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Sustainable intensification and the African smallholder farmer

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Sub-Saharan Africa needs to produce more food, feed, and fiber to support its growing population and intensification of smallholder agriculture is a crucial component of any strategy towards this goal. Sustainable Intensification (SI) acknowledges that enhanced productivity needs to go hand in hand with the maintenance of other ecosystem services and enhanced resilience to shocks. A very diverse group of smallholders dominate SSA agriculture, with large heterogeneity in socio-technical conditions, famer typologies, production objectives, and the biophysical environment. This potentially generates a multitude of pathways from the current low productivity based on nutrient mining to SI. The institutional context needs to be right for delivering the necessary goods and services underlying SI, ensuring inclusiveness across household types and facilitating local innovation.

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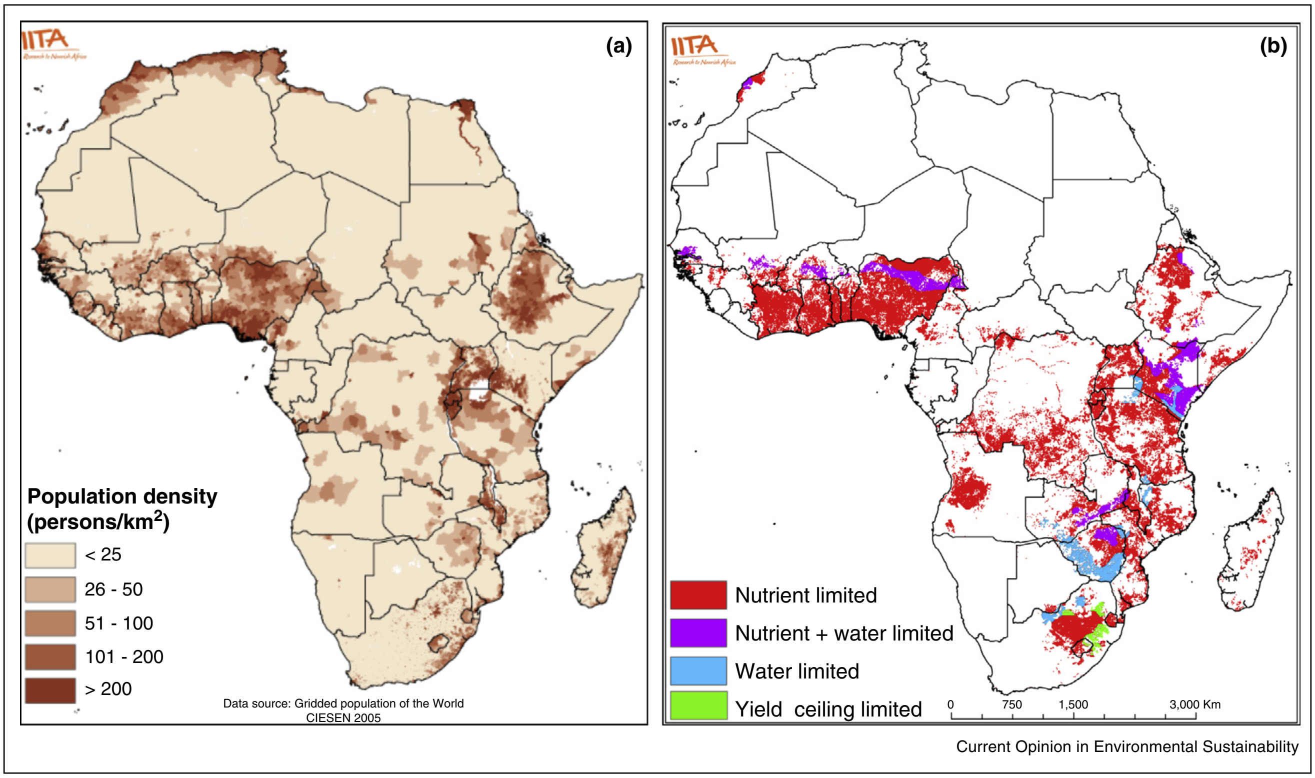
Intensification of smallholder farming systems in sub-Saharan Africa

The global population is projected to increase to 9 billion by mid-century, with Africa's population doubling in the next 40 years [1]. In sub-Saharan Africa (SSA), this increasingly urbanizing population growth has failed to match equivalent increments in yields of the major crops, with increased production resulting rather from agricultural area expansion [2], very often at the expense of the natural resource base, such as carbon-rich and bio-diverse forest land (e.g. [3]). Major areas on the continent consequently experience nutrient limitation as a major yield gap component, especially in densely populated areas, where soil fertility regeneration through fallow periods is no longer feasible (Figure 1). Nutrients moved via crops to urban centers are hardly ever recycled and commonly end up into streams, lakes, or the ocean [4].

Increasing agricultural production in SSA is likely going to be the result of intensification and area expansion [5•]. Intensification of agricultural production is a must in the more densely populated areas in order to feed the rapidly growing and urbanizing population. The recent call for an African Green Revolution [6] is an example of the urgency to remediate the current situation. For areas that contain valuable natural ecosystems, such as the primary forest in the Congo basin, intensification of agriculture is one of the pillars of the strategy to conserve forest [7]. As for the Sahelo-Saharan region, an extensive livestock-based system is likely the only option without degrading the resource base. Other areas in SSA indeed are sparsely populated, contain less valuable or diverse natural ecosystems, and could thus be opened up for agriculture, for example, the Miombo woodlands in southern Africa. However, continuing 'agriculture-as-usual' in such converted areas would merely be a stay of execution as the natural fertility will decline rapidly after conversion [8]. The commercial agricultural sector in SSA commonly produces yields that are several times higher than smallholder farmers, with demonstrable positive impacts on, for example, soil C conditions, as demonstrated for the commercial sector in Zimbabwe [9]. Recent interest from large-scale investors in SSA agriculture may provide a pathway to intensify agricultural production, for example, through contract farming models organized around 'nucleus farms', but the discourse around 'land grabbing' has raised concerns in relation to equity and sustainability impacts on rural livelihoods [10].

Initiatives and investments to intensify agricultural production can expose smallholder farmers to increased risks. A large proportion of this community is considered highly vulnerable to production risks, which is further aggravated by climate change [11]. Smallholders require options that are relatively low-risk, but that do provide

Figure 1



Population density **(a)** and nutrient-limited maize yield gaps ([41], adapted) **(b)** in sub-Saharan Africa.

short-term returns on investment. Consequently, building resilient systems is key, both from the perspective of risk management and sustainability. This requires investments beyond plot-level technologies into policy and other institutional issues that can enable adoption and reduce smallholder risk [12].

Sustainable Intensification of smallholder farming systems

Where intensification is desirable, Sustainable Intensification (SI) denotes a commonly accepted framework [13]. Although various definitions of SI circulate, most of these are phrased around three principles: (i) production of more food, feed, fuel and/or fiber per unit of land, labor, and/or capital used, (ii) preservation of important ecosystem services, including those governed by healthy soils, and (iii) resilience to shocks and stresses, including climate change [14]. Rather than trying to propose an 'ultimate' definition, SI can be characterized by a number of important traits. As a crucial first step, SI requires soil and land to be managed sustainably, including avoidance of negative nutrient balances and soil erosion, the build-up of soil carbon, and the retention of soil biological diversity thresholds to retain essential functions managed by soil biota. Secondly, external agro-inputs need to be used efficiently to minimize any possible negative environmental consequences (e.g. groundwater pollution). The Integrated Soil Fertility Management (ISFM) framework, for instance, is based on enhancing productivity through the deployment of appropriate inputs thereby aiming at maximizing their use efficiency [15•]. Intensified production can increase the build-up of pests and diseases, requiring the appropriate use of inputs such as pesticides thereby ensuring preservation of the environment and retention of biological diversity. Thirdly, farming areas need to retain sufficient levels of (agro)-biodiversity, either through land sparing or sharing, although this polemic is yet to be resolved. Recently, it was concluded that both are realistic solutions, and a number of criteria that could guide the choice towards one or the other can be identified [16•]. Certain common property resources (e.g. wetlands) have other important functions besides retaining biodiversity (e.g. filtering sediment).

Furthermore, SI also requires enabling conditions for its realization. At the institutional level, SI requires access to and use of quality inputs, including improved seeds, appropriate fertilizer and pesticides, and/or labor-reducing devices, especially in SSA where such inputs are yet to be used at scale. Investments require access to capital at crucial times in relation to the growing season thus access to profitable markets or other incentive mechanisms will be essential. Ultimately it will be the profitability of intensification that determines whether or not smallholders will engage — its sustainability will not necessarily be *their* immediate concern. Appropriate policy and incentive structures, including payments for environmental services, can also enable investments in SI. Lastly, SI is the result of farming household, community, and national level decision-making structures and processes. Consequently, a coherent multi-level strategy for SI is essential for its successful development and implementation.

The scale at which SI is defined is crucial to evaluate its status for a specific smallholder farming environment. Crop productivity is assessed at the individual plot level and aggregated at farm and higher scales through straightforward combinations of plot-level data. The sustainability dimension implies taking into account ecosystem services, with some operating at a similar scale as crop productivity (e.g. soil carbon stocks) and others operating at landscape (e.g. erosion control, agro-biodiversity maintenance) level or beyond (e.g. hydrological services). The institutional dimension is defined at the national level and includes the enabling environment for socio-technical innovations for SI. For this review, SI is defined at the level of a first order watershed, including individual farms, common property resources such as common grazing lands, forest pockets, or wetlands, and the recurring or perennial waterways exiting this watershed.

Important characteristics of smallholder farming systems

African farming systems exhibit a high degree of heterogeneity, livelihood strategies, population pressures, access to markets, institutions, and agro-ecological conditions. In SSA, 13 major farming systems were identified with the five largest systems, including maize mixed or highland perennial systems, supporting 65% of Africa's rural population [17]. Some common characteristics across these systems can be identified. The use of agrochemicals in SSA is the lowest of any region in the world with, for example, the average farmer outside SSA applying nearly 15 times more fertilizer per hectare than the average African farmer. As a result, yields of both cereals and tuber crops are low in comparison to the rest of the world [18•]. For instance, a yield gap analysis of cassava in the East African Highlands found a gap of 12.2 t ha^{-1}, 59% of which was attributed to fertilizers, 28% to genetic differences and 12% to planting method [19].

In regions where population growth is rapid and rural population density is high, the size of the average household's farming system has been rapidly declining. Eighty percent of African farms are now under 2 ha in size [20]. The fragmentation of African farming systems is exacerbated by customary land tenure that fails to allow for the development of land purchase or rental markets. The low proportion of land (10%) that is formally registered is an indicator of this failure [21]. Customary tenure institutions exclude women from land ownership, prevent more efficient farm size structures and inhibit investment [22]. In many high population regions, micro holdings have forced farmers to diversify into the rural non-farm economy in order to maintain their livelihoods. It is estimated that approximately 35% of rural income in Africa is earned from non-farm activities including trading, agro-processing, and service provision in the non-farm economy [23].

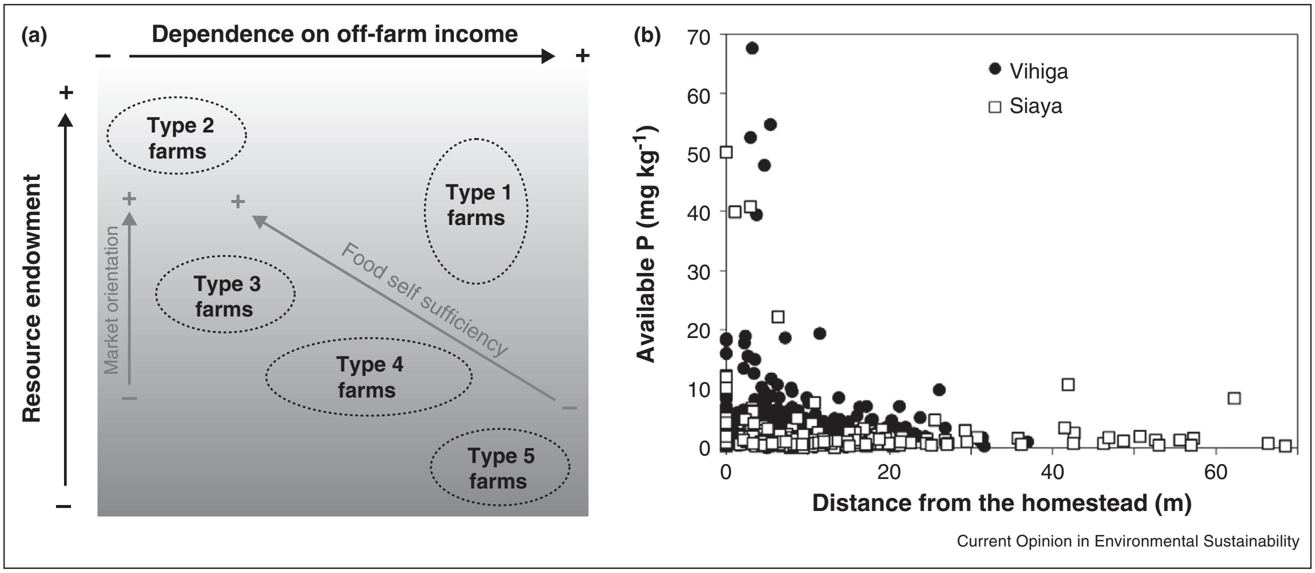
Although increasing demographic pressure implies increased labor availability relative to land, there remains significant variation within communities and across gender lines in distributions of household resources. Household typologies based on resource endowments are useful for exploring and designing appropriate technologies congruent with those endowments (Figure 2a). Within farms another level of variability exists caused by the different levels of land use intensity and the ability of farmers to apply inputs (crop residues, manure, refuse, fertilizer) to some fields (homestead), yet exploiting others (distant fields) (Figure 2b). A long-term interplay of geological and landscape conditions, and plot-specific management have generated such often called within-farm soil fertility gradients.

The heterogeneity of African farming systems is also reflected in the s wide institutional variation in, for instance, input and output market access, physical and knowledge infrastructure, service provision, and an enabling the policy environment. The interaction between these socio-organizational and more technological conditions influences to a large extent the socio-technical transition pathways towards SI and whether SI can reach scale [24]. The recent re-engagement of governments in the agricultural sector is improving the socio-organizational se conditions in many African countries [25].

A multitude of pathways towards sustainable intensification

Although SI is generally accepted as an ultimate goal of agricultural intensification efforts — as conceptually depicted with the top right circle in Figure 3a– there is no consensus on the pathway to reach SI. Most cropland in SSA, characterized by low crop productivity and poor soil health due to long-term nutrient mining and soil C decline, can be situated within the conceptual 'initial status' circle of Figure 3a. While, for example, Evergreen Agriculture advocates the integration of tree species within farming systems, aiming at improving soil fertility with gradual increases in crop productivity, ISFM prioritizes the need for increasing crop productivity in the short term, thereby gradually improving overall soil fertility conditions. Other paradigms, such as push-pull

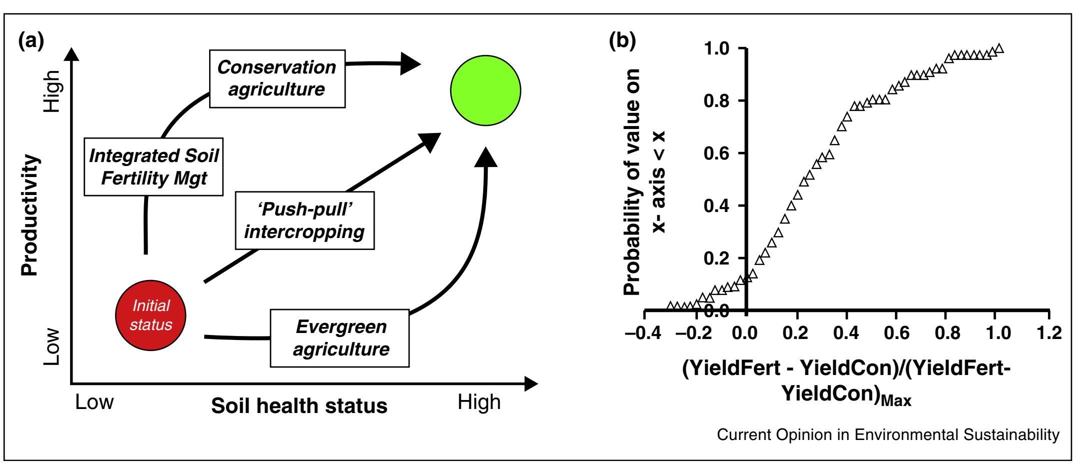
Figure 2



A proposed farm typology definition developed through a multidimensional approach considering the main source of income and production orientation for smallholder households in East Africa ([42••]. adapted) **(a)** and topsoil available P contents for different plots within smallholder farms in Western Kenya (Siaya and Vihiga districts), as affected by distance from the homestead ([43], adapted) **(b)**. In (a), the intensity of shading roughly indicates the distribution of households in a community and the farm types are encircled in dotted lines indicating that there are no actual clear-cuts between types but rather diffuse transitions between them.

systems, fit between these extremes. Recently, a 4th principle was proposed for Conservation Agriculture in SSA: 'the appropriate use of fertilizer' through application of ISFM principles to ensure that crop residue production is sufficiently high to enable mulching the soil surface [26]. Certain cropping systems are seen as inherently more sustainable, for instance, perennial tree crops systems with deep-rooted vegetative cover year-round are much less susceptible to soil erosion. Perennial systems generally have higher root mass than annual systems and are more efficient in the use of plant nutrients [27].

Figure 3

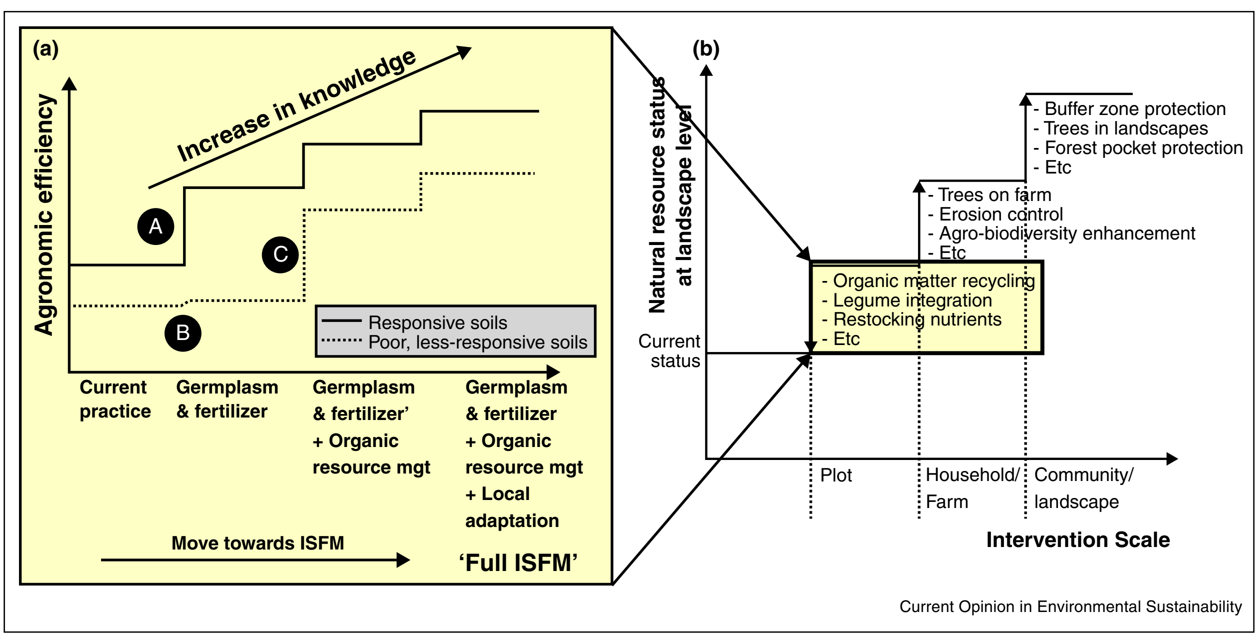


Conceptual pathways from a current situation (degraded soil with low productivity; red circle) to a SI situation (health soil and high productivity; green circle) with various intensification paradigms included based on their approximate position along specific pathways **(a)** and commonly observed variation, expressed as a cumulative frequency curve, in response of maize to fertilizer application within smallholder farming environments in Western Kenya ([44], adapted) **(b)**. In Figure 2b, 'YieldFert' refers to maize yields in the treatment with fertilizer application, 'YieldCon' to yields in the no-input control plots, and '(YieldFert–YieldCon)$_{Max}$' to the maximum response observed. Non-responsive soils are those soils on which crops to not respond to fertilizer application.

The heterogeneity of smallholder faring landscapes suggests that pathways towards SI will need to be flexible in practice and adapted to local agro-ecological conditions at region, village, farm and plot level, crop choice and cropping patterns, the farmer's ability and willingness to invest, and specific institutional conditions. Within any given community, variation in household resource endowments (Figure 2a), risk aversion, and production objectives will impact the likelihood of adopting SI practices. Relatively wealthier farmers can move into SI at the farm level but investments into knowledge acquisition for farmers to understand under which conditions agricultural inputs complement or contradict biological processes and ecosystem services could be required [14]. The high costs of delivering and acquiring such knowledge amongst smallholders is used in arguing for a large farm strategy for intensification [28]. In addition to increasing returns to scale in knowledge acquisition, large farms also achieve economies in transportation, storage, and processing and the acquisition of finance. For poorer households, more complex and encompassing incentive structures would be required, provided that such household can move out of the poverty trap [18•]. If not, SI in landscapes with a relatively large proportion of such households will unlikely succeed. Many farms in SSA may have become too small to enable households surpassing the poverty line of 1.25 USD per person per day, even after adoption of best practices across the farm [29••]. This could indicate a major impediment to SI since the latter requires investment and thus access to production factors.

The performance of plot-level crop and soil management interventions is influenced by the above-mentioned soil fertility gradients (Figure 2b), and can be depicted as a cumulative frequency graph (Figure 3b). High soil fertility plots mainly require nutrient replacement rates to maintain productivity. Adding high nutrient rates on those plots would compromise sustainability through adverse effects on, for example, water quality. Degraded soils often do not respond to applied nutrients (Figure 3b; [15•]). Intensifying production on such non-responsive plots may require more efforts and long-term investments, depending on the constraints creating non-responsiveness [30]. Plots in between those extremes often show the largest increases in productivity after application of nutrients and improved agronomic practices. Such targeting or resources is aligned to the Genotype × Environment × Management framework, pioneered within a recent initiative on legume intensification [31•]. SI will require investments in nutrients, organic matter inputs, and agronomic practices, as summarized in the ISFM paradigm (Figure 4a). The most fertile and/or most responsive plots could generate the extra produce and/or income required to provide for household food security and purchase agro-inputs, labor, and/or access to land. The extra organic resources thus generated through crop residues could be used to enhance the soil fertility status, either directly applied to the soil or recycled through livestock feed (Figure 4b). Interventions towards SI need to be implemented also between plots within a farm, such as the installation of *Calliandra* hedges for fodder provision and erosion control in central Kenya [32].

Figure 4



Conceptual depiction of Integrated Soil Fertility Management, aiming at maximizing the agronomic efficiency of applied inputs through the proper deployment of improved varieties, fertilizer, and organic inputs, adapted to local conditions ([15•], adapted) **(a)** and conceptual progression towards natural resource integrity, one of the dimensions of SI, starting with improved productivity on a single farm.

Besides improving productivity while conserving/restoring the natural resource base, SI also aims at increasing resilience to climate shocks and change. Decreasing farm size and a reduction in access to communal lands (e.g. grazing land, have increased farmers' vulnerability to short-term changes in productivity (e.g. induced by drought, flood, disease outbreaks) and profitability (e.g. rapid drop in market prices and/or accessibility). Adaptation to climate change at farm level often includes many of the elements that are key to ISFM, such as adoption of new crop varieties, adoption of mixed crop-livestock farming systems [33], optimized intercrop systems including trees and shrubs [34], and soil and water conservation practices. Farmers' ability to cope with sudden losses in productivity and profitability will directly affect their financial and natural capital. Subsequently, farmers will need to divert resources (e.g. human, financial, natural) from SI practices to coping mechanisms to overcome the crises. As such, for successful uptake of SI, farmers need to look beyond short-term (monetary) benefits and consider risk management strategies.

To convert smallholder farming landscapes to SI, areas between individual farms require attention since certain ecosystem services are provided by landscape traits that operate beyond individual farms, including hydrology, agro-biodiversity, or aboveground carbon stocks. For SI to fully materialize, measures must be implemented at plot and farm levels, for example, erosion control, input–output nutrient balances, at community level (e.g. appropriate management of common grazing land), and at landscape level (e.g. the protection of wetlands and forest pockets). Before households and communities are engaged in the latter activities, it is important to first attain sufficiently high farm productivity to ensure food security and a minimal income. Collective action to facilitate the conservation of ecosystem properties beyond individual farms will require an appropriate policy framework and direct incentives, especially when other sectors of society are reaping the benefits of such action [35•]. Although Figure 4b does not contain an explicit time dimension, it is acknowledged that the generation of natural resource integrity at landscape level likely starts with a single plot in a single farm before farmers and farming communities invest in areas between plots (e.g. more trees on farms) or between farms.

Reaching scale while allowing for diversity

Sustainable Intensification knowledge and practices need enabling socio-technical conditions to move to scale. Enhanced productivity requires, amongst other, access to agro-inputs, profitable output markets for fresh and transformed products, access to cash and credit, minimal rural infrastructure, and proper access to agricultural knowledge and information. Enabling government investments and policy frameworks will be crucial for SI, including facilitating private sector engagement and smart subsidy programs [14]. Moving enhanced productivity towards SI requires improved and/or retained provision of other ecosystem services beyond farm productivity. Since those services are often less visible, require a longer timeframe to deliver, and usually operate at scales beyond a single farm, other drivers than immediate returns-on-investment may be required to engage rural households in their provision and maintenance. In this case, policy regulations (e.g. the participatory development of micro-zones for various land uses in forested areas [35•], incentives (e.g. payment for ecosystem services), and coherent intervention strategies across national, regional, community and farm scales and levels may beare requiredessential.

Sustainable Intensification can only be achieved when the diversity in agro-ecological conditions, farm household endowment, farming systems, and socio-economic conditions within the landscape is taken into account. In particular, mechanisms need to be identified to break the vicious poverty cycle, keeping many smallholder families chronically poor, and to identify dominant positive feedback patterns [18•]. Addressing the issues of SI on the African continent will require a broad-based approach, which considers a diversity of pathways that will deliver location-specific socio-organizational (e.g., access to credit and insurance and on evolving (community) organization for marketing, processing and storage [40]) and technological (e.g., efficient use of inputs and management practices) innovations tailored to the agro-ecological potential and production systems. General principles of market access, supporting policies and partnerships, rural infrastructure, Research and Development, knowledge and information sharing, for example, will certainly apply. However, the specific technological and socio-organizational innovations to be considered would variously depend on the locality and peculiarities of the situation. This contrasts with the 'blanket' approach that characterized the Asian Green Revolution [36], and reflects the need for a 'uniquely African' Green Revolution, as highlighted during the launching of the Alliance for a Green Revolution in Africa [37]. Accelerating the expansion of Africa's technical frontier will require investment in agricultural research and extension systems that facilitate local innovation while will enhancing spill-over of targeted technologies to different parts of Africa, complemented by investments in infrastructure, markets, and other enabling conditions [38,39].

Here, the complementarity between biophysical and social sciences research becomes particularly pertinent. To fully understand the local heterogeneity, and explore, design and implement feasible and acceptable socio-technical pathways for SI, as well as other types of agricultural innovation processes, the continuous collaboration between researchers and different groups of stakeholders (e.g., farmers, private sector, government, civil society and development actors) is essential [40].

Conclusion

Intensification of African smallholder agriculture is desirable for a number of reasons and the SI concept covers the important dimensions of how such intensified agriculture could be sustained. Due to the heterogeneous nature of the smallholder farming environment in SSA, in terms of socio-technical conditions, farmer typologies and production objectives within communities, and biophysical gradients within-farm, various pathways towards SI apply aligned to the dimensions of this heterogeneity. Since smallholder farmers expect immediate benefits from farming, any pathway towards SI will necessarily require the inclusions of improved and predictable farm productivity before the conservation or rehabilitation of other ecosystem services. Models for scaling SI approaches will necessitate the integration of diversity aligned to locally prevailing conditions with an important need to foster innovation at various scales, rather than promoting one-size-fits-all solutions. The international Institute of Tropical Agriculture (IITA) in its Refreshed Natural Resource Management Strategy 2012–2020 has committed to redirect at least 7.5 million hectares in SSA into sustainable-use by 2020 following SI concepts and approaches, discussed in this review.

An issue that was not considered in this review is the future of smallholder farming. With decreasing farms size, will farms become too small to intensify sustainably (assuming that this is not already the case)? Which impact will the massive efflux from rural areas to towns have on SI initiatives, which require investments in labor? Will older farmers have the necessary motivation to change the 'traditional' way of doing business? Can SI take place without a minimal level of farm consolidation with a large proportion of the rural population thus becoming farm laborers instead of farmers? Addressing these pertinent questions will require transdisciplinary and dynamic research and development approaches towards the SI of smallholder farming in SSA.

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In this study, the authors illustrate, through approaches followed by the N2Africa project, the importance of M(anagement) for enhancing legume productivity within the overall equation (GL $\times$ GR) $\times$ E $\times$ M, where GL: the legume genotype, GR: the genotype(s) of rhizobia, and E: the environment. They emphasize the need to understand variability, in order to tailor legume-based technologies to suit the socio-ecological niches and satisfy the needs of a diverse group of farmers.

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