LANDMARC

SCALING LAND-BASED MITIGATION SOLUTIONS IN KENYA

LAND-BASED MITIGATION NARRATIVES

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2. Introduction

This report includes a description of a generic nation-wide transition scenario for the implementation of land-based mitigation technologies and practices for the AFOLU sector (agriculture, forestry, and other land use sectors) in Kenya. The report shows the outcomes of a series of research steps that have been conducted in this country since the start of the project in June 2020 until the end of 2022:

First, we performed an initial scoping of key LMTs in the case study country. The scoping assessment resulted in a long list of broad portfolios of different LMTs that could be viable within this case study country.

Second, following this long list, we developed a short-list LMT portfolio containing key LMTs that would be the most relevant for a given country context. All case study country partners were asked to propose and validate their LMT portfolio through complementary (policy) literature review and with the help of stakeholder interviews (i.e. external validation by relevant country experts and stakeholders). Ex-ante no specific guidance of criteria for LMT portfolio short-listing was provided to allow for a free and open co-design process with stakeholders. The scoping process and results are presented in section 3 of this report (step 1 & 2). In Kenya, the long-list was derived based on a combination of reviewing global literature and local policy documents. Short-lists were derived from Kenya climate and agricultural policy documents and discussion with stakeholders from CGIAR centers based in Nairobi, and with stakeholders from the ministry of agriculture and the Kenya Climate Smart Agriculture Project.

Third, after the short-listed LMT portfolios were validated, the LANDMARC case study country partners were asked to develop national scaling narratives or storylines for each LMT included in their portfolio. The assessments focusses on climate risks, vulnerabilities as well as socio-economic co-benefits and trade-offs associated with upscaling LMTs in the case study countries. The analysis is based on a broad range of information/literature sources, and stakeholder consultations conducted. This process is supported through a risk and impact assessment (i.e. an online survey and workshops/seminar/webinars) conducted through the LANDMARC tasks 4.1, 4.2 and 5.2. The most important insights from these risk assessment interviews were also implemented into the present narrative document The results of this analysis are a set of LMT narratives which are presented in section 4 of this report.

The research steps are designed to enable both an **analysis of the risks and (climate) impacts of scaling up land-based mitigation and negative emission solutions**. As such this report mainly contributes to objectives 2, 3 and 4 of the six LANDMARC key objectives (see Table 1).

Table 1: LANDMARC project objectives.

	Project key objectives
1	Determine the potential and effectiveness of LMTs in GHGs mitigation using Earth Observation (EO)

2	Improve climate resilience of LMT solutions at the local level for large-scale implementation
3	Assess the risks, co-benefits, and trade-offs of scaling up local LMTs nationally
4	Scaling up LMT solutions to the continental and global level to assess effectiveness
5	Improve current methodologies to estimate emissions and removals for LMTs
6	LMT capacity building and develop new tools and services for decision making

While the results shown in this report represent a mostly qualitative storyline describing the context and impact of scaling up LMTs in a country context, they also enables project partners to proceed with the translation of the outcomes in a manner so that they can serve as direct model input.

Furthermore, these national level assessments provide a testing ground and empirical basis for the continental, and global assessment of the realistic scaling potential of land-based mitigation and negative emission solutions implemented in Work Packages 6 and 7 of the LANDMARC project (***Objective 4***).

3. Scoping of land-based mitigation and negative emission solutions

3.1. Overview of potential of LMTs in Kenya

3.1.1. *Introduction*

Although Kenya considers itself as a low emitter of greenhouse gases (GHG) that contributed historically less than 0.1% of globally released GHG, it is determined to reduce its GHG emissions (Government of Kenya, 2020). Kenya is a developing country with a growing population and industry. It therefore considers its GHG emission reduction goals against a business as usual (BAU) scenario and not against historical emissions. This BAU scenario is based on projections of population and economic growth and estimates an increase of annual emissions from 96 Mt CO_2 equivalent (CO_2e) in 2020 to 143 Mt CO_2e by the year 2030 (Government of Kenya, 2018a). Kenya's government has committed to a "nationally determined contribution" towards fighting climate change, which has a timeframe until the year 2030. In 2015 Kenya initially committed to reduce GHG emissions by about 30% compared to the BAU scenario. This plan has been updated in 2020 to a reduction of 32% compared to BAU, which would mean that emissions stay roughly at the level of 2020. Kenya requests international financial support for 87% of the project costs (Government of Kenya, 2020). Due to its strong dependency on the primary sector, Kenya expects to be severely impacted by climate change. Therefore, many of the policies aim to increase the resilience of the primary sector, while simultaneously reducing or mitigating GHG emissions (Government of Kenya, 2018a). Compared to the EU, GHG emissions of Kenya are very low (about 5% on a per capita base in 2016; World Bank 2021b). Due to much lower emissions and Kenya being a developing country, GHG emissions are less rigorously monitored than for example in EU states and data availability is scarce. This report tries to identify the most promising LMTs from the available data and predictions, but the lower certainty about the data should be kept in mind. Most of the measures which are intended by the Kenyan government are not primarily targeted towards achieving negative emissions, but instead aim for a reduction of Kenya's GHG emissions. Despite Kenya's focus on reducing identified emissions, a few of the proposed measures carry the technical potential of sequestering additional carbon on top of their mitigation potential. Technologies which could be called LMTs are located in the agricultural and forestry sector (Table 2), which both occupy about 10% of land area in Kenya, each.

Table 2: Estimated GHG emissions and GHG reduction potential in Kenya in 2030

Category	Sector	Estimated total emissions (2030)	Technical potential of emission reduction (2030)	Nationally determined contribution - targeted reduction (2030)	Technical potential relative to estimated emissions
		Mt CO_2e/y	Mt CO_2e/y	Mt CO_2e/y	(%)
Emission mitigation or reduction	Electricity generation	41	18.63	9.32	45.4
	Energy demand	10	12.17	6.09	121.7
	Transportation	21	6.92	3.46	33.0
	Industrial processes	6	1.56	0.78	26.0
	Waste management	4	0.78	0.39	19.5
Land management solutions with LMT potential	**Agriculture**	39	5.53	2.77	14.2
	Forestry	22	40.2	20.1	182.7
	Total	143	85.8	42.9	60

Source: adapted from Government of Kenya (2018b).

Due to a lower population density of about 80 persons/km² of Kenya compared to European countries (about 100 persons/km²) and much lower per capita emissions (about 1.03 vs 6.9t CO_2 equivalents per year; World Bank, 2021b), LMTs could have a considerable potential for GHG mitigation in Kenya. To get an overview of the overall potential of LMTs, a comparison of the net primary production (NPP) of land in relation to total emissions seems feasible. The average annual NPPof land is between 3 and 5 t of carbon assimilated per ha and year (Foley, 1994; Running et al., 2004). With a land area of 58 mln ha, the NPP of Kenya would be in the range of 174 to 290 Mt of carbon per year, equivalent to capturing about 640 to 1060 Mt of CO_2 per year through photosynthesis. Thus, from a first principles theoretical estimation, between 22 and 13% of the achieved NPP would have to be removed from the land and sustainably stored in order to completely offset the yearly emissions of 143 Mt of CO_2e which were projected in the BAU scenario in 2030. Considering that many natural ecosystems are often at or close to a steady state in terms of carbon stocks and that there is also pressure on the land to satisfy other demands for biomass or food, such a high storage may be difficult to achieve. In the following sections, the most promising options are described.

3.1.2. Technologies of the forestry sector

Forestry-based projects established in many African countries carry a huge potential to sequester carbon (Akinnifesi et al., 2010) and the sector is also targeted by the Kenyan government in order to achieve GHG emission reductions. However, with less than 10% of forest cover, Kenya belongs to the countries with the lowest forest cover rates globally (Government of Kenya, 2018b), but this is largely due to the potential natural vegetation of Kenya being bushlands for the most parts (Lillesø et al., 2015). Yet, Kenya has experienced significant deforestation in recent decades. Forest cover was diminishing fast in the 90s, changing from a coverage of 8.3% in 1990 to 6.2% in 2000, but through changes in forest policies this trend was reversed (Government of Kenya, 2018b). This led to an increase in forest cover to 7.8% in 2016 (World Bank, 2021c), with the declared aim of forest policy to reach 10% of land covered by forest in 2030 (Government of Kenya, 2014). It is stated that part of Kenya's forest cover is degraded and in poor condition without an exact specification of the proportion (Government of Kenya, 2018b). As a result of the historical loss of forest and of many forests being degraded, the Kenyan administration attributes a huge potential for GHG mitigation to forest projects aiming at the reforestation of areas where forest was lost and at the restoration of degraded forests through protection policies. It is estimated that there is a potential for 1.2 million ha (about 2% of Kenya's land area) of additional forests (Government of Kenya, 2018b), which is in line with the declared goal of 10% forest cover. As can be seen from the estimated technical potentials (Table 2), the forestry sector is the main land-based sector which has an attributed technical potential to achieving net negative emissions. As Kenya has committed to realize half of this technical potential by 2030 (Government of Kenya, 2018b), this would be enough to offset most of the emissions from the forestry sector, but it would not be enough to achieve negative emissions from the forestry sector.

The Government of Kenya (2018b) has stated that the cost for their reforestation programmes until 2030 would amount to 2.7 to 4.1 billion US $ and the programmes are estimated to decrease CO_2 emissions by 10.4 Mt CO_2 per year in 2022, growing to a yearly decrease in CO_2 emissions of 20.8 Mt CO_2 per year in 2030. Under the assumption of a linear increase of these CO_2 emission offsets between 2022 and 2030, a total of 140 Mt of CO_2 emission would be offset by 2030, which would roughly correspond to a cost of 19 to 29 US $ per ton of CO_2. This could be considered rather cheap compared to offset costs in other countries (e.g. carbon taxes in Europe range between 10 and 119 US $ per ton of CO_2 and are expected to rise in the future; World bank, 2020)

The forest management measures in Kenya have been grouped into two categories: restoration of degraded forests and reforestation, both of which have the goal of reaching an intact forest cover. They both are targeted to areas that historically were covered by forest and are thus not termed afforestation. The difference in categorization depends on the action that needs to be taken in order to achieve a tree cover dense enough to meet the definition of forest. The measures of forest management also include management of mangrove ecosystems (often referred to as «blue carbon»), which are counted toward the forestry sector (Government of Kenya, 2018b).

Restoration of degraded forests

The restoration of degraded forests is considered to bear the largest potential (80% of the area). In contrast to reforestation, restoration of forests is defined as a natural regeneration of land where degraded forests can achieve a full tree cover by themselves (Government of Kenya, 2018b). It appears likely that due to pressure on land, this measure requires appropriate laws for the protection of the appointed areas, as well as sufficient law enforcement. A better management of agricultural areas leading to higher yields could indirectly contribute towards restoration of forests, as higher yields of agricultural lands would help to achieve food security and thus reduce the pressure on land.

Reforestation

Reforestation, in contrast to restoration of forests, requires the active planting of new trees on areas that cannot recover to become forests by themselves in a reasonable amount of time. It is considered that this is necessary on 20% of the appointed land area (Government of Kenya, 2018b). For reforestation, both native species and exotic species may be used, even commercial tree plantations are listed amongst the mitigation actions (Government of Kenya, 2018b) and to the understanding of the authors, they will also be counted towards reforestation.

3.1.3. Agricultural management practices

According to the latest data from 2016, about 10% of the land area in Kenya is arable cropland (World Bank, 2021a), which corresponds to a total area of 5.8 mln ha. The expected agricultural GHG emissions of 39 Mt CO_2e per year in 2030, would thus correspond to an emission of about 7 t CO_2e per ha and year, or 1.9 t CO_2-carbon per ha and year, which would have to be avoided to reach net zero emissions in the agricultural sector. Almost half of the emissions are attributed to originate from agricultural soils, whereas the other half comes from livestock enteric fermentation, the latter not being considered for GHG emission reductions (Government of Kenya, 2018b), likely due to food security issues. Due to a growing population and demand for agricultural production, a significant reduction of the emission rates by agriculture will likely not be achieved by agricultural management practices alone, but agroforestry could help to increase the amount of carbon sequestration in Kenya.

Agroforestry

Of all agricultural practices, agroforestry is seen as the technology with the largest potential in Kenya. The technical emission reduction potential estimated was estimated to be about 4 Mt CO_2e per year in 2030, if 281,000 hectares (corresponding to roughly 5% of arable land) would be converted to agroforestry systems with at least 10% of tree cover (Government of Kenya, 2018b). However, there is no data on how much of Kenya's arable land is already under agroforestry (Government of Kenya, 2018b) and how much tree cover these systems usually have. Further information on this baseline adoption rates as well as on the adoption barriers, such as enhanced labour requirements, would be crucial. Apart from sequestering carbon, agroforestry systems can enhance the resilience of agroecosystems by enhancing water use efficiency (Government of Kenya, 2017) or by providing additional nutrients (e.g. by uptake from deeper soil layers or by nitrogen fixation). Thus, agroforestry systems bear the potential to enhance crop yields, for example if leguminous trees (e.g. *Calliandra calothyrsus*) would be used, as they can provide additional nutrients to marginal soils (Chivenge et al., 2009).

Conservation agriculture

Other practices that are attributed to bear the potential of reducing GHG emissions in 2030 by about 1Mt CO_2e annually, are summarized as the adoption of conservation agriculture. This term includes management practices such as conservation tillage, legume planting, incorporating crop residues, alongside efficient fertilizer use (Government of Kenya, 2018b). If successful in sequestering carbon, these methods naturally increase the amount in soil organic matter, which has the co-benefit of increasing the soil fertility, water holding capacity and nutrient storage capacity. It was shown that conservation agriculture and/or integrated soil fertility management practices in Kenya, such as using farmyard manure, no tillage and leaving crop residues in the field may reduce initial emissions from agriculture (in the range of 0.1 to 0.9 t carbon per ha and year) by up to half, while a net sequestration of carbon could not be achieved (Sommer et al., 2018). A further suggested method to reduce emissions from agriculture is the reduction of fire use in field management (Government of Kenya, 2018b), with the potential of mitigating 0.29 Mt of CO_2e per year in 2030.

3.2. Determining the LMT scope for national level simulation modelling

In this section we discuss which set of LMTs we will study in detail in Kenya. Table 2 summarises the main LMTs and indicates which ones are included in the short-list of the LMT portfolio for Kenya. The main rationales for including the various LMTs in the national level scaling simulation assessment are presented below.

Table 3: Long-listing of relevant land based LMTs

LMT	Specification	Included in national LANDMARC LMT portfolio
BECCS	-	N
Biochar	-	N
Wetlands	Peat soil management	N
Cropland	Conservation tillage	Y
	Integrated soil fertility management (e.g. use of harvest residues, crop rotation, mulching, fertilizer)	Y
	Agroforestry	Y
	Grassland management	N
Forest land	Avoided deforestation	Y
	Afforestation/ reforestation	Y

Conservation tillage

Conservation tillage has been explicitly stated by the Government of Kenya (2018b) as a measure to reduce GHG emissions from agriculture. It has also been found in literature that zero-tillage combined with residue retention can reduce carbon losses from soils in Kenya (Sommer et al., 2018).

Integrated soil fertility management

Integrated soil fertility management is a practice that combines the use of organic manures and chemical fertilizer with good management practices (Yadav and Soni, 2019). It is similar to the kind of management practices which are summarized in the Kenyan official documents as "conservation agriculture" (Government of Kenya, 2018b). It is the goal of such management practices to make best use of several options to make agricultural systems more resilient, increase soil carbon storage and yields. They include a use of available farmyard manure and locally available organic residues, integrating legumes into the crop rotations, incorporating crop residues into the soil, alongside an efficient use of chemical fertilizer where available. Many of the measures are included in the climate smart agriculture strategy (Government of Kenya, 2017).

Agroforestry

The use of agroforestry has been identified as the measure with the highest potential to mitigate GHG emissions in Kenya, but the utility of agroforestry is not limited to GHG. A systematic review of agroforestry system studies across whole sub-Saharan Africa, showed that, in the majority of cases, there was an increase in yield (68%), a better microclimate (61%), enhanced nutrient cycling (60%) and soil fertility (53%) while negative effects, such as lower yields, higher water requirements, or worse microclimatic conditions, were observed only on average in 15% of cases (Kuyah et al., 2016). As it was proposed to increase the amount of agroforestry systems in Kenya by 200,000 ha (Government of Kenya, 2018b), it seems feasible to test the GHG mitigation potential in Kenya. Also, the mentioned benefits could help to make agronomic systems more resilient. The use of agroforestry in Kenya should further be facilitated by the World Agroforestry centre, which has it's headquarter located in Nairobi, Kenya.

Afforestation/ reforestation

The Kenyan government has set a focus on afforestation and forest remediation as a cost-effective option for GHG emission mitigation at the national scale (Government of Kenya, 2018b). As stated in detail before, forest-based measures are the only LMTs that have been judged to carry the technical potential of leading to negative emissions. Thus, the strong focus and clear commitment of the Kenyan government make the inclusion of forest-based measurements an imperative.

Despite a possible potential in the future, some of the LMTs seem not yet ready to be applied at large scale in Kenya within the coming decades. Thus, they are excluded from the national simulations. The reasons to exclude these other LMTs from the national analysis are the following:

BECCS

No mentioning of any use of BECCS in Kenya was found in the screened documents.

Biochar

The use of biochar as a potential mitigation measure was not found in the screened documents of the Kenyan government. Yet, initial trials show that biochar use in Kenya may have potential as a soil amendment. It was shown that the addition of biochar facilitated the storage of carbon in the soil: including losses by erosion and vertical translocation, 60% of biochar was still present after one decade while simultaneously crop yields were increased by about 1.2 t per ha for maize and 0.4 t for soybean (Kätterer et al., 2019). However, judging from biochar prices globally, the biochar production in Kenya at larger scales may be too expensive and the technological requirement too high for it being attractive in Kenya at this time. Also, no data could be found on the economic adoption feasibility and willingness at household level. The use of biochar in Kenya is thus excluded in LANDMARC, but there could be potential in the future.

Peatland management

Peatland management was not mentioned in any of the screened documents, nor could the percentage of land covered by peatlands be found. Kenya's interest in peatland management is therefore considered to be low and hence not included in the short list.

Grassland management

Grassland management options were not specified in any of the screened official documents. However, the high share of grassland in Kenya (42%; Kamoni et al., 2007) could make it interesting to use mitigation options connected to grassland managements. For example, a high potential of East African grasslands on a per area base, between 0.1 to 3.1 t of carbon sequestration per ha and year, was found by Tessema et al. (2019) within their systematic review. However, as there is no stated intent to include grassland management in Kenyan GHG mitigation policy, it is at the moment not included in the list of considered options.

3.3. Discussion on short-listing LMTs

3.3.1. Land use change dynamics

The Kenyan plan to increase forest cover by up to 2% of the land area, reaching a forest cover of 10%, is quite ambitious. Despite the relatively low forest coverage of Kenya there may be difficulties to achieving this amount of forest cover. This could be due to a lack of law enforcement, but ultimately it is driven by the pressure on land, which again depends on the population dynamics and on the productivity of land. The rapid decrease of forest cover in the 1990s by more than 2% is an indication of the high pressure on land and given the increase of population size in Kenya which is estimated to continue until the year 2100 (United Nations, 2019), the pressure will likely remain high. This pressure is exacerbated by the low increase in cropland productivity in Kenya. Crop yields in Kenya have been stagnating within the past decades (Table 4), whereas a dramatic increase was realized in the rest of the world (e.g. up to a doubling of yields most regions from 1980 to 2010, excluding Africa). Apart from increased climate vulnerability and pest pressure, the stagnating yields in Kenya are mostly due to insufficient nutrient input, thus agriculture mainly depends on nutrient mining (Vanlauwe et al., 2011) on highly weathered soils. With a growing population leading to a higher demand for agricultural goods, increasing the yields of Kenyan agriculture will not only be important to achieve climate resilience of agricultural systems, but also to reduce the pressure on land.

Sustainable use of forest products

An issue that has not been addressed in the screened government reports but may be crucial for longer timescales, is how the newly established forests are managed after 2030. Considering the relatively short time horizon of only 9 years until 2030, the mitigation of GHG by forest restoration and reforestation until then may be realistic: newly planted trees and recovering forests may not yet be intensively used. However, in the longer term, it is likely that there will be pressure to use the forest biomass and how the biomass will be used will be crucial in determining the GHG mitigation potential. For example, an energetic use of forest biomass without any CCS technology would drastically reduce the potential for negative emissions of forests in the long run, as it would release the biomass-stored carbon and which is more half of the carbon stored in forests in soils and biomass combined (Government of Kenya, 2018b). This is a real risk, given that 87% of the rural population still depends on firewood for cooking (Government of Kenya, 2018b). In contrast, a sustainable extraction and material use may allow high yearly sequestration rates for a long time and increase the carbon sink potential of Kenyan forests.

Table 4: Agricultural land use in Kenya and yields from 1970 to 2016 (% of total land)

Data	1970	1990	2000	2010	2016
Forest share (%)	n.d.	8.3	6.25	7.4	7.8
Agricultural land share (%)	44	47	46.9	48	48.5
Arable land share (%)	6	8.8	8.6	9.7	10.2
Non-arable agricultural land share (%)	38	38.2	38.3	38.3	38.3
Cereal yield (t per ha; 5-year average)	1.25	1.7	1.44	1.56	1.57

Source: World Bank 2021; n.d. = no data.

3.3.2. Land management dynamics

While land management options in Kenya promise the double benefit of reducing GHG emissions and increasing soil fertility, an analysis of adoption barriers seems to be crucial. It is somewhat telling, that there are no official numbers on the actual adoption of agroforestry or conservation agriculture in Kenya (Government of Kenya, 2018b), while the stagnation of cereal yields (Table 4) compared to strong increases in rest of the world shows a strong need to improve the management of land, while simultaneously limiting GHG emissions. The main goal of all climate change mitigation options of the national strategy of Kenya is to achieve food security and make production systems resilient (Government of Kenya, 2018a), but the co-benefit of climate smart agriculture or integrated soil fertility management in reducing GHG emissions is also acknowledged. The need to increase arable land, e.g. from 6% in 1970 to 10% of total land in 2016, (Table 4) could be largely due to the stagnation in yields on a per area base while a higher population needed to be fed. Thus, tackling the yield gap may also be important to assure other measures of GHG reduction, which require land. With only around 1.5 t ha of cereal yield, the actual yield gap in Kenya may be very high. For example, whereas the actual achievable yield of rainfed maize systems in western Kenya that had a baseline grain yield of 1.7 t per ha, its technical potential was estimated to be 5.4 t per ha, showing a yield gap of 3.7 t per ha (van Ittersum et al., 2013). From the perspective of competition for land, it therefore seems crucial to reduce this yield gap, while simultaneously improving soil fertility.

A key question to resolve is how the adoption of GHG reducing and yield promoting land management techniques can best be achieved, and what barriers exists. It was suggested that characteristics that influence the adoption of climate smart agriculture management practices are partly influenced by the perceived benefits compared to costs (e.g. labour requirement) and partly by access to education about the practices (Ouédraogo et al. 2019). In this regard it may also be important that the poorest farmers seem to be the ones that are least likely to adopt improved management practices (Cavanagh et al., 2017) and may require special extension services. Policies that could facilitate a faster adoption of agroforestry, for example, could be the improved extension services, but also payments to farmers for providing enhanced ecosystem services or for carbon sequestration (Wilson and Lovell, 2016), which could help to cover the initial setup costs of agroforestry systems.

Lack of data on Kenyan soil carbon stocks and their development

Overall, there is a lack of systematic national soil carbon stock assessments in Kenya and thus estimates are only rough and based on models. A modelling study by Kamoni et al. (2007) was assumed that Kenyan soils have lost carbon in the recent decades and will continue to do so (Table 5). However, real measurement data of Kenyan soil carbon stocks were not found. On the other hand, new technologies which might allow for a better estimation of soil carbon stocks in Kenya, at a relatively low price compared to classical soil surveys, were emerging recently. For example, new low-cost portable measurement devices which rely on spectroscopy show potential for a better soil carbon stocks monitoring (Segnini et al, 2019). The data obtained by this could be combined with satellite imagery to achieve monitoring of soil carbon stocks together with land use monitoring in the future.

Table 5: Predicted levels and losses of organic matter in the topsoil of Kenya

Carbon stocks (Mt carbon)	1990	2000	2030
Century	1428	1416	1311
RothC	1611	1522	1308
IPCC	2022	2003	1975
Mean change since 1990 (%)	0.0	-2.4	-9.8

Source: Kamoni et al. (2007)

4. Co-design of LMT narratives

4.1. Introduction

We developed the narratives based on the short-listed LMTs that were selected based on Kenyan policy documents and a first round of stakeholder interviews. The further trajectory of the selected LMTs was then delineated in a two-step process. First, an in-depth literature research was conducted in 2021. The first version of the narratives was written based on this literature review. Second, further one-on-one interviews throughout 2022 were conducted within LANDMARC tasks 4.1, and 5.2 and through a workshop on the upscaling potential on an individual LMT (integrated soil fertility management). The final version of this report was then enriched with key insights gained through the stakeholder interviews, to complete the picture.

All short-listed LMTs for Kenya represent low-tech solutions, that are in alignment with Kenya being in the status of a developing country. As population increase will be a key driver in land-use changes, the LMTs conservation tillage, integrated soil fertility management and agroforestry are all possible on arable land. Additionally, they offer some potential synergies, and could in theory be implemented on the same piece of land. Afforestation, the last LMT was chosen as it is very effective as CO_2 sink and because it is included in Kenyan law to afforest. From the literature reviews and stakeholder engagements, it became clear that an LMT portfolio is needed, because the different land uses are connected. For example, pressure on land, which threatens afforestation, is also related to cropland productivity, which is addressed by the other LMTs. Agroforestry, in that regard is a hybrid, as it integrates agriculture and trees, with potential synergies.

4.2. Conservation tillage

4.2.1. *Introduction*

While being an effective measure to reduce weed pressure, soil tillage in agricultural fields is disturbing soil structure and soil life, ploughing under soil cover such as plant residues and redistributing soil within the plough layer. From the mechanistic point of view, it has been realized that ploughing amongst other factors increases the turnover of soil aggregates by disrupting them mechanically (Six et al. 1999) which makes intra-aggregate particulate organic carbon available to decomposition and thus is leading to a faster turnover of soil organic carbon (SOC). Thus, conservation tillage aims at either applying tillage practices that less strongly disturb the soil, or at eliminating tillage altogether and applying methods of direct seeding. The advantage of conservation tillage compared to other LMT is that it does not need any additional biomass and that it is relatively simple to implement. While early studies about conservation tillage systems focused mostly on temperate agricultural systems, some more recent studies indicate that the effect of conservation tillage could be more profound in tropical agroecosystems, which is not surprising, given the faster overall turnover of SOC due to higher temperatures. For example, studying several long-term experiments indicated that conservation tillage can reduce losses of SOC compared to standard tillage practices (Sommer et al., 2018). It was also shown that reduced tillage can slow down nitrogen mineralization, especially when nitrogen rich plant residues are present (Butnan and Vityakon, 2020). Yet, the effect of tillage could be site specific and strongly depending on soil texture. For example, a meta-analysis indicated that conservation tillage lead to increased SOC stocks in only about half of the studies reported (Palm et al., 2014).

4.2.2. Policy context

In Kenya reduced tillage is one of the techniques that is promoted under the umbrella term “climate smart agriculture”, a portfolio of strategies aiming at climate change mitigation and simultaneously making systems more resilient against climate change impacts. Increasing the use of reduced tillage systems could have the double benefit of lowering soil erosion, because reduced tillage not only leads to less soil disturbance and therefore better soil structure but also leaves mulching biomass on the surface, decreasing the impact of heavy rains. Therefore, it is one of the government-promoted land management techniques and the application of reduced tillage has been explicitly stated by the government in the Kenya climate smart agriculture strategy as tool to mitigate climate change within their official communication to the UN (Government of Kenya, 2015). As tillage is a standard agricultural practice, reduced tillage can in theory be applied by all farmers cultivating arable land. However, not all cropping systems may be suitable in the same way. A potential side effect in reduced and especially in no-till systems is an increased weed pressure in many cases. The control of such an increased weed pressure might need to be counteracted by the application of herbicides (Palm et al., 2014), so the feasibility of no-till in Kenya could be limited to farmers who have access to pesticides and the capital to invest in this. On the other hand, reduced tillage with shallower ploughing depths may be feasible for a larger share of farmers but could still come at a higher labour requirement for weeding. As it is part of climate smart agricultural practices, the extension of reduced tillage could benefit from the international and national funds which are directed at climate smart agriculture implementation. One of the largest projects dedicated to this is the Kenya Climate Smart Agriculture Project, which is internationally financed with 280 mln US $ to by the world bank to be spent until 2023 (Development Projects : Kenya Climate Smart Agriculture Project - P154784 (worldbank.org)).

4.2.3. Current land use and potential land-use competition

While there is no clear data on how much farmers practice reduced tillage, it was estimated that at least 25% of farmers use conventional tillage (Government of Kenya, 2018b). It was assumed that over 10 years it would be possible to change 475.000 ha of agricultural land (roughly 8% of 5.8 mln ha of arable land in Kenya) from conventional to reduced tillage and that this would offset significant amount of CO_2. The potential for national yearly emission reductions resulting from this application of conservation tillage was estimated to 0.65 mln ton CO_2 equivalent in 2020 which should increase to 1.09 mln ton CO_2 equivalent in 2025 and then stay at this level, if the additional 475,000 ha would be transformed to conservation tillage (Government of Kenya, 2018b). It should be mentioned, that it was not clearly identifiable where these numbers exactly originate from and what type of conservation tillage (e.g. reduced or no-till) is exactly intended. As the assumptions made were not explicitly stated, it seems advisable to interpret the stated goal as statement of intent rather than an exact prognosis on the exact amount of CO_2 sequestered and area to be converted to reduced tillage.

An advantage of conservation tillage is that, while having a rather moderate rate of carbon sequestration (for example, less than 0.2 ton C sequestration ha^{-1} were reported by Prasad et al., 2016), the practice is not in competition with other land use - it is simply and agricultural practice that can applied in most agricultural fields. However, a constraint could be increased pest pressure leading to higher input costs, either for pesticides or labour for manual removal. Thus, the scaling up of reduced tillage may be mainly affected by the availability of extension to generate the knowledge on how to manage reduced tillage systems and, depending on which system is used by the availability of pesticides needed to implement, for example no-till systems, or the availability of more labour required to do the weeding.

4.2.4. Climate risks & sensitivities

As reduced tillage is a land management practice and not a land use, it is not directly affected by climate risks additional to these that affect agriculture. Yet, reduced tillage may have several beneficial effects that make crop production more resilient to climate extremes. For example, reduced or no-till systems in contrast to conventional tillage maintain a higher soil cover. This reduces the direct impact of raindrops and their potential to detach soil particles, thus reducing the potential for erosion during intense rainfall events. Reduced tillage is also associated with a better soil structure which also increase water infiltration and reduces runoff (Palm et al., 2014). This has a double benefit as it increases plant available water while simultaneously reducing erosion potential. Maintaining a higher soil cover through reduced tillage, e.g. higher levels of mulch, can also reduce evaporation in dry periods, thus reducing the amount of unproductive water loss and maintaining higher levels of soil water. One issue that came through in the interviews was that the carbon sequestration potential of reduced tillage may be reduced by droughts, as this reduces plant growth and thus C inputs.

4.2.5. Economic implications

In general, there is a scarcity of implementation cost estimates for reduced tillage systems in the sub-Saharan Africa context. Most studies on reduced tillage systems have so far been conducted in temperate regions, where reduced or no-till is usually associated with a high level of mechanization, so it is difficult to judge the costs of reduced tillage systems in the tropics. According to an interviewed specialist, no-till is very common in Brazil where it is favoured because of lower input costs. However, the high level of mechanization and large parcels of Brazil are not comparable to the very small scale low mechanized Agriculture of Kenya. As most agricultural practice being manually implemented, labour costs vary region specific. As labour cost can be one of the strongest barriers that hinder the adoption of new technologies (Hermans et al., 2020), the effect of reduced tillage on labour costs should be investigated in more detail. Additionally, there are several side effects of reduced tillage systems which may impact the economics. While increased soil moisture during dry spells enhances crop yields (Palm et al., 2014) other studies have reported that reduced tillage led to lower yields due to weed competition (Prasad et al., 2016; Okeyo et al., 2016). Thus, in the case that not enough labour is available for the additional weeding required in reduced-tillage systems, the feasibility of reduced tillage could be doubted.

4.2.6. *Co-benefits and trade-offs*

While any increase of SOC due to the carbon sequestration by reduced tillage offers a better nutrient storage, actually observed increases of SOC due to reduced tillage are only observed in about half of the cases and are often rather small. There is some evidence that no-till is more effective in storing SOC in the tropics compared to temperate regions (Six et al., 2002; Derpsch et al., 2010). Yet, increased SOC will not be the main benefit of reduced tillage systems. According to one expert, no-till has to be seen as a practice in the centre of conservation agriculture, where it assures minimal soil disturbance to limit the loss of C to the soil. Yet, the C input depends on the cropping system, which also has to be carefully designed. An improved water infiltration and reduced evaporation due to improved soil cover in successful no-till are expected to have a beneficial effect on agricultural production in water limited systems. Reduced erosion due to better soil cover and soil structure will also have positive impacts, for example on regional water quality, as less soil material is introduced into streams and less nutrients end up in rivers. On the other hand, increased pest pressure, because mulch provides a habitat for pathogens, and increases weed pressure (Prasad et al., 2016), making the application of herbicides or increased manual weeding frequencies necessary could reduce agricultural production or increase the cost of inputs. The local conditions could thus be an explanation why there have been mixed outcomes from reduced tillage systems with regard to crop yield (Palm et al., 2014). One study in Kenya found lower grain yields under reduced tillage, which they accounted to insufficient surface cover in reduced tillage treatments (Okeyo et al., 2016). Tillage has been shown speed up the nitrogen cycle reducing soil microbes, which can in the long run significantly reduce soil nitrogen (Xiao et al., 2019), but could also lead to higher amounts of plant available nitrogen in the short term, thus explaining observed lower yields in some reduced tillage studies. A clear tendency was also not found for the effect of reduced tillage on N_2O emissions (Palm et al., 2014), which calls for a better understanding on how reduced tillage in tropical agroecosystems affect turnover cycles of residues in the soil and the synchrony between plant demand and nutrient release as well as nitrification and denitrification processes. This understanding is crucial to estimate trade-offs of reduced tillage systems, as different processes are relevant for GHG at the same time. For example, Bayer et al. (2016) found in their study, that there were increased N_2O emissions under reduced tillage, but considering GHG on a CO_2 equivalent, these were more than offset by the overall enhanced CO_2 sequestration under reduced tillage. This is in alignment with a meta-analysis of Six et al. (2004), finding that increased N_2O emissions in no-till are offset by SOC sequestration after about 10 years, when the system stars to become a sink of GHG. As adopting reduced tillage may increase labour cost due to higher weeding frequency, and food security is a major issue in Kenya, it is very important to apply reduced tillage only to suitable soils. Monitoring negative side effects and making region specific decisions should be the priority over blanket recommendations, and thus reduced tillage should only be applied where its benefits are assured.

4.2.7. Risks associated with scaling up

As addressed before, there seems to be a strong site specify in the efficiency of no-till and reduced tillage leads to achieve CO_2 sequestration. At the same time, N_2O emissions could be increased due to increased soil moisture. As a conclusion, no-till systems are only a sink if they are applied long-term. A massive upscaling could thus lead to the risk of increased emissions in the initial years followed by an abandonment of the method, due to policy changes. This is especially relevant for countries that are still in rapid development, such as Kenya. Hence, in scaling, it should be assured to make the transition sustainable, as transitioning to no-till and then back may lead to higher GHG emissions than not transitioning in the first place. While in some areas and with some soils reduced tillage may be highly suitable, in other areas it may lead to increased N_2O emissions, while in the worst case not increasing SOC and reducing yields. The main two risks associated with scaling up reduced tillage are thus that it will be recommended as a blanket solution, not only targeted to the areas where benefits are assured, and that it will not be maintained long enough. Thus, more research is needed on the feasibility of reduced tillage as a function of soil properties, cropping systems and social context.

4.2.8. Research gaps

Main research gaps are connected to the main risks. There is a need to better establish how reduced tillage efficiency depends on local soil properties. Also, as reduced tillage reduces aggregate destruction and thus should slow down SOC turnover in theory, it would be important to know how different residue amounts and qualities interact with reduced tillage. As adding residue increases the amount of particulate organic matter, the fraction that is also negatively affected by tillage (Six et al., 1999), it could be that the combination of residue inputs with reduced tillage is most effective in enhancing soil sequestration. Thus, the combination of reduced tillage practices with for example integrated soil fertility management could be synergetic.

4.3. Integrated soil fertility management

4.3.1. Introduction

The term of integrated soil fertility management (ISFM) was defined as a measure to enhance crop yield and maintain soil fertility by the combination of several inputs, such as the use of fertilizer, organic residue inputs and improved germplasm, all adopted to local conditions and aiming at maximizing the agronomic use efficiency of nutrients (Vanlauwe et al., 2010). To be attractive to farmers, the focus of ISFM is on increasing agricultural yields but the main method to do so is focusing on the soil fertility and thus also SOC stocks. Higher crop yields are usually associated with higher amounts of crop residues that can be retained in the field, and together with the recommended application of additional organic residue inputs within ISFM, mostly farmyard manure, this leads to a significant increase in carbon inputs into the soil under ISFM practices. Maintaining and increasing SOC in ISFM is more than a co-benefit, it is the basis for long-term sustainability of yields. Another important point is that ISFM aims to increase yields, thus reducing pressure on other land-uses, such as forests, that are effective C sinks and biodiversity hotspots. The use of ISFM therefore offers the potential to be a double-win strategy, serving as way to enhance agricultural production and food security while simultaneously offering the potential to be an LMT. In that regard, it is important to note that ISFM in most cases may not be a sink of GHG, as in the highly weathered African soils, SOC is almost always lost when they are cultivated (Sommer et al., 2018). Yet, ISFM has to be compared to the baseline condition of farming without inputs, where SOC is lost at 2-4 times higher rates, simultaneously producing having only half the yields. Thus, ISFM can play a very important role in the Kenyan LMT portfolio, as is reduces agricultural emissions and pressure on land for other LMTs (e.g. agroforestry/afforestation). It has been identified that the success of ISFM to enhance yields and SOC stocks depends strongly on the local soil properties, and soils are often categorized into soils that are either responsive or nonresponsive with regards to ISFM (Vanlauwe et al., 2010). Different strategies exist for these soils and while for responsive soils, improved germplasm and fertilizer may already lead to the desired outcome, nonresponsive soils need increased inputs of organic material to achieve higher yields and SOC sequestration (Vanlauwe et al., 2015). ISFM can be seen as a strategy to practice climate-smart agriculture and sustainable intensification.

4.3.2. Policy context

The importance of improved agricultural production techniques that address the currently low productivity of maize systems, improve climate resilience and offering to some extent mitigation of GHG has been recognized in Kenya. Thus, the implementation of climate smart agriculture strategies has been a key strategy and is represented in several important documents such as the official communication of Kenya to the UN regarding actions against climate change (Government of Kenya, 2015). Similar as reduced tillage, ISFM is one of the methods summarized under the umbrella term climate smart agriculture. The goal to increase the use of ISFM in the arable land of Kenya has, for example, been stated by the government in the Kenya climate smart agriculture strategy (Government of Kenya, 2017) as tool to mitigate climate change. The intended actions are in the form of regulatory framework development, capacity building by extension services through NGOs, research institutions and development partners. The ISFM strategy is also included as a strategy in the Kenya National Adaption Plan to climate change (Government of Kenya, 2016). The implementation of ISFM can in theory be done by all farmers that practice agriculture on arable land but it depends on access to the required resources, such as fertilizer, germplasm and organic material, most commonly farmyard manure. As ISFM represents a set of practices in combination, there is no national statistics on how much of it is used. However, local studies make it clear that most farmers possess knowledge on individual parts of ISFM, mainly on mineral fertilizer and manure application, while the use of improved germplasm and the combination of the practices (full ISFM adoption) is less common (Mucheru-Muna et al., 2021). At the moment it is not clear, how commonly established ISFM practices are already at the national level, but once they are established, ISFM practices seem to be beneficial and uptake after extension is high. For example, a study by Mugwe et al. (2009) reported adoption levels of ISFM close to 50% after extension services had been successfully implemented. Many of the ISFM practices are part of the common agricultural practices, but are often applied in isolation, so extension services aiming to promote using all ISFM practices combined could lead to further synergies. For example, a recent study by Wawire et al. (2021), conducted in Meru and Tharaka Nithi counties, reported that adoption rates of different ISFM practices differed and were about 95% for manure and fertilizer application but only around 80% for the application of available residues. While the mentioned studies are not representative for whole Kenya they at least indicate that some ISFM practice are already commonly established and well received. On the other hand, several barriers that hinder the adoption of ISFM on larger scales were identified. The adoption of ISFM seems to be less pronounced under the poorest farmers, as they lack the investment capital necessary to buy fertilizer and germplasm, and there is often the tendency that ISFM is only applied on fields close to the house of farmers, which accumulate a lot of SOC and nutrients, while fields further away are mined for nutrients (Vanlauwe et al., 2015).

In general, funds that are available for the broader umbrella topic of climate smart agriculture should also be available to ISFM. For example, through the Kenya Climate Smart Agriculture Project, 280 mln US $ from the World Bank are available to be spent until 2023. Furthermore, within the Kenya climate smart agriculture strategy 25 bln Ksh (about 230 mln US $ at time of writing) have been attributed to foster the deployment of ISFM in Kenya (Government of Kenya, 2017), but it was not fully clear, if these are the same funds as for the Climate Smart Agriculture Project or additionally available resources.

4.3.3. Current land use and potential land-use competition

As discussed above, there is no exact knowledge on the current level of ISFM adoption across the whole Kenya and the identified studies show differences in adoption depending on the region. Summarizing the findings of different studies, the adoption rates may be as high as 90% (Wawire et al. 2021) for individual ISFM practices. The adoption of all techniques at once in combination, also called complete ISFM, seems to be much lower. For example, Adolwa et al. (2017) only found a 36% adoption rate of full ISFM in Kakamega county. However, as ISFM comprises a double-win strategy, tackling both the need to increase yields and to reduce GHG emissions, the use of ISFM has the potential to be adopted at a much broader scale in the future. The extent to which this will happen is not clear, as official documents only state that it shall be promoted, without specifying an explicit target, neither for ISFM nor for climate smart agriculture. Yet, there is little that speaks against a large-scale adoption of at least some of the ISFM techniques and one of the main benefits of ISFM as a LMT is, that it is not directly in competition with other land uses. In fact, the higher yields that ISFM promises compared to current low-input agriculture (about double), would mean that it reduces competition of agriculture with other land uses.

However, as organic input is required for ISFM, there is the potential for a resource competition for available biomass, for example between the use for animal fodder and input into the soils. That the resources are insufficient to apply ISFM in all fields is already visible in fertility gradients of fields in Kenya, where it is often observed that the fertility of soils decreases with increased distance to farmers homes, because the resources such as organic input are mostly allocated to fields close to the home (Vanlauwe et al. 2015). This is also associated with the way of cultivating, as most is still done with manual labour and many organic inputs, such as farmyard manure are produced close to the home. An even distribution of organic input without mechanization would thus require a lot of additional labour. This could be a barrier for the most efficient utilization of biomass to build up of SOC stocks and increasing nutrients use efficiency, which would probably be highest, if inputs would be evenly distributed on all land used.

4.3.4. Climate risks & sensitivities

The practices of ISFM possess the potential to reduce pressure of climate change in several areas. For example, higher SOC usually is accompanied by improvements in soil structure leading to a better infiltration of rain and to a higher water storage capacity which can reduce the susceptibility to drought. Also, while ISFM is not a specific measure against water erosion, improved soil structure through ISFM could reduce erosion. Yet, erosion control by ISFM alone is likely much less effective than additional climate smart agriculture strategies, such as mulching or conservation tillage, which both lead to an increased soil cover. On the other hand, the effects of climate change could decrease the efficiency of ISFM practices compared to nowadays. For example, all other drivers such as moisture being equal, increased temperatures usually speeds up the turnover of SOC in the soil (Davidson and Janssens, 2006), which could negatively influence the overall potential of ISFM techniques to sequester CO_2 compared to lower temperatures. However, such increased temperatures would affect all soils regardless of whether ISFM is applied or not, so even under increased SOC turnover, should the practice of ISFM be beneficial in comparison to agriculture without improved management. Another sensitivity is related to the availability of biomass. If climate change, for example through drought or heat spells, would reduce net primary productivity, it will indirectly affect the feasibility of ISFM, as less biomass would be available as organic amendment and biomass competition with livestock feed could increase.

4.3.5. Economic implications

Due to the double-win potential of sequestering CO_2 and increasing yield, ISFM has the strong potential to be applied in a cost-efficient way and could already pay off just by the increased yield. However, as the responsiveness between soils differs (Vanlauwe et al, 2015), the application of ISFM may only be cost-efficient in responsive soils, while unresponsive, typically very weathered soils, may not be worth the additional costs for input and labour. The economics surrounding additional labour requirement are context specific and often depend on opportunity costs. For example, Hörner and Wollni (2021) showed in an Ethiopian case study, that despite leading to higher yields, the adoption of ISFM only lead to higher household incomes compared to non-adoption when it was not in competition for labour with other income generating activities. Also, the prices of fertilizers required may be different in different regions of Kenya. For example, Cedrez et al. (2020) showed that regional fertilizer prices within Kenya varied by about a factor of 1.3, depending mostly on how well the road network was in the area. Due to these region-specific differences, estimating a general cost for the CO_2 sequestration by ISFM is difficult to impossible. In the best cases, ISFM may pay off by increased yields alone, while in the worst case with unresponsive soils, ISFM may under no circumstances sequester any CO_2.

4.3.6. Co-benefits and trade-offs

The main aim of ISFM is to increase and sustain yields, so even if it`s implementation is funded with the aim of mitigating CO_2 emissions, it should lead to higher agricultural production. Thus, compared to other LMT, the application of ISFM is not projected to negatively affect agricultural production in any way. In fact, it rather should increase yields, with positive relieve of pressure on other land. The share of arable land in Kenya has, largely due to increased need for food and due to low national yield levels and population growth, increased from about 6% in 1970 to about 10% in 2016 (World Bank 2021). Hence, yield increases reduce the pressure on other land especially given the expected population doubling in the next 35 years (European-Commission and Joint Research Centre, 2018). Often the land cleared for agriculture produces low yields, as it is mostly mined for available nutrients without a proper replenishment, leading to a rapid decline in yields after the first few years. Thus, it seems that the sparing potential for land when increasing yields by applying ISFM could help to leave more land to other land uses.

There may, however, be a trade-off concerning N_2O emissions. Transforming a subsistence agriculture field to ISFM will increase the level of nitrogen inputs, originating both from chemical fertilizer and from plant residues. The change in nutrient inputs can be very significant as traditional subsistence agriculture may have almost no external nitrogen input, while in ISFM, applications of 50-100 kg nitrogen per ha and season are desired. Such an increase of nitrogen inputs on one hand usually increases N_2O emissions on a per area basis. On the other hand, ISFM N_2O emissions may still be lower on a per yield basis, and in responsive soils can be offset by CO_2 sequestration. For example, Dhandli et al. (2016) found that about double the N_2O emissions of ISFM treatments compared to the control treatment on a per area basis. However, yield was increased by a factor of more than 3, so on a per yield basis ISFM had significantly lower N_2O emissions. Also, Sommer et al. (2016) showed clearly that the higher nitrogen inputs through farmyard manure within ISFM lead to higher N_2O emissions. However, many ISFM trial operate at very high input levels of 200 kg nitrogen and more, while farmers may not have as much capital and apply much lower levels, such as only adding 50 kg nitrogen ha^{-1} and season. At such low levels N_2O emissions should be less. To reduce the trade-off by increased N_2O emissions, the focus should be put on the nitrogen use efficiency of organic and chemical nitrogen inputs, and on increasing synchrony between soil nitrogen availability and plant demand, which would lead to both lower N_2O emissions and higher cost-efficiency of ISFM. Also, any GHG emissions from ISFM should be scaled to yield, not per area base, to account for lower land-use competition. The increase of nitrogen inputs also bears the potential of increased NO_3^- leaching, which could affect the ground water quality, if fertilization is overdone. The central concepts of nutrient use efficiency and synchrony within ISFM have thus to be followed rigorously to reduce the risk of inefficient nitrogen use and of environmental pollution.

One additional risk associated with ISFM could be that the need to use improved germplasm, such as hybrid varieties increases the dependence of farmers external actors to provide seeds. Hybrid seeds are poor material for regrowing crops, so they need to be bought each season, increasing the dependence of farmers on seeds vendors. Due to different success rates of ISFM in responsive vs unresponsive soils there is also the risk of poor performance of ISFM if its application is not accompanied by sufficient extension and capacity building.

Overall, the application of ISFM presents a strong potential for a double-win strategy, increasing yield while simultaneously mitigating CO_2 emissions. However, as addressed above, there are risks associated with higher rates of nitrogen application, so it is important to do a case sensitive application of ISFM. For example, the addition of nitrogen fertilizer should be distributed across the season, to best match plant demand and the simultaneous application of mineral fertilizer and plant residues with low nitrogen content can temporarily immobilize soil nitrogen, increasing synchrony between plant demand and release (Gentile et al., 2011).

4.3.7. Risks associated with scaling up

The main risk is likely in the need to consider local differences in the efficiency of ISFM and to properly account for them when scaling up to a national level. More knowledge is therefore needed on the interactions between soil properties, climate and ISFM efficiency. In other words, detailed knowledge on the responsiveness under different soils (Vanlauwe et al, 2015) and climates is needed to apply ISFM in the most efficient way and to avoid negative side effects, such as increased nitrate leaching or N_2O emissions. Apart from that, if ISFM is upscaled, the need for organic inputs may create competition for other biomass uses, such as animal feed. Yet, this may be partly circumvented, as animal manure is one of the most efficient organic inputs into ISFM. In fact, stakeholders frequently stated that the recommended application of green manures is not regularly practiced by farmers, so farmyard manure is the most realistic organic resource for ISFM. The demand for residue inputs may be significant, if high rates applied at some ISFM trials of up to 4 ton carbon per ha and year are followed. Yet already smaller amounts of organic amendments, such as 1.2 ton of carbon, have led to positive effects of ISFM on yield (Chivenge et al., 2009). A key insight from our stakeholder workshop was, that the up to 4 ton carbon per ha and year, as implemented in research trials on ISFM are unrealistic rates at scale. Also, the Kenyan stakeholders stated that the most important organic resource is farmyard manure and that green manures are not commonly applied and rather fed to animals. Farmyard manure should thus be the focus of any upscaling exercise. Realistic rates of application are equivalent to 1 or 2 ton carbon per ha and year, at the low and high end.

4.3.8. Research gaps

Several research gaps exist with respect to ISFM in Kenya. First of all, the national level of ISFM application is currently unknown, so national data on ISFM adoption would be important as a starting point. Also, while the benefit of ISFM with regards to yield and GHG mitigation has received attention, the farm level economics of ISFM adaption may be an important barrier (Hörner and Wollni, 2021) but have not been studied in detail in Kenya. The level of market access to fertilizer for smallholder farmers is an important concern, and lack of infrastructure may hinder access to fertilizer or make it more expensive (Cedrez et al., 2020). Another research gap is how ISFM will affect the yields of crops other than maize, which due to its` importance for nutrition has been the focus of research, while for other crops such as millet only few studies exists (e.g. Dass et al., 2013). Finally, a better understanding of N_2O emissions of ISFM is required to better estimate the emissions on a per yield base and to evaluate the overall GHG sequestration potential of ISFM techniques which may be acting simultaneously as a sink of CO_2 and source of N_2O. This will be crucial to make sure that ISFM will be applied in a form that is most likely to lead to negative emissions and that makes most efficient use of the applied nitrogen.

4.4. Agroforestry

4.4.1. Introduction

Agroforestry is a broad term that addresses the combination of trees or shrubby elements with agricultural production. According to the FAO "Agroforestry can be defined as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels" (Agroforestry (fao.org)). In many ways, agroforestry systems are not a new technology - the presence of trees and shrubs in agricultural landscapes was and still is common around the globe. Also, many species which require shading, for example coffee, are commonly grown in agroforestry systems applying shading trees. However, only in recent decades have intentionally designed agroforestry systems with two or multiple strata become more popular as an increased level of research that focuses on the interactions between the different strata. This is important both in terms of nutrient and light competition. The improved agroforestry systems specifically aim at optimizing synergies between different components while reducing competition to be able to harvest more yield from the tree and crop component on a per area basis, than would be possible in a monoculture system. This is also referred to as reaching a land-equivalent ratio (LER) > 1. A special case where agroforestry coincides partly with ISFM is the introduction of legume trees, where nitrogen can be symbiotically fixed by the trees and enters the soil to become crop available through litterfall or pruning, or provide the feedstock for animals to supply manure to the fields. Agroforestry serves as LMT, mainly due to the clearly measurable increase of aboveground carbon stocks in the woody biomass. Belowground root biomass and even SOC are further potential CO_2 sinks, but they are more difficult to measure and they are also less important in terms of magnitude. According to an estimation by the Kenyan government agroforestry has the largest GHG mitigation potential of all agricultural technologies in Kenya (Government of Kenya, 2015).

4.4.2. Policy context

The target to increase the land under agroforestry has been stated in several policy documents such as the Kenya climate smart agriculture strategy (Government of Kenya, 2017), the official communication of the nationally determined contribution to the UN (Government of Kenya, 2015), the Kenya National Adaption Plan (Government of Kenya, 2016) and the National Climate Change Action Plan (Government of Kenya, 2018b). Most recently the government of Kenya committed to planting an additional 350,000 agroforestry trees as part of their updated nationally determined contribution submitted in 2021. The prospect and perception of agroforestry in Kenya are quite positive. Many farmers in Kenya already apply a simple kind of agroforestry by including trees at the edge of their fields, for example. Furthermore, the World Agroforestry Centre (ICRAF) has its main location in Kenya, and it promotes many projects around agroforestry propagation. However, there are no clear numbers on how much agroforestry is already used in Kenya, which has partly to do with it being a traditional technique in many ways and partly with the difficulty to account for agroforestry systems due to their broad diversity.

In a broader sense, agroforestry could benefit from funds that are expected to be available to target the nationally determined contributions of Kenya. Those are 62 bln US $ until 2030 of which 44 bln US $ will be targeted at adaptation and mitigation options which include agroforestry. It is, however, not clearly specified how the funds will be used exactly. Other funds are available through the 280 mln US $ climate smart agriculture programme (Development Projects : Kenya Climate Smart Agriculture Project - P154784 (worldbank.org)) which includes agroforestry and has assigned 7.4 bln Ksh (about 68 mln US $) to the promotion of agroforestry (Government of Kenya, 2017).

4.4.3. Current land use and potential land-use competition

While it is an understanding that trees in agricultural systems are common in Kenya, a clearly measured baseline on the exact spatial extent of agroforestry is lacking, and it is thus a goal of the of the government to develop a baseline understanding of the extent of agroforestry adoption in Kenya (Government of Kenya, 2017). A major challenge for such a project is the diversity of agroforestry systems, as they are often very heterogeneous and therefore difficult measure through satellite imagery but even ground truthing. The combination of trees agricultural production presents unique challenges for classification and exact quantification of carbon stocks, not only because of difficulties to distinguish between forest and agroforestry systems (Rosenstock et al., 2019) but also because of the diversity of species used, and because allometric equations developed for closed tree stands are not suitable for agroforestry systems (i.e. the growth pattern and shape of trees differ). The most up to date estimate, which however only covers about half of Kenya`s arable land, classified between 5 and 10% of agricultural production areas within the study area as agroforestry systems (Marshall et al., 2017). Through the strong investment in agroforestry, and as agroforestry may partly count to afforestation programmes which Kenya committed to by national law, an increase in agroforestry is to be expected in the coming decades. A clear projection and baseline are however lacking.

A central goal of the Kenyan environmental and climate change mitigation policy is the increase of forest area to at least 10% of Kenya`s land area. One could therefore say that the expansion of forest, as stated by the law and included in the nationally determined contribution, can compete with the expansion and intensification of arable land, as has historically definitely been the case, where forest areas have been cleared to make room for arable land (World-Bank, 2021). Agroforestry in this sense offers a consolidation of the competition between these two land-uses, where trees and agricultural production areas can synergistically be used. More than agricultural area, it may be the labour requirement that prevents upscaling of agroforestry, as the systems due to the need to prune the trees, for example, are labour intensive.

4.4.4. Climate risks & sensitivities

In many ways, agroforestry systems are less vulnerable to extreme climates than traditional arable monocrop systems. Due to the shade that agroforestry systems provide, the crop component in agroforestry systems is more resilient towards many stresses associated with climate change (Sheppard et al., 2020). The shade helps to buffer extreme heat events and the trees provide a better microclimate. Agroforestry systems can also improve soil water status in several ways, for example by reducing the evaporation of a system, both due to shading and by serving as windbreaks. However, the trees do increase the transpiration of the system, which could overall lead to a stronger competition for water between the tree and arable component (Sheppard et al., 2020) but this may not be the case for deep rooting trees, mostly getting water from areas inaccessible to the crop. The additional canopy provided by the trees also provides protection against heavy rains, reducing soil detachment and runoff. This can increase infiltration and reduce erosion, with and additional runoff reduction if trees or shrubs are planted along the contour line, with the root system protecting against landslides or gully erosion. The trees and stripes on which they are established on also provide additional room for biodiversity (Rosenstock et al. 2019), such as habitat for insects or other plant species in the tree stripes.

4.4.5. Economic implications

As agroforestry provides many benefits apart from GHG mitigation, it may already be feasible to apply it, even if there is no compensation for the carbon sequestration. However, through the need to prune the trees for example, agroforestry increases labour demand, so the additional labour required could be an adoption barrier, especially if other off-farm income generating activities are possible (Hörner and Wollni, 2021). While detailed per ha cost of agroforestry implementation in Kenya was not found, based on cost data reported by the Government of Kenya (2018b), it can be estimated that the cost of CO_2 sequestration of afforestation would be in the range of 19 to 29 US $ per ton of CO_2. This does not directly translate into agroforestry systems as they require additional labour and provide additional benefits but could give a rough range. Yet, even if the cost is considerably higher (e.g. double that of forests), agroforestry would still be a rather cheap option to mitigate GHG on a global price perspective and would alleviate the inherent competition for land between agricultural production and trees.

4.4.6. Co-benefits and trade-offs

Yield losses compared to monocropping systems have been reported in some instances (Sheppard et al., 2020), but as light is usually not a limiting factor in the tropics, they are not the norm in tropical agroforestry systems. Most often, and especially if tree provide has marketable fruits or high value timber, agroforestry systems have a land equivalent ratio significantly above 1, meaning there is a strong benefit for agricultural production and increased productivity of the land. Several stakeholders also reported on additional benefits, such as a higher biodiversity. Due to the generally positive yields and ecosystem services, increased labour requirements of agroforestry systems could be the main limiting factor, for example when agroforestry operations are competing with other economic on-farm activities. However, other benefits that agroforestry offers are increased landscape diversity and for the farmer income diversification (Sheppard et al., 2020), so they may be worth the additional labour required. In the special case of implementing legume trees into agroforestry system there exists the possibility that N_2O emissions increase (Rosenstock et al., 2014), yet this may only happen under a strong mismanagement leading to a poor synchrony between crop nitrogen demand and provisioning (Palm et al., 2001). In general agroforestry systems increase nutrient use efficiency, reduce nutrient losses and sometimes even fix additional nutrients (i.e. nitrogen by legume trees). Thus, from a nutrient cycling perspective the benefits largely dominate, and introduction of symbiotic nitrogen fixation is a wanted trait under nitrogen limited systems, common in Kenya. Therefore, with the exception of poorly managed legume tree systems, agroforestry does not lead to increases N_2O emissions but rather improves nutrient cycling (Kim et al., 2016). An additional benefit of agroforestry systems is the more profound depth of tree roots compared to annual crop roots. This presents an efficient safety net to reduce nutrient leaching, as trees can take up nutrients that are leached beyond the root zone of annual crops. This effect can be rather strong, for example Wolz et al. (2018) found that in a maize soybean rotation alley cropping, a modern agroforestry system, reduced nitrate leaching by 90% compared to the monoculture system. Additionally, the permanent root system and vegetation stripes of agroforestry present an effective measure against erosion, which also benefits water quality. As already mentioned, the main trade-off that seems to exist for agroforestry implementation is the increased labour requirement, which is in competition with other income activities and is one of the main adoption barriers for agroforestry (Gosling et al. 2021). Thus, it is worthwhile to understand how this adoption barrier can be overcome. An option would be to provide additional adoption incentives, for example through promoting of high value fruit trees that provide additional income. Also, external payments could be an option, but such incentive systems have to be designed with care and bear the risk of lowering the actual interest in the trees making their implementation only a way gain money. An interesting finding is, that social norms and community pressure play a key role in the adoption of agroforestry (Buyinza et al., 2020) and thus improving the social perception of agroforestry could be a leverage point to enhance agroforestry adoption.

4.4.7. Risks associated with scaling up

If done well, with at suitable selection of trees and crops, there is very little risks associated with scaling up agroforestry to the national level in Kenya. The main barrier could be household economics regarding labour constraints rather than any environmental or food security concerns. It may thus be the best way to provide additional incentives to adopters of agroforestry. Even payments for ecosystem services could be an option but would need to be accompanied by open and suitable communication, so that adopters still feel that they adopt agroforestry due to the additional benefits it provides and do not only do it to get short term access to capital, abandoning it as soon as capital flows stop. This “buy-in” into the technology is especially important for agroforestry as it is a long-term investment and needs some time until it is fully established.

4.4.8. Research gaps

Several key research gaps that are yet to be closed include the baseline of how much agroforestry is already adopted in Kenya, but also how to estimate the amount of carbon stored in these highly diverse systems (Rosenstock et al., 2019). As they are not exclusive, it would also be of interest how agroforestry could be coupled with the other discussed LMT, such as reduced tillage or ISFM, as further synergies might be possible. Finally, more attention should be paid to adoption barriers, such as labour requirements. A special focus with regard to social justice agenda should be how poverty affects agroforestry adoption, as it has been indicated that the lack of capital often hinders the economically poorest households to adopt agroforestry, as they are in need for short term economic gains and lack the capital to invest in agroforestry, which does only start to pay off after several years (Cavanagh et al., 2017).

4.4.1. Introduction

According to the FAO definition, which is also used in Kenya, forest is defined as land with a tree cover of at least 10% and an area of more than 0.5 ha with trees being at least of 5 m height, once they reach maturity (FAO, 2000), so some agroforestry systems may also count as forest. This section, however deals with forests that only/mainly consist of trees and to not target food production by agriculture. Forests store large amounts of carbon, mostly in the biomass, and regrowing forests can therefore be a strong sink of CO_2. Additionally, as most of the carbon stored in forest is stored aboveground in the trees, it is relatively simple to estimate the amount of carbon stored in homogeneous forests. Thus, reforestation of suitable land, such as areas that were initially forests but have been deforested, represent effective, reliable, and quantifiable sinks of CO_2 and is therefore seen as a highly suitable LMT. In Kenya, due to historical deforestation of major portions of the indigenous forest, starting in colonial period (Government of Kenya, 2014), there is a lot of land that bears the natural potential to accommodate forests, but which is currently not covered by forest. Deforestation was very high towards the end of the 20th century and only roughly 6% of land was covered by forest in the early 2000s (World-Bank, 2021). However, there have been afforestation measures in recent decades leading to an increase of forest cover, which is now around 8%, with an official goal of reaching at least 10% of forest cover by 2030. This aim of achieving 10% of forest cover in Kenya has been implemented into state law (Government of Kenya, 2014). The importance of afforestation in Kenya is also highlighted by the fact that afforestation has been identified as the only technology in the sector of climate change mitigation which can lead to significant negative emissions in Kenya in the official analysis of mitigation potential (Government of Kenya, 2018b).

4.5. Afforestation and forest conservation

4.5.1. Policy context

Several official Kenyan policy documents state the clear goal of afforestation to reach 10% of forest cover in Kenya (Government of Kenya, 2014; 2018a). This is derived from the constitution of Kenya, which in article 69(1)b, states explicitly that the “state shall work to achieve and maintain a tree cover a tree cover of at least ten per cent of the land area of Kenya". This commitment is not only internal, but the government of Kenya has also committed internationally to reaching the 10% forest cover in within their nationally determined contribution submitted to the UN (Government of Kenya, 2015). Several governmental afforestation programmes are enacted, but it was stated that community and private land need to be included into afforestation efforts to reach the target 10% cover (Government of Kenya, 2020). There are also several important NGOs which promote which strongly promote an afforestation in Kenya. The most famous one is certainly the green belt movement founded by Professor Wangari Maathai in 1977 (The Green Belt Movement), which combines the planting of trees with communities taking more responsibility for their land and with women empowerment. The importance of afforestation in national policies has also been confirmed by stakeholder interviews. However, they identified a difficulties to implement these policies on the ground level, mainly due to local laws and national laws not being aligned, as well as unwritten "traditional community rules" being opposed to afforestation in some ares.

Large finances are to be made available for the afforestation programmes. Kenya has identified a need of about 4 bln US $ until 2030 for their reforestation programmes (Government of Kenya, 2018b), which are to come out of the money dedicated to Kenya`s nationally determined contribution (Government of Kenya, 2020b). Additional, private funds are available for the reforestation programmes which can be received for specific project upon application, for example from the reforestation grants of the world wildlife foundation (Reforestation Grants | Projects | WWF (worldwildlife.org)).

4.5.2. Current land use and potential land-use competition

From a spatial coverage of forests on about 12% of Kenya`s land area at the time of independence in 1963 (Government of Kenya, 2018a) only half (i.e. 6%) remained in the early 2000s (Government of Kenya, 2018a). However, due to strengthened forest policies and afforestation programmes a recovery to about 7.8% of land area in 2016 (World-Bank, 2021) was achieved. As the stated official objective implemented in the constitution of Kenya is to increase forest cover to at least 10% of Kenya`s surface area in 2030, there is a clear target line which must be met and can be anticipated if policies do not fail. To which extent forest cover will surpass the 10% of land area is open, as much of the land in Kenya is too dry to support forests and is a savanna type of vegetation. While the clear goal of 10% forest cover exists, the main competition to forest is area for agricultural production, especially as low-input agriculture which is still very common in Kenya (total fertilizer consumption ~ 60 kg per ha and year, less than half the world average; World-Bank, 2021). It is also foreseeable that there is an increasing pressure on land in Kenya, the strongest drivers of which are the population growth and the resulting need for food. This trend is not expected to end any time soon, as Kenya is still a strongly developing country, aiming at 6% GDP growth per year and population growth is expected to only level of around the year 2100 and with a population around 120 mln people, which is more double the population compared to today (United Nations, 2019). This development is exacerbated by the relatively low productivity of agricultural land in Kenya, compared to the global average. This highlight the need to think of LMTs as a portfolio where synergies (e.g. between afforestation, agroforestry and ISFM) must be sought if any land use change shall be sustainable. In that sense, the yield gap presents an opportunity in a synergistic scenario, as an increased productivity from agriculture could make more land available to afforestation. Apart from the threat of forest clearing for agricultural production area, the fact that 87% of the rural population still depend on firewood for cooking, poses additional pressure on the forest biomass (Government of Kenya, 2018b), which could be alleviated with the introduction of alternatives for cooking to reduce the pressure on forest, while also providing health benefits. In this context, also poverty itself has been named as a driver of deforestation (Müller and Mburu, 2009) as people in strong financial need may cut trees as a means to quickly generate money by selling either the wood or charcoal.

4.5.3. Climate risks & sensitivities

Forests are threatened by climate change in several ways. They could suffer severely both from increased heat, and increased frequency and strength of drought events. The change in precipitation distribution was also identified by stakeholders as one of the main risks. The situation is exacerbated in the early stages of afforestation, as small trees do not yet offer much protection against erosion and soil degradation. Also, naturally emerging trees tend to be at lower risk than trees planted as seedlings. The major stress on forests that climate change poses, could reach a degree where forest ecosystems are destabilized and the climate becomes more suitable for savanna than forest ecosystems (Hély et al., 2006). According to stakeholders, the risk of this is higher for afforested areas than for natural forest. Also, forest fires, which occur mainly during dry season, are a major threat to forests in Kenya (Ongeri et al. 2020), and the risk for them could increase with increased severity of droughts due to climate change. Yet, most forest fires in Kenya, to date, are related to human activities, such as land clearing, charcoal production, or hunting, while natural ignition is extremely rare (Poletti et al., 2019). However, even for man-made forest fires could increase severity due to climate change if higher temperatures and drought occur in combination. Apart from forests being under threat from climate change, afforestation can alleviate some risks from climate change. For example, forests are associated with high biodiversity (Muriithi and Kenyon, 2002), so increasing the area of forest could combat the loss of biodiversity, which however strongly depends on forest species decomposition and management.

4.5.4. Economic implications

While exact costs for CO_2 sequestration by forests in Kenya are not clear, it is very likely from other international studies, that afforestation will be one of the most cost-efficient ways to sequester CO_2 in international comparison with many other more technical LMT. For example, Torres et al. (2010) estimated the cost of carbon sequestration through afforestation in Mexico to be somewhere in the range between 10 and 40 US $ per ton of carbon, which roughly corresponds to 3 to 11 US $ per ton of CO_2. Even though this is not directly transferrable to Kenya, it gives a hint on how cost-efficient afforestation could be compared to for example technical solutions such as BECCS, which are often estimated to only start at around 100 US $ per ton of CO_2. While there is no official statement of cost for GHG sequestration by afforestation, it can be roughly estimated using the estimated project costs and sequestration potential from available data stated by the Government of Kenya (2018b). Using this data, it can be estimated the cost of GHG sequestration by afforestation would be roughly 19 to 29 US $ per ton of CO_2 sequestered. One point that was raised by a stakeholder, was that the cost of afforestation is often overly optimistic, mainly representing the cost of planting. Yet, many earlier afforestation projects failed as they did not consider the cost of managing the trees, even watering in some case, so that they would survive. The cost of good an sustainable afforestation may thus be higher. It also has to be mentioned in this context, that the storage in the woody biomass of forests is not permanent and may be lost for example due to forest fires. From a sequestration perspective it would probably be best to sustainably extract the wood for a long-term material use, which could also represent an economic activity.

4.5.5. Co-benefits and trade-offs

With the expected population increase in Kenya, the biggest risk of large-scale afforestation projects is most likely the competition for land between agriculture and forests. As stated before, this risk would be exacerbated, if agricultural production remains at the low levels that it is currently at. Yet it also shows how the implementation of productivity enhancing techniques, such as integrated soil fertility management, at the same time as afforestation are needed to partly alleviate this competition. As forests provide many ecosystems services, such as increased biodiversity, provisioning of clean water and landscape diversification, many co-benefits of afforestation are likely. In terms of social justice, it will be very relevant how forest protection will be realized, so that local people are not alienated from their land. Often forest protection policies, especially the establishment of conservation areas bears colonial heritages, remove local people`s right to use the land and offers little to them apart from temporary labour to establish the protected area (Pulhin et al., 2010). Also, it has been noted that many large-scale afforestation projects in Africa, such as the Bonn challenge, ignore the initial suitability of afforestation and plan to implement forest or rather tree plantations on originally grassy biomes (Bond et al., 2019). It will therefore be very important take local people`s knowledge into account when conducting afforestation programmes and to assure that they directly benefit from the afforestation and implementation. Finally, these large initiatives, according to a stakeholder view, sometimes sell tree plantations as forest, which clearly have much less of the biodiversity and resilience compared to diverse forest. As a result, enabling afforestation through local NGOs such as the green belt movement, could be a better way than top-down implementation mainly by governmental action or, worse, foreign investment that does not consider the local context at all. From a trade-off and social justice perspective it seems to be most relevant to make sure that afforestation is not done in isolation, but instead as part of a portfolio of techniques that enables the provisioning of ecosystem services to local people, including sufficient food production and water availability. It should also be made sure that afforestation is done rather as restoration of degraded forest to be as natural as possible rather than planting tree plantations on originally grassy biomes (Bond et al., 2019). With a high projected population increase, the increase of yield on agricultural areas seems to be key to reducing the pressure on land in total and to enable any afforestation to be lasting. Additionally, it is important that it is implemented in a local way, that people benefit from it and have a sense of ownership due to the ecosystem services they gain from the forest, and because they maintain the right to use the forest products in a sustainable way, instead of "protecting" the forest by restricting people from any use.

4.5.6. Risks associated with scaling up

As already mentioned above, one of the main risks associated with afforestation is the competition for land with agriculture, especially if agricultural production does not increase at the same time. At areas which are very suitable for agriculture, the establishment of agroforestry may be the most efficient way to allow for a higher tree cover, while offering synergies for agricultural production. Another risk is that afforestation is done with a lack of local biome understanding, mis-specifying grassy biomes as deforested area and implementing, in the worst cases, tree plantations on them (Bond et al., 2019). Even in suitable forest areas there could be a risk for unsuitable choices of tree species, if afforestation is done with a centrally planned blanket approach, only using a few tree species. The local suitability should therefore be a key component in afforestation programmes. Finally, a key risk is that afforestation is understood as only planting trees. From the stakeholder interviews it became clear, that intensive nourishment may be necessary, especially in the first years to establish new forest areas. Additionally, it was highlighted that long-term protection of new afforested sites is crucial. This should best be done by communities reaping benefits from forest areas and allowing them to sustainably use the forest, instead of top-down protection and law enforcement.

4.5.7. Research gaps

The main research gaps to address involve how the need for afforestation and increased agricultural production can be brought together. In this regard, it is also a relevant question how afforestation can be implemented in a way that is sustainable, i.e. that there is an interest to maintain planted trees after the planting project duration. This is especially relevant in Kenya, where firewood is still the most used form of fuel for cooking and thus there is a demand for timber that could be in conflict with the afforestation programmes. With regards to the definition of forests at having at least 10% of tree cover, it is also of interest to better differentiate agroforestry systems from real forests, because 10% cover could also be achieved in agroforestry systems.

5. Conclusions

As indicated by the NDCs and the constitutional 10% forest cover that Kenya pledged to, there is significant interest in LMTs. Kenya is already affected by a changing climate and Kenyan politicians are strongly aware of the fact that the role of Kenya in historic emissions is very low. Hence, there is the (justified) expectation of Kenyans to receive international support in the implementation of LMTs. At the same time, there is a focus on LMTs that do not only store carbon, but also increase ecosystem resilience to a changing climate. The highest potential in Kenya is attributed to afforestation and forest conservation. At the same time, the importance of the agricultural sector is well recognized in two aspects: 1) the storage potential of soil carbon by improved practices itself and 2) the indirect effect of higher crop productivity. The second aspect may well be the most important one, as the need for agricultural production is realized to be a key driver of conversion of natural land, such as forest, to agricultural area. This highlights the importance of a portfolio of several LMTs, including sustainable intensification schemes of lower carbon storage potential, such as ISFM and conservation agriculture, and LMTs of higher carbon storage potential such as afforestation/forest conservation. Agroforestry in that sense represents an interesting combination, as is a sustainable intensification scheme, provides climate resilience and, depending on the tree density, can also be counted as afforestation. For the authors of this report, no clear priority of LMTs in Kenya emerges. Rather, it seems that a successful implementation is only possible if they are implemented simultaneously and with a focus on ecosystem climate resilience.

6. References

Adolwa, I.S., Schwarze, S., Waswa, B., Buerkert, A., 2019. Understanding system innovation adoption: A comparative analysis of integrated soil fertility management uptake in Tamale (Ghana) and Kakamega (Kenya). Renewable Agriculture and Food Systems 34, 313–325. https://doi.org/10.1017/S1742170517000485

Akinnifesi, F.K., Ajayi, O.C., Sileshi, G., Chirwa, P.W., Chianu, J., 2010. Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. Agron. Sustain. Dev. 30, 615–629. https://doi.org/10.1051/agro/2009058

Bayer, C., Gomes, J., Zanatta, J.A., Vieira, F.C.B., Dieckow, J., 2016. Mitigating greenhouse gas emissions from a subtropical Ultisol by using long-term no-tillage in combination with legume cover crops. Soil and Tillage Research 161, 86–94. https://doi.org/10.1016/j.still.2016.03.011

Bond, W.J., Stevens, N., Midgley, G.F., Lehmann, C.E.R., 2019. The Trouble with Trees: Afforestation Plans for Africa. Trends in Ecology & Evolution 34, 963–965. https://doi.org/10.1016/j.tree.2019.08.003

Butnan, S., Vityakon, P., 2020. The interactive effects of soil disturbance and residue quality on soil nitrogen mineralisation in a tropical sandy soil. Soil Res. 58, 277–288. https://doi.org/10.1071/SR18350

Buyinza, J., Nuberg, I.K., Muthuri, C.W., Denton, M.D., 2020. Assessing smallholder farmers' motivation to adopt agroforestry using a multi-group structural equation modeling approach. Agroforest Syst 94, 2199–2211. https://doi.org/10.1007/s10457-020-00541-2

Cavanagh, C.J., Chemarum, A.K., Vedeld, P.O., Petursson, J.G., 2017. Old wine, new bottles? Investigating the differential adoption of 'climate-smart' agricultural practices in western Kenya. Journal of Rural Studies 56, 114–123. https://doi.org/10.1016/j.jrurstud.2017.09.010

Cedrez, C.B., Chamberlin, J., Guo, Z., Hijmans, R.J., 2020. Spatial variation in fertilizer prices in Sub-Saharan Africa. PLOS ONE 15, e0227764. https://doi.org/10.1371/journal.pone.0227764

Chivenge, P., Vanlauwe, B., Gentile, R., Wangechi, H., Mugendi, D., Kessel, C. van, Six, J., 2009. Organic and Mineral Input Management to Enhance Crop Productivity in Central Kenya. Agronomy Journal 101, 1266–1275. https://doi.org/10.2134/agronj2008.0188x

Dass, A., Sudhishri, S., Lenka, N.K., 2013. Integrated Nutrient Management to Improve Finger Millet Productivity and Soil Conditions in Hilly Region of Eastern India. Journal of Crop Improvement 27, 528–546. https://doi.org/10.1080/15427528.2013.800828

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173. https://doi.org/10.1038/nature04514

Derpsch, R., Friedrich, T., Kassam, A., Hongwen, L., 2010. Current status of adoption of no-till farming in the world and some of its main benefits 3, 25.

Dhadli, H.S., Brar, B.S., Black, T.A., 2016. N2O emissions in a long-term soil fertility experiment under maize–wheat cropping system in Northern India. Geoderma Regional 7, 102–109. https://doi.org/10.1016/j.geodrs.2016.02.003

European-Commission, Joint Research Centre, 2018. Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries. Publications Office of the European Union, LU.

FAO, 2000. FRA 2000 ON DEFINITIONS OF FOREST AND FOREST CHANGE. Rome.

Foley, J.A., 1994. Net primary productivity in the terrestrial biosphere: The application of a global model. Journal of Geophysical Research: Atmospheres 99, 20773–20783. https://doi.org/10.1029/94JD01832

Gentile, R., Vanlauwe, B., Chivenge, P., Six, J., 2011. Trade-offs between the short- and long-term effects of residue quality on soil C and N dynamics. Plant Soil 338, 159–169. https://doi.org/10.1007/s11104-010-0360-z

Gosling, E., Knoke, T., Reith, E., Reyes Cáceres, A., Paul, C., 2021. Which Socio-economic Conditions Drive the Selection of Agroforestry at the Forest Frontier? Environmental Management 67, 1119–1136. https://doi.org/10.1007/s00267-021-01439-0

Government of Kenya, 2020a. Re: Submission of Kenya’s updated nationally determined contribution. Ministry of Environment and Forestry, Nairobi.

Government of Kenya, 2020b. DRAFT NATIONAL FOREST POLICY,. Ministry of Environment, Water and Natural Resources, Nairobi.

Government of Kenya, 2018a. National Climate Change Action Plan (Kenya) Volume 3: Mitigation Technical Analysis Report. Ministry of Environment and Forestry, Nairobi.

Government of Kenya, 2018b. National Climate Change Action Plan (Kenya) 2018-2022. Ministry of Environment and Forestry, Nairobi.

Government of Kenya, 2017. Kenya Climate Smart Agriculture Strategy-2017-2026. Ministry of Agriculture, Livestock and Fisheries, Nairobi.

Government of Kenya, 2016. Kenya National Adaptation Plan: 2015-2030. National Environment Management Authority, Government of Kenya, Nairobi.

Government of Kenya, 2015. Second National Communication to the United Nations Framework Convention on Climate Change. National Environment Management Authority, Government of Kenya, Nairobi.

Government of Kenya, 2014. Forest Policy. Ministry of Environment, Water and Natural Resources, Nairobi.

Hély, C., Bremond, L., Alleaume, S., Smith, B., Sykes, M.T., Guiot, J., 2006. Sensitivity of African biomes to changes in the precipitation regime. Global Ecology and Biogeography 15, 258–270. https://doi.org/10.1111/j.1466-8238.2006.00235.x

Hermans, T.D.G., Whitfield, S., Dougill, A.J., Thierfelder, C., 2021. Why we should rethink 'adoption' in agricultural innovation: Empirical insights from Malawi. Land Degradation & Development 32, 1809–1820. https://doi.org/10.1002/ldr.3833

Hörner, D., Wollni, M., 2021. Integrated soil fertility management and household welfare in Ethiopia. Food Policy 100, 102022. https://doi.org/10.1016/j.foodpol.2020.102022

Kamoni, P.T., Gicheru, P.T., Wokabi, S.M., Easter, M., Milne, E., Coleman, K., Falloon, P., Paustian, K., 2007. Predicted soil organic carbon stocks and changes in Kenya between 1990 and 2030. Agriculture, Ecosystems & Environment, Soil carbon stocks at regional scales 122, 105–113. https://doi.org/10.1016/j.agee.2007.01.024

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., Nyberg, G., Vanlauwe, B., Röing de Nowina, K., 2019. Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. Field Crops Research 235, 18–26. https://doi.org/10.1016/j.fcr.2019.02.015

Kim, D.-G., Kirschbaum, M.U.F., Beedy, T.L., 2016. Carbon sequestration and net emissions of CH4 and N2O under agroforestry: Synthesizing available data and suggestions for future studies. Agriculture, Ecosystems & Environment 226, 65–78. https://doi.org/10.1016/j.agee.2016.04.011

Kuyah, S., Öborn, I., Jonsson, M., Dahlin, A.S., Barrios, E., Muthuri, C., Malmer, A., Nyaga, J., Magaju, C., Namirembe, S., Nyberg, Y., Sinclair, F.L., 2016. Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. International Journal of Biodiversity Science, Ecosystem Services & Management 12, 255–273. https://doi.org/10.1080/21513732.2016.1214178

Lillesø, J.-P. B., van Breugel, P., Kindt, R., Bingham, M., Sebsebe Demissew, Dudley, C., Friis, I., Gachathi, F., Kalema, J., Mbago, F., Minani, V., Moshi, H.N., Mulumba, J., Namaganda, M., Ndangalasi, H.J.,, Ruffo, C.K., Jamnadass, R. and Graudal, L, 2011. Potential natural vegetation of eastern Africa. Volume 1: The Atlas. . Forest & Landscape Working Paper 61-2011.

Marenya, P.P., Barrett, C.B., 2007. Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya. Food Policy 32, 515–536. https://doi.org/10.1016/j.foodpol.2006.10.002

Margenot, A.J., Pulleman, M.M., Sommer, R., Paul, B.K., Parikh, S.J., Jackson, L.E., Fonte, S.J., 2017. Biochemical proxies indicate differences in soil C cycling induced by long-term tillage and residue management in a tropical agroecosystem. Plant Soil 420, 315–329. https://doi.org/10.1007/s11104-017-3401-z

Marshall, M., Norton-Griffiths, M., Herr, H., Lamprey, R., Sheffield, J., Vagen, T., Okotto-Okotto, J., 2017. Continuous and consistent land use/cover change estimates using socio-ecological data. Earth System Dynamics 8, 55–73. https://doi.org/10.5194/esd-8-55-2017

Mucheru-Muna, M.W., Ada, M.A., Mugwe, J.N., Mairura, F.S., Mugi-Ngenga, E., Zingore, S., Mutegi, J.K., 2021. Socio-economic predictors, soil fertility knowledge domains and strategies for sustainable maize intensification in Embu County, Kenya. Heliyon 7, e06345. https://doi.org/10.1016/j.heliyon.2021.e06345

Mugwe, J., Mugendi, D., Mucheru-Muna, M., Merckx, R., Chianu, J., Vanlauwe, B., 2009. DETERMINANTS OF THE DECISION TO ADOPT INTEGRATED SOIL FERTILITY MANAGEMENT PRACTICES BY SMALLHOLDER FARMERS IN THE CENTRAL HIGHLANDS OF KENYA. Experimental Agriculture 45, 61–75. https://doi.org/10.1017/S0014479708007072

Müller, D., Mburu, J., 2009. Forecasting hotspots of forest clearing in Kakamega Forest, Western Kenya. Forest Ecology and Management 257, 968–977. https://doi.org/10.1016/j.foreco.2008.10.032

Muriithi, S., Kenyon, W., 2002. Conservation of biodiversity in the Arabuko Sokoke Forest, Kenya. Biodiversity and Conservation 11, 1437–1450. https://doi.org/10.1023/A:1016234224819

Okeyo, J.M., Norton, J., Koala, S., Waswa, B., Kihara, J., Bationo, A., Okeyo, J.M., Norton, J., Koala, S., Waswa, B., Kihara, J., Bationo, A., 2016. Impact of reduced tillage and crop residue management on soil properties and crop yields in a long-term trial in western Kenya. Soil Res. 54, 719–729. https://doi.org/10.1071/SR15074

Ongeri, D., Kenduiywo, B.K., 2020. BURNT AREA DETECTION USING MEDIUM RESOLUTION SENTINEL 2 AND LANDSAT 8 SATELLITES, in: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Presented at the XXIV ISPRS Congress, Commission V and Youth Forum (Volume XLIII-B5-2020) - 2020 edition, Copernicus GmbH, pp. 131–137. https://doi.org/10.5194/isprs-archives-XLIII-B5-2020-131-2020

Ouédraogo, M., Houessionon, P., Zougmoré, R.B., Partey, S.T., 2019. Uptake of Climate-Smart Agricultural Technologies and Practices: Actual and Potential Adoption Rates in the Climate-Smart Village Site of Mali. Sustainability 11, 4710. https://doi.org/10.3390/su11174710

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, P., 2014. Conservation agriculture and ecosystem services: An overview. Agriculture, Ecosystems & Environment, Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia 187, 87–105. https://doi.org/10.1016/j.agee.2013.10.010

Palm, C.A., Giller, K.E., Mafongoya, P.L., Swift, M.J., 2001. Management of organic matter in the tropics: Translating theory into practice. Nutrient Cycling in Agroecosystems 61, 63–75. https://doi.org/10.1023/A:1013318210809

Poletti, C., Dioszegi, G., Nyongesa, K.W., Vacik, H., Barbujani, M., Kigomo, J.N., 2019. Characterization of Forest Fires to Support Monitoring and Management of Mount Kenya Forest. mred 39, R1–R12. https://doi.org/10.1659/MRD-JOURNAL-D-18-00104.1

Prasad, J.V.N.S., Rao, Ch.S., Srinivas, K., Jyothi, Ch.N., Venkateswarlu, B., Ramachandrappa, B.K., Dhanapal, G.N., Ravichandra, K., Mishra, P.K., 2016. Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi arid tropics of southern India. Soil and Tillage Research 156, 131–139. https://doi.org/10.1016/j.still.2015.10.013

Pulhin, J.M., Larson, A.M., Pacheco, P., 2012. Regulations as Barriers to Community Benefi ts in Tenure Reform, in: Forests for People: Community Rights and Forest Tenure Reform. Earthscan, London, UK, pp. 155–175. https://doi.org/10.4324/9781849774765-18

Rosenstock, T., Tully, K., Arias-Navarro, C., Neufeldt, H., Butterbach-Bahl, K., Verchot, L., 2014. Agroforestry with N2-fixing trees: sustainable development’s friend or foe? Current Opinion in Environmental Sustainability, Sustainability challenges 6, 15–21. https://doi.org/10.1016/j.cosust.2013.09.001

Rosenstock, T.S., Dawson, I.K., Aynekulu, E., Chomba, S., Degrande, A., Fornace, K., Jamnadass, R., Kimaro, A., Kindt, R., Lamanna, C., Malesu, M., Mausch, K., McMullin, S., Murage, P., Namoi, N., Njenga, M., Nyoka, I., Paez Valencia, A.M., Sola, P., Shepherd, K., Steward, P., 2019a. A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa. One Earth 1, 330–344. https://doi.org/10.1016/j.oneear.2019.10.017

Rosenstock, T.S., Wilkes, A., Jallo, C., Namoi, N., Bulusu, M., Suber, M., Mboi, D., Mulia, R., Simelton, E., Richards, M., Gurwick, N., Wollenberg, E., 2019b. Making trees count: Measurement and reporting of agroforestry in UNFCCC national communications of non-Annex I countries. Agriculture, Ecosystems & Environment 284, 106569. https://doi.org/10.1016/j.agee.2019.106569

Roser, M., Ritchie, H., Ortiz-Ospina, E., 2013. World Population Growth. Our World in Data.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M., Hashimoto, H., 2004. A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. BioScience 54, 547–560. https://doi.org/10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2

Segnini, A., Posadas, A., da Silva, W.T.L., Milori, D.M.B.P., Gavilan, C., Claessens, L., Quiroz, R., 2019. Quantifying soil carbon stocks and humification through spectroscopic methods: A scoping assessment in EMBU-Kenya. Journal of Environmental Management 234, 476–483. https://doi.org/10.1016/j.jenvman.2018.12.108

Sheppard, J.P., Bohn Reckziegel, R., Borrass, L., Chirwa, P.W., Cuaranhua, C.J., Hassler, S.K., Hoffmeister, S., Kestel, F., Maier, R., Mälicke, M., Morhart, C., Ndlovu, N.P., Veste, M., Funk, R., Lang, F., Seifert, T., du Toit, B., Kahle, H.-P., 2020. Agroforestry: An Appropriate and Sustainable Response to a Changing Climate in Southern Africa? Sustainability 12, 6796. https://doi.org/10.3390/su12176796

Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems. Soil Science Society of America Journal 63, 1350–1358. https://doi.org/10.2136/sssaj1999.6351350x

Six, J., Feller, C., Denef, K., Ogle, S.M., Sa, J.C. de M., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. Agronomie 22, 755–775. https://doi.org/10.1051/agro:2002043

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biology 10, 155–160. https://doi.org/10.1111/j.1529-8817.2003.00730.x

Sommer, R., Mukalama, J., Kihara, J., Koala, S., Winowiecki, L., Bossio, D., 2016. Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in Western Kenya. Nutr Cycl Agroecosyst 105, 229–248. https://doi.org/10.1007/s10705-015-9693-6

Sommer, R., Paul, B.K., Mukalama, J., Kihara, J., 2018. Reducing losses but failing to sequester carbon in soils – the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. Agriculture, Ecosystems & Environment 254, 82–91. https://doi.org/10.1016/j.agee.2017.11.004

Tessema, B., Sommer, R., Piikki, K., Söderström, M., Namirembe, S., Notenbaert, A., Tamene, L., Nyawira, S., Paul, B., 2020. Potential for soil organic carbon sequestration in grasslands in East African countries: A review. Grassland Science 66, 135–144. https://doi.org/10.1111/grs.12267

Torres, A.B., Marchant, R., Lovett, J.C., Smart, J.C.R., Tipper, R., 2010. Analysis of the carbon sequestration costs of afforestation and reforestation agroforestry practices and the use of cost curves to evaluate their potential for implementation of climate change mitigation. Ecological Economics 69, 469–477. https://doi.org/10.1016/j.ecolecon.2009.09.007

United Nations, 2019. World Population Prospects - Population Division - United Nations [WWW Document]. URL https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/404 (accessed 2.16.21).

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—A review. Field Crops Research, Crop Yield Gap Analysis – Rationale, Methods and Applications 143, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N., 2010. Integrated Soil Fertility

Management: Operational Definition and Consequences for Implementation and Dissemination. Outlook Agric 39, 17–24. https://doi.org/10.5367/000000010791169998

Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. SOIL 1, 491–508. https://doi.org/10.5194/soil-1-491-2015

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339, 35–50. https://doi.org/10.1007/s11104-010-0462-7

Wawire, A.W., Csorba, Á., Kovács, E., Mairura, F.S., Tóth, J.A., Michéli, E., 2021a. Comparing farmers' soil fertility knowledge systems and scientific assessment in Upper Eastern Kenya. Geoderma 396, 115090. https://doi.org/10.1016/j.geoderma.2021.115090

Wawire, A.W., Csorba, Á., Tóth, J.A., Michéli, E., Szalai, M., Mutuma, E., Kovács, E., 2021b. Soil fertility management among smallholder farmers in Mount Kenya East region. Heliyon 7, e06488. https://doi.org/10.1016/j.heliyon.2021.e06488

Wilson, M.H., Lovell, S.T., 2016. Agroforestry—The Next Step in Sustainable and Resilient Agriculture. Sustainability 8, 574. https://doi.org/10.3390/su8060574

Wolz, K.J., Branham, B.E., DeLucia, E.H., 2018. Reduced nitrogen losses after conversion of row crop agriculture to alley cropping with mixed fruit and nut trees. Agriculture, Ecosystems & Environment 258, 172–181. https://doi.org/10.1016/j.agee.2018.02.024

World-Bank, 2021a. Prevalence of severe food insecurity in the population (%) - Kenya, World, Sub-Saharan Africa, Malawi | Data [WWW Document]. URL https://data.worldbank.org/indicator/SN.ITK.SVFI.ZS?locations=KE-1W-ZG-MW (accessed 4.21.21).

World-Bank, 2021b. Forest area (% of land area) - Kenya | Data [WWW Document]. URL https://data.worldbank.org/indicator/AG.LND.FRST.ZS?locations=KE (accessed 2.11.21).

World-Bank, 2021c. Fertilizer consumption (kilograms per hectare of arable land) - Sub-Saharan Africa, World | Data [WWW Document]. URL https://data.worldbank.org/indicator/AG.CON.FERT.ZS?locations=ZG-1W (accessed 12.17.21).

World-Bank, 2021d. CO2 emissions (metric tons per capita) - Kenya, European Union | Data [WWW Document]. URL https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=KE-EU (accessed 2.15.21).

World-Bank, 2021e. Cereal yield (kg per hectare) - Kenya | Data [WWW Document]. URL https://data.worldbank.org/indicator/AG.YLD.CREL.KG?locations=KE-1W (accessed 4.20.21).

World-Bank, 2021f. Arable land (% of land area) - Kenya | Data [WWW Document]. URL https://data.worldbank.org/indicator/AG.LND.ARBL.ZS?locations=KE (accessed 2.11.21).

World-Bank, 2020. State and Trends of Carbon Pricing 2020. World Bank, Washington, DC.

Xiao, S.-S., Ye, Y.-Y., Xiao, D., Chen, W.-R., Zhang, W., Wang, K.-L., 2019. Effects of tillage on soil N availability, aggregate size, and microbial biomass in a subtropical karst region. Soil and Tillage Research 192, 187–195. https://doi.org/10.1016/j.still.2019.05.006

Yadav, S.K., Soni, R., 2019. Integrated Soil Fertility Management, in: Panpatte, D.G., Jhala, Y.K. (Eds.), Soil Fertility Management for Sustainable Development. Springer, Singapore, pp. 71–80. https://doi.org/10.1007/978-981-13-5904-0_5