying these approaches by comparing rainfall availability to crop requirements under three conditions:

i. **Where precipitation is less than crop requirements:** strategies include land treatment to increase run-off onto cropped areas, fallowing for water conservation, and the use of drought-tolerant crops with suitable management practices.
ii. **Where precipitation is equal to crop requirements**: strategies are to conserve local precipitation, maximise storage within the soil profile, and store excess run-off for subsequent use.
iii. **Where precipitation is in excess of crop requirements**: strategies are to reduce rainfall erosion, to drain surplus run-off and store it for subsequent use.

Figure 15: Vegetable farmer in Ghana watering his crops. Credit N. Palmer/CIAT.

In some parts of sub-Saharan Africa there is plenty of water available. Yields of cereals in irrigated lands are 60% higher than in rain-fed lands. As such the challenge in areas where water is available is to increase the amount of irrigation, in a sustainable manner, from the current level of 6% of arable land., and indeed this amount is expected to double by 2050 (Rosegrant et al., 2009). In fact sub-Saharan Africa is the only region rated as having a high potential for irrigation expansion (Molden, 2007). Targets for expansion were set in 2000 by the Africa Water Vision 2025, the African Union and the African Development Bank (AfDB), aiming to expand the area under irrigation by 50% by 2015 and 100% by 2025. The Comprehensive Africa Agriculture Development Programme (CAADP) also prioritises agricultural water management, aiming to "extend the area under sustainable land-management and reliable water-control systems" (IFAD, 2012).

Figure 16 Dry soil in Kenya. Credit, T. Cronin, CIFOR.

Although the total annual rainfall in an area may be enough to sustain farm needs, it is often unevenly distributed so that droughts are interspersed with periods of intense rainfall. In many cases, crops are unable to use much of this water because it is lost through run-off (the flow of water that occurs when excess storm water over the earth's surface) or leaching (the loss of rainwater from soil through the percolation of water).

In other parts of the continent, water is very scarce: an estimated 200 million sub-Saharan Africans (18%) face serious water shortages. In these arid and semi-arid regions, a large portion of rainfall is lost as evaporation, percolation and run-off. This can be as much as 70-85% of the rainfall, depending on land management conditions (Liniger et al., 2011), and less than 15-30% of the rainfall is used for plant growth. Surface run-off is the flow of water that occurs when excess storm water or other sources flows over the earth's surface. This might occur when soil is saturated because rain arrives more quickly than soil can absorb it, or because impervious areas send their run-off to surrounding soil that cannot absorb all of it (Beven, 2004).

Climate change also continues to pose a challenge to water management in agriculture. Most of the agriculture in sub-Saharan Africa is rain-fed and prolonged periods of drought are becoming increasingly frequent (Rockström and Oweis, 2009). This places increased pressure on valuable water resources and agricultural irrigation. NASA's GRACE (the Gravity Recovery and Climate Experiment) has monitored global water distribution since 2002 and found that groundwater reserves have been in decline globally, whilst dry areas are becoming more drought-prone and wet areas are becoming more flood-prone (Famiglieti and Rodell, 2013).

Saving valuable run-off from violent thunderstorms can be a problem in tropical Africa. If the rain and the growing period do not coincide, water needs to be stored for later use. Run-off can be collected where streams flow onto flatter plains, where stream banks are intermittently flooded naturally or where run-off collects in naturally occurring depressions, such as the 'cuvettes' in West Africa (shallow basins which collect surface run-off for cereal or fodder production in the basin) (Hudson, 1987). Examples from Africa show how, with the help of run-off, sorghum can be grown with an annual rainfall of less than 200mm (Hillman, 1980; Cullis, 1985). Where annual rainfall is more than the 500mm sufficient for annual planting, it may still be possible to make use of run-on (where run-off collects) by increasing the cropping intensity. For example, when growing wheat or barley, a plant density of 70-90 plants/m2 is used on land receiving rain only, but the plant density is increased to 90-120 plants/m2 in depressions, which collect run-on.

Figure 17 Community-built irrigation canal in Ethiopia. Credit, N. Terrell, USAID.

The challenge in areas experiencing water shortages or mismatches between rainfall and growth periods is to design and implement cheap and efficient small-scale water harvesting methods that collect rainwater or run-off for later use (Montpellier Panel, 2013). Water harvesting practices, such as micro-catchments techniques, contour bunds and ridges, small run-off basins and the collection of rainwater show promising results for reducing smallholder farmer risk from climate shocks and stressors, improving yields and delivering positive environmental impacts (Shiferaw et al., 2014). Water harvesting, in general, can be defined as the concentration, collection and storage (in different structures or in the soil) of rainwater or run-off for use either on-site or at a different location, immediately or at a later time (Siegert, 1994). In the case of crop production, water harvesting aims to decrease the amount of rainfall "lost" through unproductive evaporation to increase the amount of water available to the plant for crop transpiration and as a result, increased crop growth and production (Bulcock and Jewitt 2013).

Five different methods – contour harvesting, earth basins, planting pits, drip irrigation and ridge tying – highlight a spectrum of approaches currently available to farmers (Garden Organic, No date):

• **Contour harvesting**: Ploughing (turning up the earth before seeding) and furrowing (making a rut, groove, or trail in the soil), then planting along the ridges or contours rather than up and down the slope conserves water by reducing surface run-off and encouraging filtration of water into the crop area. Several water harvesting techniques are based along contours including: contour ploughing; contour ridges; stone lines; grass strips; and terraces.

• **Earth basins**: Square or diamond shaped basins with earth ridges on all sides, earth basins can be constructed on any gradient and whilst most suitable for growing trees, they may also be used for other crops. Run-off water is channelled to the lowest point and stored in an infiltration pit (a shallow artificial pond). Earth basins are usually used for fruit trees and the seedling is planted in or on the side of the infiltration pit. The size of the basin depends on local rainfall and the water requirements of the trees. In general, earth basins are usually 1-2m long and in some cases, particularly on flat land, can reach up to 30m in diameter. Earth basins are suitable in arid and semi-arid areas with annual rainfall amounts of 150mm and above.

• **Planting pits**: Easy to construct small pits in which individual or small groups of plants are sown. The pits catch rainwater run-off and concentrate soil moisture around the roots. Normally the pits are 10-30cm in diameter, 5-15cm deep, and spaced 1m apart. Before planting, compost or manure may be added to improve soil fertility and structure. Planting pits are particularly successful in areas of low rainfall (350–750mm) and are suitable for crops with low water demand such as sorghum or millet. They are more suitable for heavier clay soils, which tend to form a crust and have poor infiltration. Additionally, they are only suitable for gentle slopes with less than 2% gradient.

Figure 18: Zai pits in the Sahel. Credit M.Tall/CCAFS

• **Drip irrigation**: Drip irrigation conveys water to fields through a system of plastic tubes where the water is slowly dripped onto the soil through small perforations in the tube. A small petrol pump can be used to push the water along the tubes for larger areas, but this will add a fuel cost and will need servicing. Therefore drip irrigation is more likely to be used on smaller areas of high value crops that require regular watering.

Where rainwater and water harvested is insufficient to meet crop requirements, some form of irrigation is typically relied upon. Irrigation has direct benefits in terms of production and incomes, and indirect benefits in terms of reduced incidence of downstream flood damage. However, there have also been costs associated with large-scale irrigation in particular, which may at times outweigh the benefits (Gleick, 2002). Irrigation has the potential to cause increased soil erosion, pollution of surface water and groundwater from agricultural biocides; deterioration of water quality; increased nutrient levels in the irrigation and drainage water resulting in algal blooms, proliferation of aquatic weeds and eutrophication in irrigation canals and downstream waterways (FAO, 1997). Irrigation-induced salinity can arise as a result of the use of any irrigation water, and salinization puts 2 to 3 million hectares out of production each year. Water-borne diseases are commonly associated with the introduction of irrigation, including malaria, bilharzia and river blindness, because disease vectors proliferate in irrigation waters (FAO, 1997).

Drip irrigation is a system that aims to solve many of the limitations that traditional irrigation systems pose in hot, arid countries (Montpellier Panel, 2014) and is also suitable for use in developing countries due to its low-tech nature and resource efficiency. When water is targeted directly to the root zone, the amount of water lost through evaporation compared to sprinkler systems is considerably reduced (FAO 1988). Compared to surface irrigation and sprinkler methods (with efficiencies of 50–75% in high-management systems), drip irrigation can achieve 90–95% efficiency (Awulachew et al., 2009). Other benefits include reducing weed growth and leaching of plant nutrients in the soil.

Figure 19: Light cultivator with tie-maker mounted, showing the creation of ridges. Credit, FAO

Another method of water conservation, ridge tying, uses tillage methods to increase germination and yields (Fig. 1). Run-off is greatly reduced and infiltration rates are increased. When making ridges, the ridger body is attached to the plough instead of the mould board and produces ridges which are 250mm high. The ridger has two adjustable discs angled to form a wide `V' shape. Ridges made using this technology can be tied using hand hoes. In Zimbabwe, simple ox-drawn tie-makers have been produced locally. Ties are made by scraping the tie-maker along the furrows between the ridges until enough soil has been collected. The collected soil should be about 1/2 to 2/3 the height of the ridges.

The advantages of tied-ridges include reduced erosion and conservation of soil moisture. The equipment used is simple and easy to use, and capable of being locally manufactured and maintained in some countries. Further, the field trials clearly showed improved crop yields, but the disadvantages are that tied-ridgers require new or additional equipment, and substantial time and effort required to prepare the lands each year. This increases farmers' costs. In areas with highly variable rainfall, ridges can fail due to overtopping. When this occurs, greater soil losses may result (UNEP, 2015)

Drip Irrigation

Drip irrigation conveys water through a system of pipes to the fields, were the water is dripped slowly through emitters onto the soil, directly next to the root of the plant. Drip irrigation is widely used in developing countries due to its resource efficiency and low-tech nature. Compared to sprinkler or surface irrigation, drip irrigation is very efficient as only the immediate root zone of each plant is targeted (FAO, 1988). Drip irrigation requires little water compared to other irrigation methods. For each cubic metre of water applied, 7.3kg of aubergine was obtained using drip irrigation, as opposed to 2.4kg using hand watering. Based on these calculations, an average of 25% less water can be used.[1] (Infonet-Biovision, 2010). The small amount of water reduces weed growth and limits the leaching of plant nutrients down in the soil. Fertiliser solution can also be applied efficiently to the plants through the drip system (Infonet-Biovision, 2010).

Figure 20: Drip irrigation in Kenya. Credit, CIAT

The disadvantages of drip irrigation are that the sun can affect the tubes used for drip irrigation, shortening their usable life, and if the water is not properly cleaned, the tubes can become blocked. Finally, without sufficient leaching (most drip systems are designed for high efficiency, meaning little or no leaching fraction), salts applied with the irrigation water may build up in the root zone (Infonet-Biovision 2010).

Figure 21: Bucket drip irrigation in Malawi

Kenya suffers from unreliable rainfall leading to drought conditions subsequently increasing household vulnerability to food insecurity, especially when alternative risk management or coping strategies are unavailable or ineffective. Until recently, Kenyan smallholders, who are mostly women, use hand-watering to cultivate vegetables for their families. The practice of hand-watering is tedious and inefficient especially where water is scarce.

Figure 22: Learning to use drip irrigation in Kenya. Credit, ICRISAT

To improve productivity, the Kenya Agricultural Research Institute (KARI) introduced drip irrigation technologies. Bucket drip kits help deliver water to crops effectively with far less effort than hand-watering and for a minimum cost compared to irrigation. Use of the drip kit is spreading rapidly in Kenya and the majority of drip users, 70- 80%, are women (Ngigi et al, 2001). Drip kits do have some disadvantages but there are also many positive socioeconomic impacts. Farmers reported profits of Ksh4,000-10,000 (US$80-200) with a single bucket kit, depending on the type of vegetable and between

Ksh20,000-30,000 (US$400-600) per season with the one-eighth of an acre kit (Ngigi et al, 2001).

Mrs. Mutai is 1 of 150 women who are members of a group that started using drip irrigation in Eldoret. Four months after installation, she sold enough vegetables to invest in more lines and make her garden bigger. Another member, Anne Butia, sold Ksh10,000 (US$200) worth of vegetables in 3 months from her garden. She used the extra income to pay for school fees and buy clothes for her family.

Ridge tying

McCartney et al. (1971) reported that tied ridging in Tanzania gave higher maize yields in both low and high rainfall years, but reports of success are more common in low rainfall years. For example, Njihia (1979) reported from Katumani in Kenya that tied ridging resulted in the production of a crop of maize in low rainfall years when flat-planted crops gave no yield.

Jones (1985) reported that "on a sandy soil at Lusitu in the Zambesi valley, tied ridges increased mean crop yields (maize, sorghum, and millet) over those on flat land by 168%, 159% and 16% under seasonal rainfalls of 587, 623, and 724mm, respectively (Honisch, 1973). On vertisols (clay-rich soils that shrink and swell with changes in moisture content) at Big Bend, Swaziland, mean increases for maize, cotton, and sorghum were 64% higher when annual rainfall totalled 508mm, and 308% when rainfall only reached 310mm (Warwick 1979, 1980; University of Idaho, No date). Clearly responses can be dramatic, but recent work under very harsh conditions in Botswana has shown that there may be also negative effects. Higher soil temperatures within the ridge can be detrimental to seed germination, and where showers are light the penetration of moisture into the soil may be shallower than that in the flat soil (DLFRS, 1984).

Contribution to Sustainable Intensification

Water conservation and harvesting contributes to sustainable intensification by allowing water to be used efficiently. This results in higher agricultural production throughout the year and improved resilience to drought, thereby improving farmers' livelihoods and food security (Taddele Dile et al, 2013; Rockstrom et al., 2002). Taddele Dile et al. (2013) find that water harvesting meets the criteria for Sustainable Intensification by (1) improving water availability during dry spells; 2) improving agricultural yield for food security; (3) rehabilitating degraded lands to restore biodiversity; (4) minimizing use of external inputs that has adverse effects on the environment; (5) allowing the increased sequestration of carbon in soils to mitigate climate change; and (6) reducing downstream river pollution from release of nutrients from upstream agricultural lands.

The challenge of meeting global food demand requires an increase in the level of agricultural water productivity and some increases in global water use (FAO, 2011). Finding ways of saving water or using 'less drop per crop' must become a mainstay of agricultural production (Montpellier Panel, 2014). Suitable water conservation methods minimise the negative environmental impacts of drought such as soil erosion and desertification, whilst increasing crop yields.

Benefits & Limitations

There are several barriers to water conservation methods in developing countries commonly cited, including a lack of awareness of the appropriate practices and their benefits, as well as low levels of knowledge and dissemination. Agriculture projects often fail to engage with farmers about how to accomplish rainwater harvesting and there are still numerous farmers that are not reached by agricultural extension services at all. In many cases, national policies do not provide sufficient incentives—such as land rights—to encourage farmers to invest in improved land and water management (Winterbottom, 2013). Scaling-up outreach and extension services for locally designed water harvesting and conservation plans would help to increase the uptake of water conservation measures in remote rural areas.

The initial installation and ongoing maintenance of water harvesting and conservation structures can also be a barrier to their implementation. Apart from labour and small hand tools or hoes, no additional cost for construction equipment is required for contour harvesting, but the method requires a great deal of hard labour and training to build and continuous labour to maintain the structures.

Similarly, although simple and cheap to install on almost any slope, the level of maintenance required to keep earth basins free of unwanted vegetation limits their use. Additionally, the system can be badly damaged if there is a storm, which requires additional labour for maintenance. In an evaluation of earth basin water harvesting systems comparing their effectiveness for collecting and storing water at different scales, the efficiency of the system varied from over 85% to as low as 7% depending on the size of the catchment and the root zone capacity. Therefore, it is important that the location, design and the crop are properly selected, which requires training or extension services to help farmers to build the basins correctly. The low crop densities required for this method suggest that farmers get a low yield in return, compared with other water conservation methods (Prinz, 1996).

In contrast with earth basins, planting pits are labour intensive to prepare. One study found that planting pit construction required 76.5 days per hectare for clay soils and 51.5 days per hectare for sandy soils, compared to 6 days per hectare under conventional tillage (Rusinamhodzi, 2015). Many smallholder farmers lack draught power – either from animal traction or machinery – so despite the initial labour, digging planting pits is often easier than ploughing (Twomlow et al., 2006). Further, pits can be dug over several months before the rainy season, spreading out the labour requirements over time. Once the pits are dug, they need to be restored for the next planting season. Weeding in planting basins required 40% more labour compared with conventional tillage (12 human days per hectare) due to high weed densities (Rusinamhodzi, 2015)

Drip irrigation may be laborious to set up and initial costs for equipment may be high for smallholder farmers, yet a system is cheap, efficient and simple to use when compared to large scale irrigation. A drip irrigation system costs an estimated $1,565, compared to $924 for a watering can-based system (otherwise known as a 'bucket drip kit,' (Lennart et al, 2011). Whilst this is expensive, a comparison study between drip irrigation and hand-watering of aubergines in Niger found that drip irrigation reduced labour-hours from 4.7 to 1.1 per day per 500m^2 of farmed land (Woltering et al., 2011).

Where labour accounts for 45% of the cost of food production when irrigated by hand, the value per m^2 of aubergine crop increased from $0.1 to $1.7 with drip irrigation. With a drip irrigation system, water is also saved; for each cubic meter of water applied, 7.3kg of aubergine was obtained, as opposed to 2.4kg using hand-watering. Based on these calculations, an average of 25% less water can be used (Lennart et al., 2011).

Drip-irrigation systems also face risks. The sun can damage the tubes and shorten their usable life. The system should include a simple wire mesh filter between the storage tank and the drip irrigation pipes that requires regular cleaning as it may get clogged up with algae. Without sufficient leaching of water onto the soil, salts applied with the irrigation water may build up in the root zone (Infonet-Biovision, 2010). To avoid these pitfalls, support should be made available to farmers after implementation. An International Crop Research Institute for Semi-Arid Tropics (ICRISAT) study in Zimbabwe found that 60% of households reported that they needed additional advice after implementation, despite that more than 90% of households received basic training (Belder et al., 2007).

One study of tomato yields in South Africa found that the average yield was 75 Mg/ha under drip irrigation, which can be compared with the average marketable yield for South Africa of approximately 31.4 Mg/ha Combining low-cost drip irrigation with plastic mulch increased the yield by on average 10 Mg/ha (Karlberg, L et al., 2007).

Room for Innovation

Many of these practices, forms of water harvesting, mulching, no-till or OA are innovations in and of themselves, and any further innovation needed is around understanding which techniques are appropriate where, what is needed to support and maximise adoption, and how these techniques can be integrated into a holistic farming system. To truly innovate and achieve SI a combination of remedies is needed to restore, conserve and enhance soils and water. All of these approaches whether conservation or organic agriculture or water conservation and harvesting can be combined with other traditional and ecological approaches such as intercropping with nitrogen enriching legumes, mixing crops with livestock and trees, or digging planting pits and erecting windbreaks to minimise wind erosion, which improve soil fertility and increase yields with minimal environmental impact (Montpellier Panel, 2014).

Combining water-harvesting and -conservation with good agricultural practices in general can help farmers to make effective use of soil water reserves and improve soil health. Deeper rooting crops, such as grasses or cereals will exploit soil water reserves more effectively than shallow rooting crops and therefore can be grown in drier periods. Practices such as avoiding ploughing too deeply or when the soil is wet, will also promote the efficient use of soil water reserves. Adding mulch or manure to break up the intensity of rainfall will reduce the tendency of the soil to form a crust, minimising run-off. Thus the interconnectedness of water, soil and nutrient conservation is critical. The most successful systems are those that provide water, nutrients and a supportive soil structure in a synergistic fashion (Montpellier Panel, 2013).

Figure 23: Organically farmed maize in Kenya. Credit, COLEACP.

Similarly combining water conservation with soil mapping and testing (see Precision Farming) could help farmers gain a better understanding of the soil types in a specific location and ensure that the appropriate water-harvesting or -conservation method is implemented. For example, when water drains out of the soil, essential nutrients such as nitrogen are also washed out. This problem is greater on light sandy soils, but can be reduced by adding compost. Manures or plant residues will eventually increase the amount of water a soil can retain. Farmers can be better equipped to select the correct methods of water conservation and prevent both a loss of soil moisture and nutrients with a combined understanding of their soils.

Figure 24: Ugandan farmers use conservation agriculture techniques to grow organic cotton. Credit, Invisible Children.

Finding ways to overcome the barriers to the adoption of CA, OA and methods of water conservation and their context-specific nature are potential areas for future innovation. Identifying the most appropriate forms of CA, OA and water conservation in different ecological and social conditions is needed particularly as together these three practices encompass such a broad range of techniques. The whole gamut of these techniques is not going to be successful in every place and thus local verification and modification of the technologies is required. Similarly the short-term benefit, particularly of CA can be variable, with the productive benefits more often accumulating over time as mulching gradually improves the soil (Erenstein, 2002).

Further work is needed to identify the causes of the short-term reductions and how they can be avoided, as well as work on the broader impacts of these techniques such as the downstream impacts of large-scale water-harvesting or irrigation schemes or the safety of compounds already used under OA, some of which have been called into question (Taddele Dile et al., 2013).

Critically, if ecological methods that preserve natural capital are to become mainstream then any yield differences between ecological and conventional farming need to be minimised. For example, if OA is going to move beyond its niche and expensive nature to become more widespread then organic agricultural yields need to increase to match conventional yields. Performance could be improved by breeding organic crop varieties (conventionally or through biotechnology) to make better use of scarce resources, to better synthesize their own nitrogen, to better resist pests and diseases, and to better tolerate drought (Conway, 2012).

Genetic methods of improving seeds to increase resistance to weeds and pests and strengthening their resource use efficiency are also needed, but require advancements in socio-economic intensification to ensure these seeds and other inputs are available and accessible to farmers, in particular farmers need to be trained on their use. In general the lack of appropriate, available and affordable equipment and inputs in sub-Saharan Africa needs to be addressed in order to cut labour time and help to improve farm health.

Aside from major land reforms and responsible knowledge transfer, which relate to almost all forms of ecological intensification, enabling environments including appropriate policies, which support the adoption and market growth for ecological forms of farming need to be developed. With regards to organic agriculture for example, access to and increased development of (local) markets for organic products, local processing possibilities, and export infrastructure are of particular importance.

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Precision Farming

Precision agriculture aims to ensure that inputs – whether nutrients, pesticides, seeds or water – are used in a precise, sparingly, effective and strategic way to ensure that they exert minimal environmental impact (McBratney et al, 2005). It recognises the spatial and temporal variability of crop production at the field scale (Wells and Dollarhide, 1998) and accounts for these differences by targeting the application of inputs to optimise returns (Adamchuk et al, 2004). To this end, the amount of inputs needed to achieve set production levels can be reduced. These methods were developed in response to increasing environmental degradation and the rising cost of inputs that threaten the production of food around the world.

Land degradation, for example, is particularly acute in parts of sub-Saharan Africa, where long-term overuse of soil and low, unpredictable rainfall are prime reasons for poor food production. Land degradation affects nearly half of the earth's land area and reduces the productive capacity of agricultural land by eroding topsoil and depleting nutrients, resulting in enormous environmental, social and economic costs. In sub-Saharan Africa an estimated 180 million people are affected, while the economic loss due to land degradation is estimated at $68 billion per year (Nkonya et al, no date).

Unless nutrients are replaced, soils become depleted, causing the yields and crop quality to decline (ICRISAT, 2009). However, farmers are often unable to invest in inputs as they are increasingly costly and often inaccessible. There is also limited knowledge amongst smallholder farmers about what inputs to use and how to apply them effectively. When fertilisers are used inefficiently, as is often the case, the result is soil nutrient deficiencies if underused, or the severe pollution of natural resources if overused. Some farmers are also unwilling to invest in inputs because they may not be guaranteed a return on their investment (CGIAR, 2011).

In addition to significant soil nutrient deficiencies, fertiliser use in sub-Saharan Africa is very low, using on average 7kg/ha and accounting for 3% of global fertiliser consumption. In contrast, Asia uses 150kg/ha on average (Druilhe and Barreiro-Hurlé, 2012). In June 2006, the African Union Heads of State and Government adopted the 12-resolution Declaration at a special summit in Abuja, Nigeria to increase fertiliser use to 50kg of nutrients per hectare by 2015 (Wanzala, 2011). Although 50 kg/hamay be excessive in some situations, no region of the world has been able to increase agricultural growth rates and

reduce hunger without increasing fertiliser use (African Union, 2006). Many African farmers need to use more inorganic fertiliser, but they need to do so sustainably. Farmers must complement existing methods – manure applications and intercropping with nitrogen-fixing legumes or crop residues – with increased but targeted use of fertilisers to return nutrients to the soil, a form of precision agriculture. Farmers in developed countries, on the other hand, are more likely to need to decrease their fertilizer use, which in many places is excessive. Long-term studies in the US, UK and elsewhere indicate that rice, wheat and barley could all be grown with reduced Nitrogen (N) fertiliser applications without yield penalty (Allen and Beatty, 2011).

Farms in developed countries are typically larger than in developing countries (10 – 1,000ha or more) and better resourced allowing for mechanised crop production systems. Access to training and advanced technology means that precision agriculture increasingly involves new technologies like satellite imagery, information technology and geospatial tools (Tran and Nguyen, 2006) . Farmers may use these technologies to collect, analyse and plot data on productivity levels, environmental, and soil quality variables in different parts of their fields and subsequently to apply different fertiliser mixes in accordance with soil needs in specific locations (Sonka, Bauer and Cherry, 1997) .

In many developing countries, there is little to no use of western precision agriculture technology. This is due to smaller field sizes, limited access to technology, financial capital and training. Nevertheless, farmers explore the means and resources available to them in order to increase agricultural productivity and production, make better use of limited resources and produce a greater yield (Tran and Nguyen, 2006). Precision farming is perhaps of even greater importance where the need for resource efficiency is driven by a lack of resources without access to substitutes. Through the prudent and targeted application of inputs, precision agriculture contributes to sustainable intensification by enabling farmers to increase their yields with fewer inputs than other application methods such as broadcasting (scattering over a large area) fertilisers or seed, for example. This can also improve soil quality and moisture whilst minimising the environmental impact that excessive input use can cause (Montpellier Panel, 2013). Further, the targeted application of inputs can help farmers to be more competitive by lowering production costs.

There are several methods in the precision farming family from measuring and monitoring farm conditions, such as soil testing, to calculating, locating and applying a variety of organic or inorganic inputs, for example through microdosing. These steps can be more or less technologically sophisticated, making precision farming universally applicable in different forms.

Soil Testing

Soil testing is the analysis of a soil sample to determine its composition, nutrient levels and other characteristics such as the pH level. Yields can vary within fields for many reasons: weeds, insects, microclimate, soil nutrient status, and other soil properties (such as texture, topography, or wetness). Testing the soil, therefore, is the first step in gathering information about individual fields from which to base soil nutrient management and fertiliser decisions and monitoring over time. Soil tests can help to determine how fertile the soil is and indicate nutrient deficiencies, potential toxicities and trace minerals. It is also important to help monitor the various types of land degradation (FAO, 2000). Soil testing is usually carried out as part of a soil testing programme, which consists of four phases: 1) soil sampling; 2) sample analysis; 3) soil-test data interpretation; and 4) soil management recommendation.

Figure 25: Soil testing in a lab. Credit, D. Sierra, LLC & Earth Institute, Columbia University.

In developed countries, soil tests are more commonly carried out in laboratories. For smallholder farmers in remote rural areas, field-testing kits may be more appropriate. Techniques used in the field can include field test strips whereby farmers use different types of fertilisers in strips on their land to determine the soil nutrients limiting crop growth and the most effective fertilizer and soil sampling either through using portable test kits or sending samples to laboratories. Soil samples are collected across the field to a uniform depth. Sangina and Woomer (2009) recommend a minimum of 9 to 12 samples or cores be taken across a 1 acre field. These samples are then mixed and analysed. Soil samples from Africa are often sent to laboratories, even as far away as Europe, adding to the cost and reducing the appeal of soil testing to farmers. Laboratories in Africa are typically under-funded, lacking more sophisticated technologies. The Kenyan Agricultural Research Institute (KARI) is a public institution offering plant and soil analyses for a fee, its services mainly employed by students, researchers and commercial organisations. The cost to prepare one soil sample and analyse it for N, P and K is $12.65, a cost prohibitive to most farmers (Sanginga and Woomer, 2009). An alternative is the use of home soil kits, but these are rare in Africa, and despite only needing relatively basic test kits to aid fertilizer decisions, their cost is a significant barrier to their use. The results from test kits may also be crude and imprecise given the small soil samples they generally analyse. It may also be difficult to translate the quantitative results they produce into fertilizer recommendations. For all of these soil testing methods farmers need to be able to afford the cost of the tests, have access to fertilizer and be able to understand and interpret the results. Improvements in extension services and local soil testing facilities would enable farmers to better understand their soil types and nutrient deficiencies, as well as the soil testing facilities available to them, in order to minimise the amount and types of fertilisers they need to buy and use to maximise the benefits.

Contribution to Sustainable Intensification

Soil testing helps farmers to produce more with less: minimising nutrient deficiencies, reducing costs and limiting environmental damage through the targeted and precise use of inputs. For example, under the guidance of Ethiopia's Agricultural Transformation Agency (ATA), farmers growing hybrid maize were able to achieve 6-8 tons/ha – reaching the European average – when they applied an appropriate balance of NPK (Nitrogen, Phosphorus and Potassium). This was coupled with Boron that, after soil testing, was determined to be deficient in the region (Montpellier Panel, 2014) Soil testing acts as a natural precursor to microdosing; the identification of low productivity areas allowing for the precise application of inputs directly to the target area. This reduces the costs of inputs for the farmer and contributes towards improved food security and nutrition with greater yields, whilst promoting better environmental practices.

Benefits & Limitations

Figure 26: A portable soil testing kit made by SoilDoc. Credit, D. Sierra, LLC & Earth Institute, Columbia University.

Yield improvements and input reductions

Soil testing has the potential to minimize nutrient deficiencies and reduce costs by eliminating or reducing application rates at sites with sufficient lime or fertiliser, or both. The correction of localized nutrient deficiencies should lead to an increase in nitrogen use efficiency, since other nutrients will not be limiting (Taiz et al, 2015). If these benefits can be met, then more efficient nutrient utilization should reduce run-off and leaching risks.

By testing their soils, farmers are able to identify where inputs are needed and which ones are most appropriate for their soil type(s). This results in reducing environmental damage from limiting fertiliser broadcasting and improved soil quality, leading to greater yields and typically additional income (Sangianga and Woomer, 2009).

Limited availability of correct inputs

After the soil test has identified what nutrients are required, inputs often need to be added. Yet, there is a lack of widely available and affordable inputs for smallholder farmers. Supplies of inorganic inputs such as fertiliser are tight and individual African countries are small players in global fertiliser markets where suppliers prefer to sell large bulk orders. Farmers' access to fertiliser is limited by a lack of credit for purchasing inputs. In addition, farmers in inland Africa pay more than twice as much for fertiliser as farmers in Europe due to transport costs (AfSG, 2015). The lack of infrastructure means that buying agricultural inputs is complicated and the supply is often unreliable because of poor distribution systems (Gilbert 2012). *Inaccuracies in testing and results*

Soil testing, particularly for large areas, is not in itself a solution to issues of soil infertility or poor yields. Soil quality may vary within a field due to weeds, insects, microclimate, nutrient levels, and other soil properties (texture, topography, wetness). This is especially true in larger fields, where soil test results cannot accurately represent the entire field. The results mask scattered areas of both higher and lower levels of plant nutrients. Care, therefore, needs to be taken in collection, analysis and interpretation of the data that likely requires a level of expert knowledge. As such the inability to obtain soil characteristics rapidly and inexpensively remains one of the biggest limitations to precision agriculture in poor countries (Adamchuk et al, 2004). If the test data are inaccurate, interpretation is useless, misleading and costly to farmers who adopt recommendations based on invalid data (FAO, 2000). Therefore trained staff are needed to both conduct and interpret soil tests

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The mobile soil testing and training laboratory truck, Uganda (2015).

Access to soil testing kits in rural Africa is limited, as is the training and knowledge in how to interpret soil test results. A new mobile soil testing and training laboratory truck aims to change this and tour rural areas of Uganda with researchers from the National Agricultural Research Organisation (NARO) to offer free agricultural training and soil testing to smallholder farmers. A public-private partnership between the K+S Kali GmBH, the Sasakawa Africa Association (SAA) and the University of Göttingen are supporting the project by providing soil analysis expertise and funding.

Figure 27: Mobile testing laboratory. Credit, FarmbizAfrica


Figure 28: Testing the soil. Credit, CGIAR

The project began in Northern Uganda in January 2015. Researchers are collecting soil samples from farmers, analysing and providing recommendations regarding the type and quantity of fertiliser that should be used, and where it should be used if necessary. Free training is also offered on farming methods to increase yields and maintain soil fertility. By bringing soil testing to the farmers, the project aims to improve livelihoods through informing better land management decisions, hopefully leading to increased crop productivity (Omondi, 2015).

Lack of funding/capacity to provide services

Many African countries have serious problems in providing effective and expert advisory services on soil resource management to farmers, even after they have established soil and water testing laboratories (SWL). The FAO identified the main limitations to include inadequate funding for equipment, lack of trained staff to both maintain equipment and manage the laboratories, and finally a poor capacity to interpret laboratory test data and make the correct recommendations.

There is a strong need for adequate and effective training by lab staff of extension workers and farmers for simple diagnosis (FAO, 2000). Working to reverse the situation is AGRA's soil health program. They have trained 4,800 extension workers and 134,000 lead farmers, whilst also supporting more than 170 students—half of whom are women—to study soil science and agronomy at African universities (AGRA, 2014).

A potential alternative to laboratory soil testing is the use of field-testing kits. Field-testing kits have the benefit of being simple, quick and convenient to use. A test for N, P and K can be completed in less than 5 minutes and the kit is easily carried to remote rural field locations. Portable kits are much cheaper than laboratory testing, but that isn't to say that they are universally affordable. Further, extension services for soil testing in Africa are limited, and most farmers are not trained to interpret the results, bringing about a limited uptake of soil testing methodologies in Africa. Although a test kit is not an alternative to a soil-testing laboratory in terms of the depth of analysis, soil management recommendations arising from test kits can be beneficial to productivity (FAO, 2000).

Communication of results

An inability to obtain soil characteristics rapidly and inexpensively remains one of the biggest limitations to soil testing in poor countries (Adamchuk et al, 2004). In many countries, delays of up to 6 months in forwarding the lab reports and recommendations to farmers are common (FAO, 2000). Work is needed to reduce the delay for communication of soil test results from laboratories to farmers.

Microdosing

Microdosing is a highly efficient but simple, technique developed to minimise the application of and over-reliance on inputs, and improve nutrient use efficiency. Fertiliser microdosing involves the application of small, quantities of fertiliser onto or close to the seed at planting time, or a few weeks after emergence. This can be done by filling a soda bottle cap with fertiliser and applying it directly to the root of the crop. The same principle can be applied to herbicides that, far too often, are sprayed indiscriminately, killing not only weeds but other wild plants and sometimes damaging the crops themselves (Montpellier Panel 2013). Drip irrigation is a method of water microdosing, applying a limited amount of water directly to where it is most needed, reducing wastage and evaporation.

Farmers apply 2 to 6g of fertiliser (about a three-finger pinch) in or near the seed hole at the time of planting (equivalent to about 20 to 60kg of fertiliser per hectare). About 25,000 smallholder farmers in Mali, Burkina Faso, and Niger have learned the technique and increased sorghum and millet yields by 44% to 120%. Their family incomes increased by 50% to 130%. Fertilizer use has been reintroduced in Zimbabwe, Mozambique and South Africa. Although microdosing is time consuming and laborious, its use in Zimbabwe resulted in 170,000 households increasing cereal production levels by 40,000 tons, saving US$7 million in food imports (ICRISAT, 2009).

Figure 29: Microdose of fertilizer in combination with small amounts of manure and improved crop varieties can lead to greater yields. Credit, ICRISAT

Contribution to Sustainable Intensification

Microdosing helps to raise yields and reduce the environmental impact of excessive input use by increasing the efficiency of fertiliser, herbicide and water use. In the case of fertiliser application, the method has been found to use approximately one-tenth of the amount typically used on wheat, and one-twentieth of the amount used on maize in the US (ICRISAT, 2009). Water and fertiliser microdosing can help to improve the soil quality and fertility of highly eroded soils in Africa in a sustainable and affordable way (compared to conventional agriculture), reducing the costs of acquiring inputs. Thus microdosing can improve livelihoods and contribute to sustainable intensification by producing more with less. To improve the efficiency of the approach, microdosing could be combined with the use of organic manure or compost, improved seed, and water conservation techniques in arid regions to greatly increase yields and build natural capital (Camara et al, 2013).

Benefits & Limitations

Crop growth and yields

The benefits and limitations of fertiliser microdosing have been reviewed and evaluated in demonstrations and on-farm trials with hundreds of farmers in Burkina Faso, Mali and Niger between 1998 and 2004 (Tabo et al 2009). Microdosing may result in rapid growth early on and earlier maturation times compared to crops grown with no inputs, avoiding drought later in the season and increasing crop yields overall (Tabo et al. 2006, Tabo et al. 2007). Rebafka et al., (1993) found through plot and field experiments conducted in 1990 and 1991 on acidic sandy, P deficient soils in

Niger that by coating pearl millet seeds with ammonium phosphate at a rate of 100g P/ha, there were large increases in early millet growth compared to farmers who did not apply fertiliser. Higher P availability early in the planting process was also found to increase the plants resistance to storms and early season drought (Michels et al., 1995; Bagayoko et al., 2000) especially when combined with ammonium nitrate (Strasser & Werner, 1995; Lima et al., 2010).

Yield increases for millet, sorghum and groundnuts (Rebafka et al., 1993; Muehlig-Versen et al., 2003) have been reported across Africa and span a broad range of climatic and soil conditions (Bagayoko et al., 2011), indicating that microdosing is applicable in a variety of conditions.

Impact of fertiliser microdosing on crop yields in the Sahel

Less can be more if the appropriate fertilizer is applied at the right time, in the right quantity and in the right place. In sub-Saharan African, fertiliser microdosing developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and partners has increased agricultural productivity. In order to improve the productivity of pearl millet and sorghum, at least 100kg of NPK is required per hectare, but Dr Ramadjita Tabo, ICRISAT's Director for West and Central Africa, recognized that the cost of $40 per hectare to meet this requirement was prohibitive to smallholders. Further, the region's sandy soils were phosphorous deficient so ICRISAT recommended that farmers use 6g of NPK (15-15-15) plus 2g of DAP and 1g of Urea, just a 3-finger pinch, resulting in only 2g required per plant and limiting total fertiliser use to just 20g per hectare.

Figure 30: Microdosing in Burkina Faso. Credit, The Hunger Project UK

On-farm tests were carried out to assess the effect of microdosing in the semi-arid climate of Mali, Burkina Faso and Niger (Tabo et al, 2009). In the Sahel, soils are sandy with poor fertility and low levels of rainfall (500mm-800mm annually) (World Bank, 2015). In these trials, farmers selected the plant variety and fertiliser type according to what was available in their country. The table below displays the rates of fertiliser application per country. Fertiliser microdosing on average was found to increase yield for millet, sorghum, maize, cowpea and groundnut between 44% and 120% (ICRISAT, 2006).

Figure 31: Woman farmer takes home pearl millet. Credit, ICRISAT

Country	Fertiliser microdose
Burkina Faso	4 g of nitrogen, phosphorus, and potassium fertiliser (NPK) (15-25-15)
Mali	4g of NPK (17-17-17)
Niger	6g of NPK (15-15-15), 2g Di Ammonium Phosphate (DAP) (18-46-0), and 2g DAP + 1 g Urea (46-0-0)
Note: *(15-25-15) signals the blend of Nitrogen, Phosphorus, and Potassium. For example, if you purchased a 50-pound bag, 15 pounds (or 15%) would be Nitrogen, 25 pounds would be phosphorus, and 15 pounds would be potassium. The remaining 45% is simply filler, which are there mostly to help disperse the chemicals.*	

Environmental impacts

Microdosing provides an alternative to broadcasting by reducing the amount of inputs available for leaching. In conventional farming systems, excess nutrients in the soil may be leached out when it rains and washed into groundwater and surface water bodies, causing eutrophication, whereby the excess nutrients stimulate excessive plant growth such as algae. Their decomposition subsequently depletes oxygen levels leading to the death of many aquatic organisms, negatively impacting local fisheries and those whose livelihoods depend on them (USGS, 2014).

Adoption and affordability

Microdosing is often hailed as an affordable option for poor smallholder farmers (Tabo et al 2009; Twomlow et al., 2010). The small quantities of fertiliser required reduces the investment cost, yet this small investment can improve yield, reduce operation costs, improve resilience and is, overall, a relatively cost-effective method of precision farming (Twomlow et al., 2010). Despite this, farmers in sub-Saharan Africa often lack the finances to buy the adequate amount of fertiliser.

Information technology can help to make inputs available to farmers. Uganda's National Agricultural Research Organization and the University of Nebraska-Lincoln in the United States have developed a 'fertiliser optimisation tool'. This simple computer programme with information about local soil conditions allows farmers to enter the amount of money they can invest, field size, local cost of fertiliser and the market price of their crop. The programme calculates how much fertiliser they should use to get the best return on their investment. Originally developed for farmers in Uganda, the market has expanded and the tool is now being tested in Kenya, Rwanda, Malawi, Zambia, Ghana, Mali, Burkina Faso, Ethiopia, Mozambique, Tanzania, Niger, and Nigeria. There also are efforts underway to develop a version of the tool that can be accessible via mobile phones (AGRA, 2014).

Hub agrodealers that distribute seed and also provide training and advice on agricultural best practice can reduce the physical distance farmers must travel to access seed and extension services, thus making inputs more accessible. For example, the Rural Agricultural Market Development Trust (RUMARK), a grantee of the Alliance for a Green Revolution in Africa (AGRA), trains agrodealers such as Flora Kahumbe, who owns two agrodealer shops at the south end of Lake Malawi. She has been trained in the proper storage of seeds, fertiliser and chemical pesticides as well as their safe and appropriate application to achieve maximum effect. Flora is also a private extension agent providing valuable knowledge to farmers on how to make the most out of the inputs she sells (Montpellier Panel, 2014).

Microdosing requires relatively little equipment or technical skill compared to other methods such as CA and Integrated Pest Management, and is often seen as a good 'gateway' method to encourage farmers to use more sustainable farming practices. In contrast, it has also been noted that microdosing is time consuming, laborious and sometimes difficult to ensure each plant gets the right dose (ICRISAT, 2009). For example, if too much P is applied, it can lead to poor germination due to seed burning and or excessive water absorption by the seed (Buerkert and Schlecht, 2013). However, in sub-Saharan Africa, the opposite is more likely to occur as smallholder farmers mixing fertiliser with seed attempt to mix very little (0.9-1.8kg) in order to save money and plant as vast an area as possible. Buerkert and Schlecht (2013) found the amount of fertiliser applied through microdosing to be less than the recommended level – 9kg of available P (otherwise referred to as P2O5) per hectare was found to be essential to obtain optimal improvement of millet production. In the long- term, this could lead to continued nutrient depletion in the soil (Camara et al., 2013). Therefore, even if small quantities are required, the best results will be achieved when the inputs are affordable and applied in the correct volume.

One innovation to save time in the application of microdoses is the "top-dressing stick," designed by One Acre Fund, which helps their farmers use the inputs they buy more efficiently. The top-dressing stick is simply a pointed spear with a nail fixed in a perpendicular fashion just before the spear (Fig.3). The spear creates a hole in the ground where the fertiliser can be placed and the nail helps to measure the distance the fertiliser should be placed from the crop (ICRISAT, 2009).

Top-dressing stick. Credit: A4I

Seed spacing

Smallholder farmers produce an estimated 80% of the food in developing countries (Nwanze, 2011). Most smallholder farmers have little access to power or inputs, and rely upon rudimentary tools. The application of inputs, such as seeds, water, fertiliser or pesticide, is often imprecise. Precision agriculture has emerged as an approach to apply inputs at the right place and rate in the field, and as close as possible to the optimum crop growth stage. One such method of precision agriculture is **correct seed spacing**. Seed spacing is the distance between seeds in a given row and the distance between rows.

Figure 32: Farmers learning to use marked string to ensure proper seed spacing. Credit, One Acre Fund.

Whilst traditional sowing methods in sub-Saharan Africa, such as manually dropping seeds into soil or dibbling (making small holes with a stick and dropping in seeds by hand) allow for each seed to be placed in a row, broadcasting is the sowing of seeds across an area by scattering. Germination rates tend to be poorer with broadcast planting, and farmers may try to compensate by using more seeds. Yet, higher seeding rates typically result in more money spent on seed inputs without the gain in yield. Poor seeding rates from broadcast planting normally result from poor seed to soil contact, seeds being covered too deep, predation from birds and small mammals or the crowding out of plants. Seedlings can be of poor quality due to a high population of weeds and competition for available moisture.

In contrast, planting seeds in rows or straight lines by drilling or dibbling enhances yield potential and improves convenience for activities such as weeding, nutrient application or harvesting. An east-west row orientation is preferred to maximize light absorption, but this is not always possible. In many cases the shape, terrain and slope of the land, as well as other barriers, dictate the row orientation (CropsReview.com, 2015). An alternative to row planting is sowing seeds in a random but well-spaced manner. A study in Zambia found that women using the Chintipantipa method (a Lamba word used to describe a traditional method of planting crops in a random or haphazard manner) are able to plant sorghum and groundnuts in a regular and reasonably equidistant way (Russell, 1997).

Contribution to Sustainable Intensification

The more spatially uniform a crop is planted, the better the crop grows and the easier weeds are suppressed (Griepentrog et al, 2009). “Clumping” (the uneven clustering of plants in some areas with other areas left relatively sparse) can decrease the amount of nutrients available to each plant due to competition from its neighbours. Where there are large gaps between plants, weeds can grow more readily and compete with the crop species.

The correct spacing of seeds is the prerequisite for other **Ecological Intensification** methods, such as **microdosing** or **multiple cropping.** Water and fertiliser **microdosing** cannot easily occur if seeds are broadcast, as it is harder for farmers to apply inputs. **Multiple cropping** also cannot occur when seeds are randomly placed, as the method requires that seeds be planted in rows. Planting seeds at the correct spacing allows for land to be used most efficiently as crops are given the necessary access to nutrients. This in turn, increases the overall yield with a minimum seed input requirement. Farmers can maximise their profits though an increased yield and reduced input costs.

Figure 33 Row spacing in a wheat field. Credit, ILRI.

Benefits & Limitations

Reduced competition for sunlight
Correct seed spacing allows for crops to receive the maximum light exposure by reducing the excessive shading of other plants that occurs when seeds are planted too close to one another. This allows for more efficient photosynthesis and improved crop yield. Sweet potato yields can be affected significantly by shading. One study showed that the mean number of tubers per metre was 17 in direct sunlight, decreasing to 14 in 31% shade, 13 in 43% shade, 10 in 52% shade and just 2 in 67% shade. Shading also increases the number of days it takes for tuberous roots to develop, from 36 days in full sunlight to 49 days in 67% the shade (Mwanga and Zamora, 1988).

Reduced competition for nutrients
Correct seed spacing reduces competition for soil water and nutrients. Yet, different plant species require different spacing to optimise their nutrient's uptake. For example, maize can develop roots, which grow to more than 2m deep, but the main branched system, where 80% of water and nutrient uptake occurs, is located in the first 0.8m. Rainfall levels and patterns as well as any irrigation practices adopted all affect the depth and rate of root growth. In addition to soil water and nutrient status, root development is strongly influenced by textural and structural stratification, salts and the level of the water table.

Increased access for crop management
Row planting allows easy access between rows, which facilitates weeding, cultivation and other operations, including hauling. When seeds are broadcast, it is not easy to weed between the seedlings, cultivate or remove crops when they are ready for sale. The increased access that row planting offers also allows for close inspection of individual plants, making it easier to track pests and disease. Finally, it is easy to

count the plant population in a given farm area when planted in rows (CropsReview, 2015). Chintipantipa does not create the rows that facilitate cultivation, but crops are still well spaced so easier to access compared to broadcasting.

Yields
Correct seed spacing often results in higher yields, and the correct spacing required depends on the crop (Box 8). A study in Ethiopia found that when farmers planted teff seed in rows at a low seed rate, yields increased on average by 70% compared to the national average (Vandercasteelen et al, 2014). In contrast, increasing the number of maize seeds planted from the traditional 4,000 seeds per hectare up to 6,000 seeds per hectare increased the yield by 30%. Decreasing the maize row spacing from the traditional 90cm to 45cm resulted in an 11% higher yield (Fanadzo et al, 2010). In comparison, neither groundnut nor sorghum trials in Zambia showed that row planting produced higher yields than the Chintipantipa planting method. Despite appearing haphazard, the amount of seed used and the final plant population achieved by the Chintipantipa planting method was in fact very similar to that achieved by row planting (Russell, 1997).

Row planting for Systems of Rice Intensification


Figure 34: SRI dryfield in Mali. Credit, IP CALS at Cornell University

The System of Rice Intensification (SRI) is an evolving set of practices, principles, and philosophies aimed at increasing the productivity of irrigated rice by improving the management of plants, soil, water and nutrients, for example by increasing the space between rice plants (IRRI, no date). With SRI, the soil is kept alternately dry and wet, allowing the plants' roots to take oxygen from the ground surface. Seedlings are transplanted very young, in square patterns to allow enough spacing between the rice plants. These measures enhance the roots' growth and increase yields. The Better U Foundation and Africare set up a project to assess the performance of SRI during the 2008-2009 growing season in 12 villages in the Dire and Goundam administrative circles of north central Mali.


Figure 35: SRI Seed spacing and weeding. Credit, World Bank

At the time, 19,000ha of land were under rice cultivation across the 12 villages managed by 17,200 households. Africare supplied each village with 2 rotary weeders and 1 field agent for every 15 farmers for technical support. SRI seedlings were transplanted 10-12 days after germination. In the control plots, seedlings were transplanted on average 29 days after germination with 2 to 5 seedlings in each pocket.

Across all 12 villages, the results showed a yield improvement and cost benefit for adopting SRI. Seed usage decreased from 50kg per hectare to 6kg per hectare. Performance varied according to soil types, rice varieties, fertiliser regimes and weeding practices, but the average SRI yield for the 53 farmers who used the practices as recommended was 9.1 tonnes per hectare, 66% higher than the average for the control plots at 5.5 tonnes per hectare. The average yield on neighbouring rice fields where non-participating farmers used their own methods was 4.86 tonnes per hectare.

Figure 36: Malian farmers sowing rice. Credit, Cornell University

SRI also has limitations. For the participating farmers, labour increased from 161 to 251 person days and input costs were higher, increasing from CFA414,650 ($714 US) in the control group to CFA476,580 ($820 US) for SRI. On the other hand, the net revenue from SRI more than doubled: CFA1,024,920 ($1765 US) per hectare for those that adopted SRI compared to CFA491,200 ($846 US) per hectare for the control plots (Africare, Oxfam America and WWF-ICRSAT, 2010).

Technical local knowledge requirements

Root depth and distribution requirements for each plant is determined by a number of factors, including soil type (such as maize roots avoid sandy layers in soils) and soil moisture (for example, in dry years roots will typically grow wider and deeper searching for water) (Nicoullaud et al, 1995). Farmers need the right technical knowledge to be able to sow seeds efficiently and increase their yield by reducing plant and weed competition. Yet, in order to do this, farmers need access to **training** and **extension** services to help them better understand their crop requirements. **Soil testing** can also help farmers to better understand their soil properties. Farmers will also need access to training for row planting in particular, to help them better understand how to make the most of their field space.

Figure 37: A field in Milani, Kenya, ready for maize planting. Ties on the planting string indicate the new spacing for where the farmers should dig holes for their

Labour requirements

Broadcasting is the easiest of all sowing strategies, as all that is required is for farmers to scatter the seeds across their fields. However, broadcasting increases the weeding labour time due to the “clumping” of plants that almost always occurs. Monitoring crop health or targeting inputs also prove more time consuming than with uniform row planting. Row planting reduces the amount of weeds that grow compared to broadcasting, lowering weeding labour time. It also reduces the amount of time needed to apply inputs and facilitates the use of microdosing, which has multiple environmental and economic benefits. Despite this, row planting is the most labour intensive sowing strategy in sub-Saharan Africa.

In developed countries, drill-seeding technology is available to help farmers mechanically place seeds into the soil. In sub-Saharan Africa, whilst the use of a hand hoe is the standard procedure for maize planting, less than 5% of land under cultivation in Africa uses more advanced mechanisation such as jab planters, rotary injection planters or ploughs for planting seeds (Scheidtweiler, 1999). Jab planters reduce the labour time for planting from 7.5 days per hectare with hand planting to 2 days per hectare (Arthur D. Little Inc. and Meridian Institute, 2010). Jab planters make a hole in the ground and plant the seed (and, in some models, seed and fertiliser) directly into it in one operation. This is more time efficient than dibbling and requires less labour than digging planting basins with a hand-hoe. However, jab planters cost about US$30 for a high-quality planter that usually lasts 3 years, which may discourage farmers from investing in the technology (Arthur D. Little Inc. and Meridian Institute, 2010).

An alternative simple technology uses string (called a teren rope in Zambia) in which knots or bottle caps are tied at the desired plant spacing distance to act as a guide for accurate spacing. The strings can be used again in following seasons. Marking out the correct spacing of rows gives the best plant population (IIRR and ACT, 2005). To plant crops in rows, holes for the seed are dug alongside this planting rope. After each row has been planted the rope must be moved over and the process repeated. This ideally requires two people, one at each end of the rope. Those farmers do not have the help required to use these method, may be reluctant to use this method as it is can be difficult to do alone (Russell, 1997).

Room for innovation

Soil testing both as a technology and in its accessibility to farmers require innovation, particularly around adequate and effective training by laboratory staff or extension workers and farmers to make simple diagnoses (FAO, 2000). Also needed is investment in infrastructure that can support either the development of local laboratories or make portable testing more accessible for remote farms to reduce in the time it takes to communicate soil test results from laboratories to farmers - in many countries, delays of up to 6 months in forwarding the results and recommendations to farmers are common (FAO, 2000).

The Soil Care Initiative by Soil Cares Ltd, previously known as BLGG Kenya Ltd, for example have noticed that seed, fertiliser and extension provision in rural areas are generally not developed for the needs of smallholders. Further, in their efforts to bring soil testing to smallholders they have found that neither reaching them through a city hub nor going back and forth between the field and the laboratory works well. Instead they have developed indoor or in-car mobile laboratories through which farmers can collect a soil sample, get assistance in analysing it and receive the results on the same day. These labs can analyse around 75 samples per day for a price of less than 10 euros per sample. From the results, recommendations on farming practices are given to farmers based on a central database of information (Soil Cares Ltd, No date). Bringing soil testing to more farmers is needed, but support is also required for translating these results into appropriate action. Often advice is given in terms of what fertiliser will be the most beneficial. While prudent use of inputs can be hugely beneficial, a better understanding of fertiliser alternatives and which technique works best on different soil types and qualities is also needed.

Microdosing, which has the potential to increase the yields of crops, reduce environmental impacts and improve soil quality, is reliant on the accessibility of inputs. Farmers must be able to access affordable inputs even if only used in small amounts. Further, warehousing facilities need to be established to store surplus crops to sell when the market prices are in their favour. As with techniques to preserve natural capital the enabling environment is just as important as the techniques themselves.

Although a low technology approach, farmers report that microdosing is more time consuming than traditional broadcasting methods. There is a need to design and promote mechanized, low cost tools that can reduce labour time and costs (Tabo, 2005). ICRISAT is exploring the use of seed coating as one option to reduce labour costs as well as further reduce the quantity of fertiliser to be used (ICRISAT, 2012). Researchers at ICRISAT are also looking at packaging the correct dose of fertiliser as a tablet to aid its application. This is proving popular in Mali, Burkina Faso, and Niger (ICRISAT, 2009). Simpungwe et al., (2008) showed that farmers are more likely to try fertiliser if it is supplied in small, more affordable packages therefore fertiliser supplied in such packages, could better enable microdosing to be scaled-up and adopted more widely by smallholder farmers. More emphasis on product distribution and encouraging farmer adoption is needed to get these labour saving technologies to smallholder farmers.

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Diversification

Diversity – measured in its simplest form as species richness – is generally considered a key factor in maintaining relatively stable and resilient ecosystems (Mori et al., 2013). Agricultural systems are typically simplified from natural ecosystems to maximise the production of a limited number of crops or livestock but such simplification can make the system more vulnerable to external shocks and stresses.

Crop diversity in the world's food producing systems has largely been underutilised and the FAO estimate that out of a total of 300,000 plant species, 10,000 have been used for human food since the origin of agriculture. From this 10,000, only 150 to 200 species have been commercially cultivated and only four of these – rice, wheat, maize and potatoes – provide 50% of the world's energy needs. The intensification of agricultural production has led to a significant loss of genetic diversity of domesticated plants and animals, a diversity believed to be important for future food production and security in the face of climatic and other shocks (FAO, 2010).

Figure 38: Growth of several different crop species. Credit, G. Smith, CIAT.

Monocultures may produce greater yields by eliminating competition from other species and by selecting varieties based on their ability to grow well under specific conditions but this can result in crops that are unable to withstand changes to their environment, for example the weather. Such monocultures are also more vulnerable to diseases and insects and the effect is greater if the crops are genetically uniform and concentrated in one area. Without genetic diversity there is a lower likelihood that the crops will be resistant to pathogens or tolerant of fluctuating conditions in the population. Aside from genetic diversity within a plant species, crops also rely on a host of other species such as insects, birds, and bacteria for their survival (Harvard, 2015).

Diverse agroecosystems, when species present are not in direct competition, can have multiple benefits, including greater resilience and increased provision of ecosystem services (Foley et al., 2005). Diversified Farming Systems (DFS) intentionally include functional biodiversity in order to maintain ecosystem services (Kremen et al., 2012), such as soil fertility, pest and disease control, water use efficiency, and pollination.

Within agroecological systems relationships between species can take different forms and different species can benefit each other. Trees and shrubs provide shade for herbs, legumes provide nitrogen essential for plant growth, and livestock furnish manure. Mixtures of crops can provide for a diverse and healthier diet, deter pests and during times of crises such as drought, or a cyclone can provide a form of insurance that at least one crop out of many will survive. Merely increasing the number of crops and livestock on a farm, however, may not necessarily create the ecological heterogeneity and biotic interactions to support the full suite of ecosystem services needed for productive agriculture (Zhang et al., 2007; Shennan, 2008). Studies investigating the relationships between diversity, stability and resilience have found that it is not the sheer number of species present that affects stability and resilience, but their nature, their function in the systems, and the relationships they have with one another (Begon et al., 2005; Ives and Carpenter, 2007).

Diversifying an agricultural system can take many forms such as intercropping, agroforestry and integrated pest management, and although here we focus on ecological intensification, farms can also diversify their income streams and productive activities, a form of socio-economic intensification addressed in a separate brief.

Intercropping

Intercropping, is the practice of growing two or more crops together on a given piece of land (Montpellier Panel, 2013). It works by balancing key ecological processes – competition, on the one hand, and commensalism (one plant gaining benefits from the other) or mutualism (both plants benefitting each other) on the other (Vandermeer, 1989). Typically, crops in a field will be planted as close together as possible in order to utilise all the available land, but not so close that the yields are diminished by competition. When different crop species or varieties are grown together, the competition may be fierce; trees grown in a maize field, for example, may shade out the crop. This can be compensated for - the tree may be a legume and provide nitrogen for the crop plant beneath, an example of a commensal relationship.

There are numerous examples of intercropping, including mixed cropping, rotations, agroforestry, sylvo-pasture and green manuring defined below (Montpellier Panel, 2013):

Figure 39: Intercropping in Mozambique. Credit A4I

- **Mixed cropping:** interspersion of different crops on the same piece of land, either at random or more commonly in alternate rows usually designed to minimise competition but maximise the potential for both crops to make use of the available nutrients, such as N supplied by a legume.
- **Rotations**: the growing of two or more crops in sequence on the same piece of land.
- **Agroforestry**: annual herbaceous crops are grown interspersed with perennial trees or shrubs. The deeper-rooted trees can often exploit water and nutrients not available to the crops. The trees may also provide shade and mulch, creating a micro-environment, whilst the ground cover of crops reduces weeds and prevents erosion.
- **Sylvo-pasture**: similar to agroforestry, but combining trees with grassland and other fodder species on which livestock graze. The mixture of shrubs, grass and crops often supports mixed livestock.
- **Green manuring**: the growing of legumes and other plants to fix N and then incorporating them in the soil for the following crop. Commonly used green manures are *Sesbania* and the fern *Azolla*, which contains N-fixing, blue-green algae.

Contribution to Sustainable Intensification

Figure 40 Root nodules are evidence of Nitrogen-fixing bacteria.

Diversification of farm production through intercropping can, if carefully planned, boost yields, reduce pest and disease outbreaks, increase whole system resilience, and support the provision of ecosystem services such as nutrient and water retention in the soil. Intercropping can provide a more efficient use of resources, such as soil nutrients and light that would not otherwise be utilised by a single crop. It can provide support or shade for a companion crop, host a great diversity of beneficial insects, bacteria and other organisms or provide new sources of food, feed or fuel. These multiple benefits can make agriculture more sustainable and productive, a so-called win-win. Beyond farm productivity and resilience, intercropping can provide a more nutritious diet, if crops grown on-farm are consumed by the household, and provide alternate and additional income sources for households, spanning both ecological and socio-economic benefits.

Benefits & Limitations

Boosting nitrogen and yields

The diversification of agricultural production is often thought to be at odds with intensive farming, producing lower yields and thus incentivising the conversion of additional land to farming (Jackson et al., 2007; Tittonell and Giller, 2013). Greater on-farm biodiversity can cause competition between wild species and crops, reduce the land under highly productive crops, whilst practices to enhance wild species populations take land away from agriculture in general (Phalan et al., 2011). In developing countries and for smallholder farmers, however, intercropping can significantly increase yields without the environmental and economic costs associated with conventional monocultures (Altieri, 2002; Gliessman, 2007; Chappell et al., 2011; Noltze et al., 2013). In an assessment of 286 projects introducing sustainability measures, including diversification, to (mainly) small-scale farms in developing countries, yields increased by an average 79% for a variety of farming systems and crop types (Pretty et al., 2006). Indeed where farmers are unable to buy inputs such as nitrogen fertiliser, integrating plants that make nitrogen available to other crops can be an accessible way for farmers to boost yields.

The key to high yields is the presence of nitrogen in the soil. Organic nitrogen can be boosted by encouraging the growth of certain microorganisms, or more directly by applying plant and animal manures (Box 9). Several kinds of bacteria, and other microorganisms such as blue-green algae, take up nitrogen from the atmosphere and convert it to ammonia, which can be used by plants. Some of these microorganisms are free living in the soil, although they are often associated with the root zones of plants and their growth can be stimulated by certain crops. However, the best practical results have come from exploiting nitrogen-fixing microorganisms that live symbiotically in plants (Conway and Pretty, 1991).

Best known of the symbiotic, nitrogen-fixing microorganisms are the bacteria living in the root nodules of legumes called rhizobia, which can fix 100 to 200kg N/ha/yr. The fertilising properties of legumes have been recognised for thousands of years. One of the earliest of the world's cropping systems – dating to soon after agriculture began in the valleys of Central America – was the interceppingof maize and beans; the seed of both crops often placed in the same planting hole. It is a practice that in various forms, continues today. For example, when cowpeas are cropped together with maize, the bacteria in cowpea root nodules can provide 30% of the nitrogen taken up by maize (Agarwal and Garrity, 1987). Cowpea and another legume, lablab, are particularly useful in land with low productivity potential. Cowpeas are adapted to acid, infertile soils, while *lablab* is drought tolerant, produces good fodder, and can re-grow well after clipping.

Another way to capture legume nitrogen is by rotation of crops – inserting a legume such as alfalfa, clover or a bean – between cereals. In the United States, a variety of alfalfa, known as *Nitro*, bred for this purpose can contribute up to 100kg N/ha to a following maize crop (Bares et al., 1986; Yamoah et al, 1986). The deliberate incorporation of legume crops in the soil, known as green manuring, is another practice of great antiquity, yet with considerable unexploited potential today. In Bolivia, when a local lupine, *Lupinus mutabilis,* is intercropped or rotated with potatoes fixes 200kg of N/ha/yr, minimising the need for fertilisers and, incidentally, reducing the incidence of viral diseases (Augstburger, 1983).

Intercropping nitrogen-fixing shrubs in Rwandan coffee farms

The shrub *Tephrosia vogelii* can grow very quickly, up to 4 metres high, fixes nitrogen and can be used as green manure (World Agroforestry Centre, 2015). In Maraba, Southwest Rwanda, coffee productivity is constrained by poor soil fertility and lack of organic mulch.

Figure 42: New coffee trees with Tephrosia vogelii. Credit, James Steakle

A 2-year study on 8 smallholder coffee farms trialled the effect of intercropping *Tephrosia* and coffee. The mulch produced from *Tephrosia* was also used on the coffee plots. In the first year, *Tephrosia* intercropped with coffee produced 1.4–1.9 tonnes per hectare of biomass and added 42kg–57kg of Nitrogen per hectare. This treatment increased coffee yields by 400kg–500kg per hectare, compared to traditional management methods. In the second year, *Tephrosia* produced between 2.5 tonnes and 3.8 tonnes per hectare of biomass and added 103kg-150kg of Nitrogen per hectare. This increased yields of coffee by 400kgper hectare.

Over the 2-year study, coffee yields increased between 23% and 36%. *Tephrosia* mulch was 87% as efficient as inorganic fertiliser used under similar conditions, and represented a saving of 30 days of labour hours per hectare compared to current farmer management through reduced labour required for weeding. Together the labour savings and the improved yields translated into the farmers producing 5kg of coffee per labour-day, compared to 3.4kg per labour-day under traditional management (Bucagu et al, 2013).

Nutrition

Growing a diverse variety of crops is also thought to be critical to nutrition, particularly where households grow the majority of the food they eat. Undernutrition occurs when people do not eat (or absorb) enough nutrients to cover their needs for energy and growth. Micronutrient deficiencies, a sub-set of undernutrition, occur when the body lacks one or more micronutrients (for example iron, iodine, zinc, vitamin A or folate). These deficiencies usually affect growth and immunity but can also cause conditions such as anaemia (iron deficiency) or hypothyroidism (iodine deficiency) (Burgess and Danga, 2008). An estimated 805 million people around the world are thought to be undernourished, whilst those with micronutrient deficiencies, also termed hidden hunger, may number more than 2 billion (WFP, 2014; Kennedy et al, 2003).

It is likely that the greater the diversity of species you eat, the more likely you are to fulfil your diverse nutritional needs. Although the direct link between agricultural biodiversity and human nutrition is generally difficult to make, the nutritional importance of a diverse diet is now widely recognized (WHO/FAO, 2003; DeClerck et al., 2011). In developing countries, for example, this can mean integrating local crops with staple crops supplemented with wild-harvested species (Fanzo et al., 2013

Home gardens

Figure 42: Traditional home garden in Indonesia

Home gardens are traditional intercropping systems that provide subsistence, opportunities to commercialise products, and serve multiple environmental and social functions by combining agricultural crops with tree crops and livestock (Soemarwoto and Soemarwoto, 1979). Home gardens are typically characterised by a great diversity of useful plants and livestock in a small area, cultivated in intricate relationships with one another. On the island of Java, Indonesia, home gardens called *pekarangan* are particularly well developed. The most extensive areas of home gardens in Java and the most intensive cultivation occur below an altitude of 800m where the dry season is short or absent (Terra, 1958). Usually taking up little more than half a hectare around the farmer's house, home gardens contain a huge variety of plants for food, medicine, condiments and spices, and

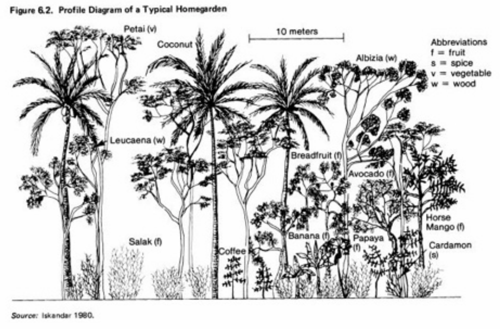


Figure 41: Home garden structure. Credit, Iskandar 1990

feed for livestock and fish stock. Much of what is produced is for household consumption, whilst some is sold at local markets (Soemarwoto and Conway, 1991).

Although most common across southern and Southeast Asia, successful home garden training programmes have been instituted in Niger, Somalia, Ghana and Kenya under the leadership of the FAO's Nutrition and Consumer Protection Division alongside supportive networks of national extension, research and training institutes and NGOs (FAO, 2010).

Figure 43: Home garden in Indonesia. Credit, Indonesia.org

The home garden may be capable of producing a large and varied harvest, contributing to food and nutrition security, but the returns are often small and typically insufficient to bring people out of poverty as a stand-alone method (Conway, 2012). In this case, however, promotional forums, campaigns, recipe booklets and cooking demonstrations teaching the nutritional value and varied uses for these vegetables changed seasonal planting methods to demand-driven and time-scheduled production to meet increased market demand. Farmers also received business support, reliable access to improved quality seed, and linkages to both formal and informal markets. The demand for AIVs grew by 135% over the 2-year project in Kenya and an estimated 9,000 tonnes of vegetables were sold delivering earnings of Ksh80 million (US$800,000) from informal markets and Ksh150 million (US $1.5 million) in formal markets (Conway, 2012).

In India, evidence suggests that smaller farms find it more necessary and or profitable to diversify, particularly where the crops grown are selected based on household food needs (Jha, 2001). National agricultural censuses indicate that on small farms (< 2ha) farmers grow mixes of seasonal crops, fruits, and vegetables, dairy cattle, and poultry in order to maximize household-labour utilisation and income. The wider benefits have been greater food security, increased rural employment, and in some cases, improved soil fertility and lower pest incidence (Singh et al., 2002).

Planning and managing multiple crops

Care must be taken when growing different crops together, however. Certain insect pests and diseases may spread easily from one crop to the next through crop residues. Markets may not exist for new crops, as part of the rotation and managing rotations requires more skill than those for a single crop. Care must also be taken to plan the timing, spacing and mixture of crops so that the balance between competition and commensalism or mutualism is enhancing. Farmers may therefore be reluctant to try out new crops that they are not used to growing or eating (FAO, No date). Although intercropping is a form of intensification that is broad in its geographic applicability, it requires knowledge and skill as well as learning from mistakes.

Figure 44: MBILI farm in Kenya. Credit, Sara Costa

MBILI Intercropping

Farmers in Western Kenya traditionally row-crop maize with nitrogen-fixing legumes to increase yields and soil fertility. Nitrogen is returned to the soil from the falling leaves and decomposing roots of the bean plants. Researchers at the Sustainable Agriculture Centre for Research, Extension and Development in Africa (SACRED-Africa), noticed that the single rows were not providing enough light for the legumes, and that the second maize crop often failed due to insufficient late rains. To address these constraints, they pioneered a new system known as MBILI (Managing Beneficial Interactions in Legume Intercrops), meaning "two" in Swahili. MBILI consists of intercropping double rows of maize and legumes, allowing for better light and soil conditions, whilst maintaining the same plant populations. The system yields nearly 3tonnes of maize and more than 500kg of legumes per hectare.

MBILI has been shown to increase production by 26% - 37% in the short rain season and around 7% in the long rain season. The greatest improvement is noted in groundnut which can increase by 101% compared to conventional conditions. Farmers earn an average of 31,689 KSh (US$325) per hectare using MBILI intercropping, compared to 26,333 KSh (US$270) with conventional methods (Woomer et al, 2004).

Intercropping, as with many multiple-element systems of farming, can have different results under different soil, resource and climatic conditions. Understanding which combinations of crops to use where and when is difficult, as is communicating these findings to large numbers of farmers. Opportunities to diversify agricultural production depend on a variety of factors from access to knowledge, extension, seeds and crop varieties to market conditions such as changes in consumer demand, market prices, government policy, trade opportunities and rural infrastructure. Conversely these factors can be barriers to farmers' ability to diversify or can limit the pool of crops that can be grown. In general, intercropping, given its adaptability and variety of forms, is relatively accessible to most farmers, despite their different needs, different levels of wealth and different locations, in comparison with more cutting-edge technologies (Singh et al., 2002).

Agroforestry

Agroforestry is a form of intercropping in which annual herbaceous crops are grown interspersed with perennial trees or shrubs. "Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence" (Lundgren and Raintree, 1983).

Figure 45: Agroforesty in action. Credit CCFAS

The deeper-rooted trees can often exploit water and nutrients not available to the crops. The trees may also provide shade and mulch, creating a micro-environment, while the ground cover of crops reduces weeds and prevents erosion. The growing of crops and trees together in food systems is an ancient practice, one that receives political popularity in international policy today with regards to maximising production from increasingly scarce land while maintaining ecosystem services (Nair, 1993). Zomer et al., (2014) found that agroforestry (agricultural land with greater than 10% tree cover) currently makes up 43% or more than 1 billion hectares of global agricultural land. 190 million hectares are in sub-Saharan Africa. Given such a broad definition and scope it is not surprising that there are many different forms of agroforestry practiced for a variety of reasons.

Agroforestry systems can be classified in a variety of ways most commonly by their structural characteristics, for example silvopastoral (trees with animals) or agrosilviculture (trees with crops), and agrosilvopastoral (crops, animals and trees) systems. Another classification is that by Torquebiau, 1990:

1. Alley Farming (hedgerow intercropping)
2. Crops under tree cover
3. Pastures and animals under tree cover
4. Agroforests (live fencing, boundary planting, windbreaks, shelterbelts)
5. Sequential technologies (shifting cultivation, improved fallow)
6. Other technologies (aquaculture and apiculture with trees). (Torquebiau, 1990; Tripathi & Psychas, 1992).

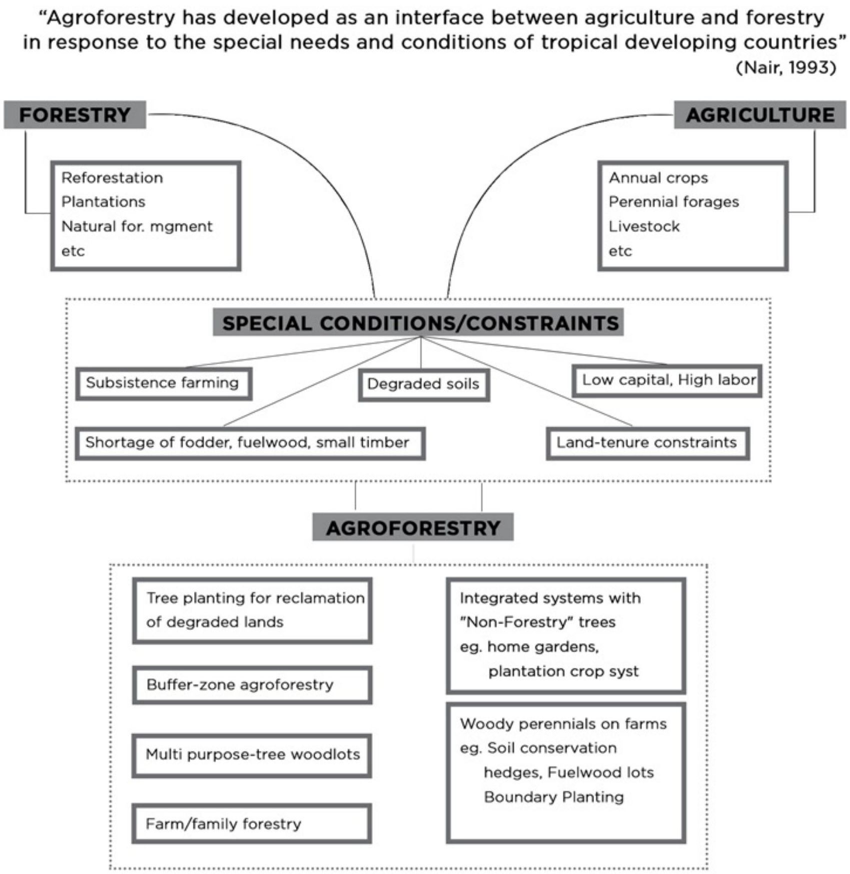
Four characteristics are used to distinguish agroforestry from other farming or forestry practices, all of which must be satisfied for a land use practice for be defined as agroforestry.

1. Intentional: The combination of trees, crops and or animals is designed and managed as a whole system as opposed to managing elements separately.

2. Intensive: The whole system is managed to maintain or increase productivity including such actions as cultivation, irrigation and fertilization.

3. Interactive: Relationships between trees, crops and animals are manipulated to enhance the production of at least one element at the same time as preserving natural capital.

4. Integrated: Trees, crops and or animals are horizontally or vertically, temporally or spatially combined within one management unit (Association for Temperate Agroforestry, No date).



Some of the most commonly practiced forms of agroforestry include:

- Alley cropping - crops and long-term trees such as oak or walnut grown in between each other in rows allowing enough space for the mature trees without over shading the crops.

- Forest farming – growing high-value forest products such as mushrooms, fruit, nuts, herbs and medicinal plants, alongside trees grown for their wood products. In both forest farming and alley cropping agricultural crops provide faster income while waiting for the trees to mature.

- Riparian buffer strips – trees or shrubs are planted along rivers or other water bodies to prevent soil, nutrients and farm inputs from running off the land into the water. In some cases the trees grown can also provide saleable products or habitat for biodiversity.

- Windbreaks or shelterbelts – trees and or shrubs are planted at the edge of fields to protect crops or livestock from wind, snow or extreme weather. Trees can also provide shelter or food sources for animals (Bamulabire, 2011).

The type of agroforestry system used and trees grown depends on factors such as the location, soil type, crops native to the region and climatic conditions. If an agroforestry system is to be successful the tree species must be chosen carefully depending on its intended use, suitability and cultural and social factors.

Contribution to Sustainable Intensification

The integration of trees on farms can have impressive benefits for yields, resource use and conservation, bringing both environmental and economic benefits. Such systems can improve farm profitability through increasing the total output per unit area (when the tree/crop/animal combination is greater than a single component alone); increase the productivity of crops and livestock by providing shelter and nutrients; and increase the financial diversity of the farm and its ability to withstand and adapt to new conditions (Shibu, 2010). Trees themselves can also be a long-term investment. Agroforestry also helps to conserve and protect natural capital by, for example, limiting soil erosion, and creating wildlife habitat. Care must be taken, however, to ensure trees do not result in losses in crop production and on-farm economic losses that can motivate the conversion of natural habitats to crop production elsewhere.

Benefits & Limitations

Enhanced resource utilisation and yields

The presence of trees and shrubs can aid crops in making better use of soil nutrients and light or provide new sources of nutrients as the tree roots reach deeper into the soil horizon (nutrients absorbed by the tree are returned to the soil in leaf litter), resulting in better production in comparison to a single crop. With nutrient cycling in the soil enhanced, weed and pest control can reduce the need for external inputs such as herbicides and pesticides. Where trees are leguminous, soil fertility and crop yields improve due to additional nitrogen being made available (Box 13). In a mid-hill region of Nepal, well-established agroforestry systems and the dominant conventional monocropping system were compared in terms of their soil properties.

The study found significant differences in soil pH, aluminium content, organic matter and nitrogen content between the two systems, agroforestry systems having a higher soil quality and more fertile soil conditions (Schwab et al., 2015).

Beyond the soil, trees can have multiple benefits that provide a better growing environment for crops and animals, allowing them to become more productive. Shrubs and trees can act as wind barriers protecting crops and livestock from weather extremes, harsh climatic conditions, and soil and water erosion. Trees can also function as "bio filters" of dusts, noise and odours, as well as provide a food source and shelter for livestock (Bamulabire, 2011). Agroforestry systems can also be managed to provide vegetative material that can be used as mulch, protecting the soil from erosion, desiccation and heat (Conway, 2012). On experiment stations at the International Institute of Tropical Agriculture (IITA), fast-growing species such as *Gliricidia sepium* and *Leucaena leucocephala* are grown in rows, with 4-metre-wide "alleys" left in between for the annual crops (IITA, 1992). The trees provide nitrogen, organic matter through their leaf fall and prunings, food for livestock, fuelwood, and timber, vegetative material for mulch, as well as conserving soil and water (Box 12). Agroforestry has also been shown to increase both crop yields and food security (Sileshi et al., 2008; Akinnifesi et al., 2010; Garrity et al., 2010). Fertiliser tree systems cannot only boost yields and food access but enhance natural capital and improve the resilience of farms (Ajayi et al., 2011; Meijer et al., 2015).

Coffee-shade tree systems

Figure 46: Shade grown coffee in Costa Rica. Credit, Rainforest Alliance

In central Costa Rica, coffee trees are intercropped with *Erythrina poeppigiana* shade trees on steep slopes to reduce soil erosion. The shade trees reduce runoff and boost water infiltration into the soil. They can also enhance coffee production by protecting coffee trees against drought. However, introducing these trees into the system can have negative impacts such as harbouring pests and diseases transmitted to coffee trees or intercepting sunlight. Whilst yields are typically higher when grown in direct light, shade-grown coffee beans are larger, weighing 0.15g per bean as opposed to 0.13g per bean, and have a higher quality.

To maximise the benefits whilst reducing competition between the two species, CIRAD (Centre de coopération internationale en recherche agronomique pour le développement) worked with a local coffee cooperative to test a novel way of overcoming these challenges. By dividing the farmers into different typologies based on environmental conditions and socio-

Figure 47: Shade grown coffee. Credit, Rainforest Alliance

economic situations, researchers were able to create a model to provide recommendations tailored to farmers within each grouping. For example, because the plots of the "labour-intensive" and "shaded system" groups receive a lot of sunlight, they could plant more shade trees to control for erosion. In contrast, for “input-intensive” and “extensive” groups, whose plots receive less sunlight but more rainfall and humidity, planting more shade trees would increase the risk of attacks by the fungus *Mycena citricolor*, that causes American leaf spot disease (Meylan et al, 2013).

The conceptual model helped analyze the key processes and trade-offs for each group and helped make recommendations of adapted erosion control practices. The model also showed that for some groups, less time-consuming erosion control actions such as building drainage canals, terraces or vegetative barriers that do not impact coffee production might be more suitable altogether. In contrast, using shade trees or manual weeding worked better to control erosion as opposed to herbicide use. Overall, the method of prototyping agricultural systems as they respond to different constraints can offer a basis for more productive discussions in **participatory research** programmes (Meylan et al, 2013).

Climate change and soils

According to the Intergovernmental Panel on Climate Change (IPCC), the majority of agriculture’s potential to mitigate climate change lies in improving the soils’ ability to sequester and store carbon (Smith et al., 2014). Trees are well-known for their ability to sequester carbon (C) from the atmosphere and, in Africa, although measures of C stocks and C sequestration vary widely across the continent, agroforestry systems have been found to be the third largest carbon sink after primary forests and long-term fallows (Mbow et al., 2014). Agroforestry systems, in general, have 3 to 4 times more biomass than traditional treeless cropping systems (Mbow et al., 2014). Whilst field measurements to validate agroforestry’s potential in mitigating climate change are limited, research has found agroforestry systems to sequester more C both above- and below-ground than treeless systems as well as to store more stable C in the soil (stores less likely to be lost to the atmosphere) (Takimoto, 2007). Similarly, in central Uganda, banana-coffee agroforestry systems were found to have higher C socks, C pools, SOM and nitrogen than banana monocultures, although other soil nutrients were not always higher under agroforestry, indicating care must be taken in making assumptions about soil quality under agroforestry (Zake et al., 2015).

In sub-Saharan Africa, 15% of farms have tree cover of at least 30%. Across the whole continent, Unruh et al*.,* (1993) found that a total of approximately 1.5 billion hectares are suitable for some type of agroforestry. This indicates that there is significant potential in Africa for sequestering carbon while maintaining, or even boosting, production on farms. Agroforestry systems can also play a part in reducing pressure on natural forests for things such as timber and fuelwood and in providing sustainable energy options (Unruh et al., 1993). One tree in particular has received attention for its ability to sequester and store carbon while providing nitrogen and shade (Box 13).

Faidherbia

Figure 48: Faidherbia trees. Credit, World Agroforestry Centre

Faidherbia albida is a nitrogen-fixing Acacia tree that is widespread throughout Africa, growing in a variety of soils and climates. *Faidherbia* is able to make large quantities of nitrogen available to nearby crops and increase the store of carbon above ground and in the soil. It sheds its leaves in the wet season and retains them in the dry season, allowing for light to pass through in the wet season whilst providing residue in the dry season. As a consequence it is possible to plant and grow maize under the trees. Yields can reach more than 3 tonnes per hectare without fertilisers, depending on the amount of nitrogen fixed by the trees. The trees also contribute 2 tonnes or more per hectare of carbon to the soil and mature trees can store more than 30 tonnes of carbon per hectare (Zomer et al, 2014).

In Malawi, *Faidherbia* provided 300kg of fertiliser per hectare and boosted unfertilised maize yields from 2.5-4 tonnes per hectare, 200% to 400% more than national averages, when planted every 10 rows (New Agriculturist, 2010). In a survey of 300 farmers in the Dedza district of Malawi, those that grew *Faidherbia* did so in order to improve soil fertility on their farms (starting when the trees are 4 to 6 years old), did not use nitrogen fertiliser and were keen to grow more trees (Phombeya et al., 2005). In Niger, *Faidherbia* has been planted on almost 5 million hectares of land leading to similar benefits.

Figure 49: Faidherbia Albida. Credit, Green Knowledge Institute

The climate change mitigation potential for systems incorporating trees with fertilising properties lies in their ability to sequester between 2 and 4 tonnes of carbon per hectare per year, compared with 0.2-0.4 tonnes of carbon per hectare per year under conventional conservation farming systems (Makumba et al, 2007). However, *Faidherbia* trees take 6 years to fully develop, making investments hard to justify, particularly if land tenure is insecure and or farmers are dependent on immediate benefits and incomes. At present *Faidherbia* is grown on only 2% of Africa's maize area and 13% of sorghum and millet area (FAO, 2010).

Economic incentives and barriers to adoption

Whilst agroforestry systems can provide additional income streams to the farmer, combining long-term and seasonal sources of income, there are many challenges farmers and other institutions face in designing and implementing tree-based farming systems. As with other forms of diversification, labour needs, resource costs and risks can be high. Agroforestry requires high labour input (at least initially), the removal of land from crop production and carries the risk of introducing new species that may harm the growth, survival and reproduction of crop species. Trees can have negative impacts, for example, aiding the spread or introduction of (new) pests and diseases or motivating wildlife to feed on trees or crops of farms, in both cases causing economic losses (Parrotta et al., 2015). Trees may also reduce the profitability of farms if they fail to match the income achieved through crop production. It is also not enough for the tree crop to provide a soil and water conservation benefit alone as farmers usually look for extra direct income. Thus knowing which trees to grow is critical and these considerations or needed expertise can limit adoption.

Rogers and Shoemaker (1971) have identified 5 attributes of technologies that make them more likely to be adopted:

1) Relative perceived advantage
2) Compatability with local culture
3) Low technical complexity
4) Trialability
5) Observability

Integrating trees on farms, given the long-time frame over which the benefits of trees become reality, can be hard to trial and to observe and may, initially, reduce a farmer's perceived advantage (Raintree, 1983). In general, knowledge of the technology, the availability of seeds or seedlings and having the appropriate skills have been found to be important in supporting adoption, which indicates the need for adequate training, extension and education in agroforestry, but many other factors can affect the likelihood of adoption, and these are not well understood (Kabwe et al., 2009). Even when adopted, agroforestry may be abandoned after a period of time (Dahlquist et al., 2007). Meijer et al., (2015) pose that many studies relating to the barriers to adoption of agroforestry have focused on extrinsic factors such as the characteristics of the farmer, their environment and of the innovation itself, and greater emphasis needs to be given to the role of intrinsic factors in decision making such as knowledge, perceptions and attitudes. Several studies have indicated that intrinsic factors are important where farmers have been able to adapt the new technology to their own situation, they have been more successful and more likely to be adopted over the long-term (Mekaya et al., 2008). Perceptions of risk and uncertainty are also important with poorer farmers who may be less likely to adopt agroforestry systems than relatively food and resource secure individuals (Jerneck and Olsson, 2014). In 1981 the World Agroforestry Centre (ICRAF) designed a methodology entitled Diagnosis and Design (D&D) to implement, monitor, and evaluate agroforestry programmes. D&D, conducted on the scale of a land use system, is based on the principle that to design an effective intervention we first must diagnose what the specific problem is, thus taking into account local context and avoiding total system transformations, which can be unappealing to farmers (Avila and Minae, 1992; Raintree, 1987)

Integrated Pest Management

Pesticides tend to be expensive, hazardous and are often inefficient at controlling pests, due in part to the risk of resistance, ineffective use and because they also kill the pests' enemies that naturally control their populations. In response to this, Integrated Pest Management (IPM) was initiated in the 1950s, which utilises all techniques of controlling pests in an integrated manner that enhances rather than destroys natural controls. If pesticides are part of the programme, they are used sparingly and selectively so as not to interfere with natural enemies (Conway, 2012). IPM takes a judicious approach, using information on pest life cycles and their interaction with the environment to employ the most effective, economical and least environmentally damaging pest control methods. The aim of IPM is to use many methods to "effectively suppress pests below injurious levels and avoiding outbreaks."

In general, a four-step approach to IPM is advocated. Firstly *setting action thresholds*, or the point at which infestation by pests requires action. This involves a level of understanding about the size of an infestation at which crop damage becomes a problem. Secondly, pests are *monitored* and identified to ascertain when levels reach action thresholds and to account for organisms that are beneficial rather than requiring control. In the third step, *prevention*, cultural methods such as diversification or planting pest-resistant crop varieties are used as a first line of pest control. Lastly, control through chemical or mechanical means may be required if pest numbers reach action thresholds and preventative methods are not working or available (EPA, 2014).

The variety of methods employed under IPM can include:

- **Cultural methods**, which improve plant growing conditions on the basis that strong plants are better able to resist pest attack or disease, whilst minimising the suitability of the environment for pests and pathogens.
- **Physical methods,** which can involve physically removing pest individuals or at least preventing them from gaining access to crops by using

Figure 50: Biological pest control. Credit, Modernagriculture.ca

barriers, mowing or traps, for example.

- **Genetic methods**, such as pest-resistant plant varieties developed through conventional plant breeding or genetic engineering, or the use of genetic techniques on pest species such as releasing sterile males into the population.
- **Biological methods,** which involve the use predators, parasites and diseases of pests to suppress pest populations through either cultural methods to improve the populations of naturally occurring biocontrol organisms or augmenting the natural population with bought individuals or introducing a new species, a specific predator of the target pest, into the farm system.
- **Chemical methods**, which includes the prudent use of conventional pesticides, biopesticides or other chemicals to control pests and diseases. Different chemicals have different actions, specificities and levels of persistence in the environment.
- **Regulatory control**, which is the role of government in containing and preventing the spread of pests into one country from another through inspection, quarantine and destruction of materials (Penn State, 2015).

Contribution to Sustainable Intensification

The FAO promotes IPM as the preferred approach to crop protection, considering it as a "pillar of both sustainable intensification of crop production and pesticide risk reduction." IPM is a system of farming designed to be sustainable, providing a cost effective, environmentally sound and socially acceptable method of managing diseases, insects, weeds and other pest in agriculture.

IPM advocates the prudent use of inputs supplemented by ecological methods of pest and disease control in part to reduce or slow down the ability of pests and pathogens to develop resistance to pest control methods but also to reduce reliance on chemical pest control. Care must be taken in achieving balance between adopting more environmentally sustainable methods of pest control and maintaining productivity.

Figure 51: A farmer woman carrying an eco-friendly, organic pesticide dispenser for spraying cabbage crops. Credit, FAO.

Benefits & Limitations

Pest control with fewer pesticides

Diversification can help reduce pest infestations as well as crop disease. Crop rotations, for example, can reduce a pest population or pathogens in the soil by interrupting the continuous cropping of a host plant with a non-host plant from a different family. Reducing pesticide use can have a variety of benefits from lessening production costs and human exposure to harmful chemicals to preventing surface and ground water contamination and boosting microbial populations in the soil (Aktar et al., 2009). One of the most effective agronomic approaches of IPM is the "push-pull" system, which has built on ecological studies to create a polyculture agriculture that protects maize, millet and sorghum from two devastating pests: the stem borer insect and *Striga* weed.

Push-Pull

Figure 52: Push-pull in practice. Credit, ICIPE

One of the most effective agronomic approaches of IPM is the "push-pull" system, built on the concept of polyculture (agriculture using multiple crops in the same space), that protects maize, millet and sorghum from two devastating pests: the stem borer insect and the *Striga* weed. Push-pull entails mixing plants that repel insect pests ("push") and planting diversionary trap plants around a crop perimeter that attracts the pests away from the crop ("pull"). In the case of maize, millet and sorghum, the main cereal crop is intercropped with the forage legume *Desmodium*. *Desmodium* emits volatile chemicals that repel stem borer moths ("push") and attracts a natural enemy of the moths, parasitic wasps ("pull") (Rothamsted Research, 2015).

Figure 53: Farmer planting Napier grass in Kenya. Credit, ICIPE

In addition, *Desmodium* secretes chemicals from its roots that cause "suicidal" germination of *Striga* seeds before they can attach to the maize roots. To ensure further protection, farmers can plant a "trap crop," such as *Pennisetum purpureum* (also known as Napier grass) around the edge of the field, which attracts the moths, pulling them away from the main crop. The system was developed in collaboration with the International Centre of Insect Physiology and Ecology (ICIPE) and the Kenyan Agricultural Research Institute (KARI) in Kenya, and Rothamsted Research in the United Kingdom. As of 2010, 25,000 smallholders in East Africa are using push-pull systems. Adopting a push-pull system allows them not only to control pests but also to increase soil fertility, protect against erosion, reduce pesticide use and gain income from marketing *Desmodium* for animal fodder (Hassanali et al, 2008).

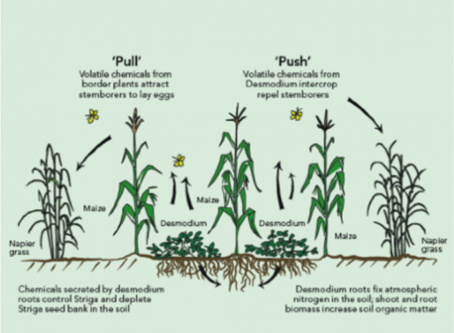


Figure 54: Push-pull infographic. Credit, Farming First

In 2014, Greenpeace researchers interviewed three sets of farmers in Kitale and Mbita, Kenya those practicing push-pull, those using pesticides, or those using neither approach. Although based on only a small number of interviews, average profitability per acre of maize per year was found to be 3 times higher for push-pull farmers than non-push-pull farmers, and this effect was even greater (up to 4 times more profitability) for women. Farmers also reported that maize yields often more than doubled compared to farmers that did not incorporate push-pull practices. In addition, push-pull farmers were also able to reduce their costs of labour and production (Curtis, 2014).

Knowledge-intensive and barriers to adoption

There is a need for farmers to use a more diverse combination of IPM approaches as many farmers rely too heavily on chemical controls alone (US EPA, 2014). IPM, as a holistic approach, has not been as widely adopted. Despite its ecological principles, it has remained until recently, a 'top-down' approach. IPM programmes have been designed by specialists and then instructions passed on to farmers. Farmer participation is thought to be key to IPM adoption and success but one assessment of the barriers to adopting IPM, conducted across 96 countries, found the top obstacle in developing countries to be the need for collective action in farming communities. While in developed countries the primary obstacle was reported as a lack of well-qualified and trained experts and extension agents (Parsa et al., 2014).

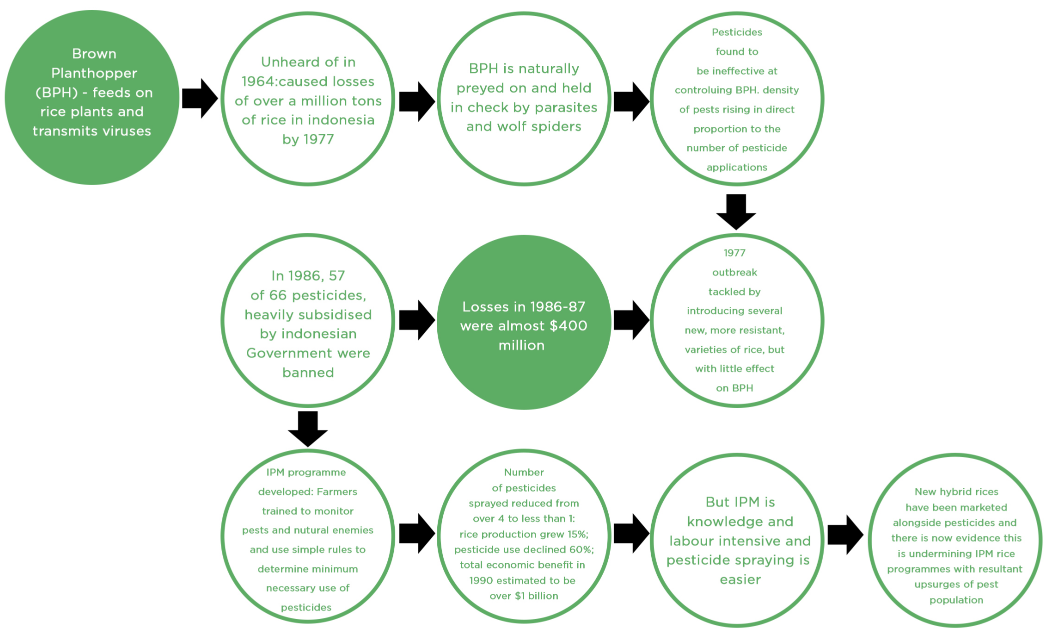
Expertise is certainly important. Pests and diseases are difficult to monitor, action thresholds difficult to estimate and the right combination of activities hard for individual farmers to prescribe. IPM is more complex than regular spraying, involving a relatively high level of skill and labour. Training programmes in IPM, however, have been relatively successful in exposing the degree to which farmers are aware and knowledgeable about pests, what controls them, and the benefits of IPM. Farmer field schools, in particular, which teach farmers how to recognise, monitor and control pest populations, have become the basis of farmer IPM groups and have spread from Asia to Africa (Pretty, 2005; van der Fliert, 1993). Nevertheless, it is often easier for many farmers to use pesticides despite the cost benefits of IPM and the likelihood that the blanket use of pesticides will fail in the long-term. Additionally, it is hard to break the habit of turning to pesticides when they are often heavily promoted or subsidised (Box 15) (Heong et al., 2014).

Controlling the Brown Planthopper in Indonesia
In Indonesia, efforts to control the brown planthopper (BPH) in rice have been hampered by both initial subsidisation of pesticides and also more recent marketing of pesticides with seeds (Fig. 4). BPH, a sucking bug that when present in large numbers can cause hopper-burn of the rice plants, transmit viruses and reduce yields. The BPH was virtually unknown as a pest before the introduction of new rice varieties,, such as those developed by IRRI in the period known as the green

revolution, but by 1977 the losses caused by BPH in Indonesia were more than 1 million tons of rice. Researchers at the International Rice Research Institute (IRRI) found that pesticide use was actually linked to BPH outbreaks (Kenmore, 1980), which destroyed the natural enemies that previously kept BPH numbers in check. The same pesticides were subsidised by the government at 85% of their cost. In 1986, the government acted on the basis of the mounting evidence implicating pesticides in the BPH outbreaks and a Presidential Decree banned 57 of the 66 pesticides used on rice and began to phase out the subsidy. Instead, IPM programmes were developed including farmer training resulting in pesticide sprays declining from 4 to 1 spray per season, an increase in rice production of 15% and a reduction in pesticide use by 60%, saving $120 million a year in subsidies. The total economic benefit in 1990 was estimated to be more than $1 billion (Kenmore, 1991). Today, market promotion and weak pesticide marketing regulatory frameworks have caused pesticide use to rise and BPH is once again a threat to rice production (Heong et al., 2014).

History of efforts to control the brown planthopper in Indonesia.

Controlling the brown Planthopper



Room for Innovation

Although an extremely old practice, new combinations of crops in new contexts do develop, driven by research organisations or farmers themselves. In the mountains of Xishuangbanna in China, for example, inhabitants in the highlands are unable to take advantage of the growing rubber industry (because rubber trees cannot survive more than 1000m above sea level). Tea is a traditionally grown crop but to cope with economic uncertainty, land shortages and environmental degradation in the area, villagers are now intercropping tea bushes with trees such as walnut. This recent innovation has been found to improve livelihoods (Leshem et al., 2010).

Given the challenges and risks faced by farmers who decide to intercrop, innovation is needed in the knowledge-sharing systems that can support its adoption. Knowing which crops to grow together, when and under what conditions is important. This is equally applicable to agroforestry systems where there is significant risk and long-term investment involved when deciding which tree species are appropriate. Finding ways to share and demonstrate this knowledge with farmers is equally important whether through farmer field schools, on-farm demonstrations or mobile technology. Innovation across research and extension institutions is also needed in order to move away from focusing on single crops and rather working across whole farm systems.

Similarly policies that support holistic farming systems are needed. In India, the National Agroforestry Policy, launched in 2014, is part of the country's target to increase tree cover in the country from 25% to 33%. India is the first country to have a national policy on agroforestry and hopefully the policy will support innovation in tree-based farming systems by simplifying regulations; incorporating agroforestry into all policies relating to land use and natural resource management; encouraging investment and facilitating coordination between stakeholders; and boosting private sector investment in agroforestry (CCAFS, 2014; Langford, 2014).

Individual elements of IPM are key sources of innovation – new, safer and more selective pesticides are continually being developed; more research on the pests themselves and their critical thresholds is undertaken; improved biocontrol agents and biopesticides are developed; and new varieties of plant species resistant to pest and disease attack are bred. Integrated Pest Management (IPM) is a prime example of holistic farming and faces many of the same barriers as other whole system farming methods. Knowledge sharing and transfer and education are difficult, as is the combination of disparate elements into a cohesive and effective whole, which can be both knowledge- and labour-intensive. Innovation in sharing information on IPM, in educating farmers and in implementing IPM is needed. Policies in support of fertiliser subsidies may undermine efforts to spread IPM, as policies that support intensive crop production may weaken efforts to diversify agriculture and therefore new policies or modifications to existing policies may also be needed.

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Conclusion

Sustainable Intensification is the pathway to increasing food production to feed a growing population while minimising or reducing the environmental footprint of farming. As one of the three pillars of SI, ecological intensification is about preserving natural capital, being precise in the use and application of resources and diversifying production to build environmental and economic resilience. Practices falling under ecological intensification are largely centred on the farm, on making it more sustainable and productive and on building or maintaining ecosystem services essential to both agriculture and outside the agroecosystem.

While ecological intensification shows considerable promise, at least in terms of sustainability and resilience, such technologies are rarely taken to scale, partly due to the considerable labour, investments and skills they require. Care must also be taken where forms of ecological intensification do not provide the higher yields required by intensification. Thus, while the practice of agricultural ecology is central to improving sustainability, as important is the process of crop and livestock breeding and socio-economic intensification. Even when combined success is often only achieved on a small scale – a plot or a farm – and with only one or two of the economic, social and environmental objectives attained. The challenge lies in meeting all the objectives and in scaling up success to a regional or national production system.

For all of the practices described in this brief, innovation is needed to achieve Sustainable Intensification whether through the development of new techniques, better understanding of the impacts and local context of existing practices, or in supporting their adoption and success on farms. Many obstacles prevent smallholders from being able to adopt new techniques and adapt them to their own environment. Some barriers such as land tenure insecurity, lack of financial capital, and safety nets span across all the methods discussed. These problems are diverse and include intellectual, social, biophysical, technical, financial, infrastructural and policy issues (Freidrich et al, 2009). What is needed is research into appropriate innovations, their utilisation and effects, targeted financial investments, active participation in the process by smallholder famers to improve rates of adoption, market development for ecological farming and, above all, political leadership.

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