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Climate-smart crop production: understanding complexity for achieving triple-wins

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1 Introduction

Agriculture worldwide faces the enormous challenge to meet increasing demands for food, feed and fuel, resulting from a growing and increasingly affluent human population (Grafton et al., 2015). This challenge is complicated by climate change, which is expected to negatively affect agriculture in many places through increasing temperature, changing rainfall patterns, increased climate variability and frequency of extreme events (Lipper et al., 2014; Rosenzweig et al., 2014). At the same time, while agriculture emits a large share of global greenhouse gas (GHG) emissions, it holds great potential for reducing these emissions (Smith et al., 2014).

Climate-smart agriculture (CSA) originated from the need to address this three-pronged challenge through a concerted effort to simultaneously improve food security by increasing productivity (pillar 1), strengthen resilience by adapting to climate change (pillar 2) and mitigate GHG emissions (pillar 3; FAO, 2010). The CSA concept aims to reverse the previously existing tendency of climate policies generally treating adaptation and mitigation separately. As such, unintended side effects (both positive and negative) were often overlooked and therefore not addressed (Locatelli et al., 2015).

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Since its launch in 2010, CSA has become a major focus of agricultural research with a sharp and continuing rise in scientific papers, conferences, tools (e.g. Andrieu et al., 2017; Brandt et al., 2017; Mwongera et al., 2017) and handbooks or guides (e.g. FAO, 2013; CSA guide of CCAFS: https://csa.guide/, accessed 11 February 2019). The concept is increasingly taken up by NGOs, donors, governments and large companies, but also increasingly criticized both in the scientific literature (e.g. Karlsson et al., 2018) and in various media (e.g. http://www.climatesmartagconcerns.info, accessed 11 February 2019). A growing body of literature comprises general reviews on CSA (e.g. Debaeke et al., 2017; Scherer and Verburg, 2017; Steenwerth et al., 2014), reviews of knowledge on specific CSA options (e.g. on agroforestry by Mbow et al. (2014); on conservation agriculture (CA) by Thierfelder et al. (2017); on cover crops by Kaye and Quemada (2017)) and site-specific case studies of CSA implementation (e.g. Long et al. (2016) for European countries and Lee (2017) for Kenya). Based on the existing literature, we provide a concise overview of CSA options with their expected effects on the three pillars and the underlying mechanisms. We aim to add value by reviewing approaches to the categorization of CSA options, and by critically examining the potential of two (groups of) options, namely CA and soil fertility management. From this, we identify gaps in our understanding of CSA and potential pitfalls in the assessment of the CSA potential. Finally, based on two contrasting case studies from the Netherlands and Zimbabwe, we show how farming systems analysis enables the operationalization of the CSA concept through participatory, integrated and cross-scale assessments.

We focus on crop production strategies, recognizing that in many farming systems of the world, cropping activities are intricately linked with livestock keeping, other land uses and a range of rural livelihood activities. Throughout the chapter, we argue that by considering the interactions between crops and the other components of the farming system, important insights can be revealed. Whereas this chapter focusses on options targeting the supply side of agricultural systems, these will have to be combined with solutions from the demand side, for example through changes in consumption behaviour (Scherer and Verburg, 2017; Smith et al., 2013). Yet, the food systems approach needed for such analyses (UNEP, 2016) is beyond the scope of this chapter.

2 Climate-smart agriculture (CSA) cropping options

Several overviews of options for CSA (e.g. Debaeke et al., 2017; Scherer and Verburg, 2017; Steenwerth et al., 2014), adaptation (e.g. Thornton and Herrero, 2014 for mixed crop-livestock systems; Wassmann et al., 2009 for rice) and mitigation (e.g. Smith et al., 2013; Cole et al., 1997) are found in the literature. The information provided in these overviews and the more in-depth papers referred to throughout this chapter is synthesized in the overview of Table 1.

Table 1 CSA options categorized by strategy and level with a qualitative indication of their effects on various CSA pillars and the underlying mechanisms

Strategy (Level)	Option	Food security/ Productivity	Adaptation			Mitigation[a]					Constraints to adoption	Comments
			Risk management	Diversification	(Sustainable) Intensification	N_2O	CH_4	CO_2	C sequestration	REDD+		
Farm production strategies (Field to farm level)	Choice of crop species/ cultivar	++	+	++	++						Limited access, high costs, reluctance to change diet	Effects on mitigation may be both positive and negative, depending on the choice
	Time of sowing	+	+++								Limited availability of labour and machinery	
	Water harvesting	++	+++		+++						Initial cost of investment	
	Conservation agriculture	+/−	++					++			Positive impacts only in long term; problems with weed pressure	CO_2 reduction from reduced fuel use for tillage operations
	Crop diversification	+	+	+++							Limited market opportunities for new crops; more knowledge-intensive and agile management required	Food security impact through diet diversity
	Agroforestry	+/−	+	++					+++	++	Possible negative effect on annual crops; trees take time to mature; young tree seedlings need protection against grazing pressure	Effects on food security depend on scale (+ at farm/ landscape; − at crop level)

(*Continued*)

Table 1 (*Continued*)

Strategy (Level)	Option	Food security/ Productivity	Adaptation			Mitigation[a]					Constraints to adoption	Comments
			Risk management	Diversification	(Sustainable) Intensification	N_2O	CH_4	CO_2	C sequestration	REDD+		
	Intercropping	+	+	++		+		+			Possible yield penalty on main crop; more laborious crop operations	Positive effect on productivity if LER >1; if legume intercrop, N fixation reduces use of mineral fertilizer, leading to less N_2O and CO_2 (for manufacturing) emissions
	Irrigation	+++			+++						High costs for initial investment and maintenance of irrigation structures; water management governance not always effective; risk of water-borne diseases	
	Integrated pest management	++	+		++			+			Knowledge-intensive	Effects on CO_2 from reduced agrochemical production

Optimize mineral fertilizer use	+++	+/−	+++	+/−	+/−		Access to and costs of mineral fertilizer; financial risk	Effects on risk depend on context, scale and availability of storage facilities; effects on mitigation depend on the context: in low-input systems, fertilizer use will increase, thus increasing emissions – in high-input systems, fertilizer application rates can be reduced, thus reducing emissions
Optimize manure use	++	+/−	+++	+/−−	+/−−	++	Labour and knowledge-intensive; investment costs for proper storage facilities	Effects are similar to mineral fertilizer but more negative in case of increased manure use because of the more difficult synchronization with plant demand, the emissions associated with manure storage and enteric fermentation. The exception is the positive impact on carbon sequestration through the build-up of soil organic matter

(*Continued*)

Table 1 (*Continued*)

Strategy (Level)	Option	Food security/ Productivity	Adaptation: Risk management	Adaptation: Diversification	Adaptation: (Sustainable) Intensification	Mitigation[a]: N_2O	Mitigation[a]: CH_4	Mitigation[a]: CO_2	Mitigation[a]: C sequestration	Mitigation[a]: REDD+	Constraints to adoption	Comments
	Organic amendments (crop residues, compost)	+/−	++			−			++		Competition for crop residues from livestock for use as feed; compost is knowledge- and labour-intensive technology	Positive effect on productivity if improvements in water-use efficiency thanks to better infiltration and/or water-holding capacity; negative effects on productivity if increased C:N ratio is not compensated by higher N application rate. The required N application will lead to a trade-off in N_2O emissions
	Legume crops	+/−		++		+		+			Possible trade-off on farm production may be a disincentive; access to legume varieties and markets may be limited	Effects on food security depend on scale: due to often lower legume productivity compared to cereal, farm-level production may go down, but cereals may benefit in case of no or low mineral fertilizer use

	Cover crops	+/-		++	+		+	+	Possible trade-off on farm production may be a disincentive	Effects on food security depend on type of crop: farm-level food security may decrease if cover crop is not a food crop
	Paddy rice management (straw, drainage, cultivar)	/			+/–	+++			Knowledge-intensive technique	Yield penalties can be avoided. Drainage may increase the emission of N_2O, but this does not offset the huge reductions in CH_4 which can be obtained
	Biochar application	/						+	No clear benefits on crop productivity; access to biomass and processing facilities may be limited	No conclusive evidence on effects on crop yields
	Soil and water conservation measures	+/–	+					+	Possible trade-off on farm production and long time horizon may be a disincentive; labour-intensive	Effects on productivity may be negative at field level due to less space for crops; and positive effects may take time to be realized
Farm financial management (farm level)	Insurance	+	+++						Absence of insurance schemes; costs	Positive effect on crop productivity because of incentive to invest

(*Continued*)

Table 1 (*Continued*)

Strategy (Level)	Option	Food security/ Productivity	Adaptation			Mitigation[a]					Constraints to adoption	Comments
			Risk management	Diversification	(Sustainable) Intensification	N_2O	CH_4	CO_2	C sequestration	REDD+		
	Income diversification; on/off-farm			+++							Off-farm opportunities may not be available	
	Mixed farming	+	+	++		–	–		+		Knowledge-intensive and agile management required	Effects are considered in comparison with specialized crop farming: negative emissions effects due to manure application ($N_{\S}O$) and enteric fermentation (CH_4). Manure can increase soil organic carbon stocks. In a smallholder context, food security improves due to inclusion of animal-sourced foods in the diet
	Investing in income stabilization	+	++								Options may not be available to all and everywhere	Positive effect on crop productivity because of incentive to invest
Land use planning (landscape level)	Land sharing	–		+++					+	+	Possible trade-off on farm production may be a disincentive; more complex farm management	Positive effect on C sequestration and avoided deforestation if perennial vegetation included

	Agroforestry	+		+++			+	++	Possible negative effect on annual crops; trees take time to mature; young tree seedlings need protection against grazing pressure	Similar effects compared to land sharing, but positive for productivity because tree component also aims at provisioning services, whereas this is not an objective in the land sharing option
	Land sparing	/			+++			++	Unless supported by policies, increased land-use efficiency may lead to more land being cultivated	Productivity on a land basis is increased so that total production can be maintained while setting land aside for nature; (sustainable) intensification is the assumed driver of this option, not the result
Technology (sector level)	Development of crop cultivars	++	+	++	++				Costly; time consuming	
	Weather forecasting	+	++						Limited trust in the forecast	
	Precision agriculture	++			+++	++	+		Costly	Cuts in CO_2 emissions from fuel savings

[a] Mitigation through reduction of CO_2 emissions includes CO_2 from fuel use, manufacturing of agro-chemicals and mineralization of soil organic matter; C sequestration includes above- and below-ground processes; REDD+ refers to the prevention of deforestation and degradation of carbon-rich ecosystems.

Existing reviews typically categorize options with the aim to bring structure in the vast and expanding collection of potential solutions or to explain the mechanisms for adaptation and mitigation. Yet, the approach to the categorization of adaptation options varies considerably. For example, Smit and Skinner (2002) propose a typology of adaptation activities based on the scale of implementation and comprising four categories of farm production practices (e.g. adapting the crop species and/or cultivars, adapting pest and weed control), farm financial management (e.g. diversifying the portfolio of income sources, crop insurance), government programs (e.g. subsidies, land use policies) and technological developments (e.g. breeding of new adapted crop cultivars, improvement in weather forecasting). This approach resembles the one of Scherer and Verburg (2017), who distinguish between technological advancement, adaptive farm management and financial management, and of Hertel and Lobell (2014), who describe three categories of current technologies, new technologies and changes in the institutional environment. Debaeke et al. (2017) follow a different approach by using the time horizon to set apart short-term risk management options, such as shifting cropping patterns or adjusting time and rate of fertilizer application, from long-term adaptations, such as breeding and knowledge-driven optimization of farm management. Finally, options can also be categorized based on the underlying mechanism towards adaptation, such as risk management, diversification and sustainable intensification (SI), as described by Thornton and Herrero (2014) and Descheemaeker et al. (2016). Examples of risk management options include adjusting planting dates and post-harvest storage. Diversification can be achieved with, for example, intercropping and agroforestry, whereas soil fertility management, water harvesting or irrigation can enable SI. In Table 1 we categorize options based on strategy and level of scale and evaluate them based on CSA mechanisms, thus showing that different approaches can be combined.

Studies reviewing knowledge on mitigation options typically employ a categorization approach that focusses on the mitigation mechanisms. The first group of options is geared towards the reduction of GHG emissions. Within this category, the type of GHG determines the mitigation options. For example, N_2O emissions can be reduced by optimizing nutrient-use efficiency with adjusted mineral fertilizer application and inclusion of legume crops; CH_4 emissions in rice systems can be cut back by agronomic management including drainage of irrigated fields, straw management and use of adapted cultivars; CO_2 emissions can be decreased by optimizing energy-use efficiency of farm operations. Likewise, potential mitigation options can be identified by considering the source of the emission, such as enteric fermentation, manure management or agricultural soils. A second category of mitigation options aims at sequestering carbon in the soil and in biomass (e.g. agroforestry). A third category entails the prevention of deforestation and degradation of carbon-rich ecosystems, such as peatlands and grasslands (e.g. the REDD+ strategies; Corbera and Schroeder, 2011). Cropping options only have an indirect influence on the latter strategy, for example through land sparing, which may (or may not) be achieved through SI on existing cropland (Carter et al., 2018). In Table 1, we differentiate effects per GHG, and for C sequestration and REDD+ strategies.

Based on our review of the literature for this chapter, we qualitatively analysed the expected effects of options on the three CSA pillars and the underlying mechanisms (Table 1). Smith and Olesen (2010) claimed that although certain mitigation measures may negatively impact adaptive capacity, most adaptation options have a mitigation co-benefit through their positive effect on nitrogen-use efficiency and soil carbon storage. Yet, Table 1 shows that the options that benefit both adaptation and mitigation are scarce. Some notable exceptions are agroforestry and the incorporation of legume crops. Further, Scherer and Verburg (2017) identified only cover crops, agroforestry and reduced tillage as truly climate-smart cropping options. In contrast, for some options listed in Table 1, clear trade-offs can be expected, such as for manure application. Several studies (see Locatelli et al. (2015) for an overview) pay attention to the possible trade-offs that may exist between adaptation and mitigation when implementing CSA practices that are primarily aimed at one or the other objective.

In the following sections, we focus on CA and soil fertility management to illustrate in more detail how cropping strategies contribute, or not, to the three pillars of CSA. These strategies are chosen because they are believed to influence all of the three CSA pillars, and extensive research has generated a wealth of quantitative information allowing a critical examination of their potential benefits and drawbacks. CA is chosen as a specific intervention, whereas soil fertility management is a more general strategy encompassing various concrete options, including, among others, cover crops, different types of fertilizer, legume crops and rotations.

2.1 Conservation agriculture (CA)

Conservation agriculture combines minimum soil disturbance by reduced or no tillage, crop residue retention on the soil surface and crop diversification through crop rotations or intercropping (FAO, 2015). CA is often claimed to be climate-smart (Kassam et al., 2018). As it is a heavily researched cropping practice both in intensive agriculture (Giller et al., 2015) and in smallholder systems (Thierfelder et al., 2017), a wealth of information is available to substantiate or question this claim.

With respect to the first pillar of CSA, crop yields may benefit from CA because of a general improvement in soil quality (Corbeels et al., 2014), but the effect varies depending on the agro-ecological context and the type of season.

A meta-analysis of CA evidence suggests that yield benefits are only obtained in dry climates (Pittelkow et al., 2015), and positive effects of CA are stronger in dry seasons (Kirkegaard et al., 1994). In addition, almost invariably, if yields increase, they do so only after some time (Rusinamhodzi et al., 2011), which may discourage farmers from adopting the practice.

The adaptation potential of CA primarily relates to its ability to improve soil water availability, thus rendering the cropping system more resilient to less and more erratic rainfall in future climates (Corbeels et al., 2014). This effect is explained both by increased infiltration rates (Thierfelder and Wall, 2009) and by reduced evaporation in CA systems compared to conventional cropping. Reduced or no-till combined with residue retention and deep-rooting legume crops in rotation or intercropping favours macro-fauna and root activity in the soil, resulting in a continuous pore system that facilitates water flows (Thierfelder et al., 2017). The higher organic carbon content in the surface soil layer improves soil structure, benefitting infiltration. By covering the soil, mulch not only reduces temperature and evaporation (Klocke et al., 2009), thus conserving water, but also tempers the direct impact of raindrops on the soil, thereby reducing erosion (Thierfelder et al., 2017). Whereas residue retention has the capacity to buffer temperature fluctuations and therefore could protect the cropping system against rising temperatures and more frequent heat stress with climate change, quantitative evidence on this aspect is hard to find. Besides the soil-related effects discussed earlier, the reduction or elimination of tillage operations also improves the adaptive capacity of the system by reducing labour requirements for land preparation. This allows more agile farm management, including early sowing or sowing with the first rains, typically leading to better and more reliable yields through a better use of in-season rainfall (Masvaya et al., 2018).

With respect to the third pillar of CSA claims of GHG emission mitigation (e.g. Corsi et al., 2012) are not generally justified. Studies on the effects of CA on carbon sequestration found that CA generally results in larger soil organic carbon content near the soil surface (Powlson et al., 2016). However, as this is due mainly to C redistribution, it goes hand in hand with a reduced carbon content in deeper layers, and thus no net increase in the carbon stock. In addition, the soil carbon sequestration is usually not maintained in the long run, as the carbon is lost when soils are conventionally tilled, which, for agronomic reasons, typically happens occasionally even in no-till systems. Also, seemingly fast initial C sequestration rates quickly drop over time as the soil becomes saturated with carbon (Baveye et al., 2018). With respect to GHG emissions, there is contrasting evidence in the literature on N_2O and CH_4 emissions, as some studies report increases and others decreases of the emissions under CA systems (Corbeels et al., 2018; Powlson et al., 2016). Also, as most studies did not investigate N_2O and CH_4 simultaneously, it is risky to draw conclusions on the overall potential of CA to mitigate GHG emissions. Another aspect on which the jury is still out relates to erosion. Although there is consensus in the literature that CA is effective against erosion, contrasting opinions exist on whether reduced erosion lowers C emissions or not, as some see erosion as a sink, others as a source of C, whereas it could also be neither a source nor a sink (Van Oost et al., 2007). In the end, the only mechanism through which CA undoubtedly contributes to the mitigation of GHG emissions is through the fuel savings from the elimination of tillage operations, resulting in less CO_2 emissions compared to conventional tillage systems.

Increased weed pressure is a common drawback of CA (Giller et al., 2009). Its associated rise in labour and/or herbicide requirements, the latter incurring costs and potential environmental trade-offs, may be a barrier to adoption in a variety of contexts. Due to the intensive use of herbicides in some CA systems, herbicide resistance in weeds is building up and becoming a headache for farmers (Kirkegaard et al., 2014). Other drawbacks are more context-specific. For example, the infiltration and soil water enhancing features of CA are a clear advantage in drier and more variable climates, whereas they present a drawback in wetter climates, in case of delayed sowing or waterlogging. Especially in smallholder agriculture, the lack of adequate planting machinery is often a barrier for adoption, as is the absence of immediate income benefits after the implementation of CA. Biomass constraints and the competing use of crop residues as animal feed is a major barrier to CA adoption in smallholder systems (Giller et al., 2009).

CA is one of the most heavily researched cropping systems worldwide. The resulting evidence from empirical and modelling studies indicates that CA is not convincingly climate-smart. This is because although the adaptation potential is relatively clear, positive effects on crop productivity and farmer livelihoods are noticed only in some contexts and after some years. Also, the mitigation potential of CA is doubtful. Moreover, important trade-offs and barriers to adoption clearly indicate that it is a worthwhile option only in some contexts and farming systems.

2.2 Soil fertility management

Soil fertility management encompasses various practices and technologies, such as the use of mineral and organic fertilizer (animal manure, compost, green manure), crop residue management, the incorporation of legume crops for N fixation, rotations and intercropping. Soil fertility management is an important part of agronomic management and through its effects on crop yield and nutrient (particularly N) dynamics in the soil, it directly influences the productivity and mitigation pillars of CSA. Its effects on the adaptive capacity and resilience of cropping systems are more complex, sometimes counteracting and often indirect (see Section 2.2.4). As soil fertility management has been part and parcel of agronomic sciences (e.g. Vanlauwe et al., 2015), it goes beyond the scope of this chapter to review the existing evidence on the effects of different soil fertility management options on crop productivity (CSA pillar 1). This section first delves into the evidence on mitigation effects (CSA pillar 3), with attention to concurrent effects on productivity (CSA pillar 1). After that, the effects on adaptive capacity and resilience (CSA pillar 2) are described.

With respect to the third CSA pillar, soil fertility management influences mitigation in four ways. First, it affects emissions, particularly of N_2O, through its influence on soil C and N dynamics. In addition, emissions of CH_4 are influenced through manure management, whereas organic C mineralization in soils, manure and organic fertility amendments influence CO_2 emissions. Secondly, soil fertility management influences C sequestration through the addition of organic materials to soils. Thirdly, as soil fertility management is required to (sustainably) intensify crop production, it may also serve to avoid the expansion of cultivated land (land sparing), thus avoiding deforestation and degradation of carbon-rich ecosystems (Carter et al., 2018; van Loon et al., 2019). Fourthly, as soil fertility management aimed at mitigation can lead to a reduced demand for mineral (N) fertilizers, it may lower the 'upstream' fossil energy consumption and associated CO_2 emissions for their manufacturing (Zhang et al., 2013). In the following sections, we will look into the first three mitigation mechanisms.

2.2.1 Mitigation through cutting emissions

Cutting the nitrous oxide (N_2O) emissions is a high-potential mitigation pathway that can be influenced with soil fertility management (Griscom et al., 2017; Venterea et al., 2012; Van Groenigen et al., 2010). N_2O is a long-lived GHG with a large warming potential that is produced during microbially governed denitrification and nitrification reactions in soils and manure, or from downstream denitrification of nitrate that is leached from agricultural soils (Bos et al., 2017; Kaye and Quemada, 2017; Smith, 2017). Many soil conditions (e.g. temperature, water content and aeration, pH) control N_2O production, but as it is largely dependent on nitrate and ammonium concentrations, the most direct and effective strategy to reduce the N_2O emissions is to cut the N input to the system by reducing the application of organic and inorganic fertilizer (Debaeke et al., 2017). Obviously, because of the direct trade-off with crop yield, a balance must be found between farmers' profit-making and/or food-production objectives, mitigation objectives and other environmental concerns such as nitrate leaching. Nevertheless, especially in high-input agriculture where only a maximum of about 60% of the applied N is taken up by the crops, there is scope to reduce the inputs without compromising yield (Bos et al., 2017; Silva et al., 2017; Zhang et al., 2015). Promising strategies for increasing the nutrient-use efficiency of the cropping system include (1) matching the fertilizer rate, time of (split) application and fertilizer composition to crop requirements, (2) precise localization and incorporation of the fertilizer to enhance root uptake and avoid losses through volatilization, (3) complete N balance calculations including the manure and crop residue sources of N that are often underestimated (Debaeke et al., 2017). Mineral N fertilization rates can also be reduced by the inclusion of nitrogen-fixing legume crops as a main crop, intercrop or cover crop, because the legume crop itself does not require N fertilization and it supplies N to the following crop. Although N fixation by legumes itself does not result in N_2O emissions (Rochette and Janzen, 2005), the inclusion of legume crops may. This depends on the fate of the legume crop biomass and the resulting time and amount of N released from its decomposition, subsequently influencing denitrification rates and N_2O losses. Another promising strategy is to include cover crops (leguminous or other), which take up any leftover nitrogen after the main crop, thus reducing the risk of nitrate leaching and its downstream denitrification. Finally, N_2O emissions can also be reduced by applying nitrification inhibitors, which are however costly (Lam et al., 2017).

Manure is an important source of nutrients and organic matter used in soil fertility management and cropping strategies. As manure is a by-product of the livestock industry, GHG emissions from manure are often considered in analyses of the livestock sector. Manure management encompasses a continuum from its production by livestock, over storage, treatment and spreading on crop or grassland. Whereas Chadwick et al. (2011) give an overview of the emissions and mitigation options in each part of this continuum, here we highlight only areas where the evidence is convincingly pointing to mitigation gains. N_2O is produced from nitrification and denitrification processes in stored manure, while CH_4 is the result of anaerobic decomposition of the organic matter in manure. Both processes are affected by environmental factors such as temperature and aeration, biomass composition and management of the manure (Chadwick et al., 2011). By affecting the N content of the diet, the livestock feeding strategy influences the N concentration in the manure and hence its N_2O production potential, while it also affects the CH_4 emissions through enteric fermentation during feed digestion in the animal. The potential to reduce the emissions of N_2O and CH_4 during storage depends on the type of manure (e.g. liquid or solid, with the latter having lower emissions). While for N_2O, it is important to keep the solid manure heaps in anaerobic conditions (e.g. compacting and covering the heap), CH_4 the emissions can be curbed by two opposing strategies aimed at promoting aeration (e.g. through composting) or promoting anaerobic conditions, so that slower decomposition of manure leads to less heating and less stimulation of CH_4 emissions in the anaerobic micro-environments. During storage, manure can also be converted to biogas through a process of anaerobic digestion, which significantly lowers GHG emissions (Cuéllar and Webber, 2008). Moreover, the process creates a methane-rich biogas which can be used as a fuel for cooking, heating or light, as well as sludge that can be used as a fertilizer. With respect to manure application, timing, rate and method influence the C and N dynamics in the plant-soil continuum. To avoid nutrient losses, timing and rate should be fine-tuned with crop nutrient demand, while taking into account that the microbial processes responsible for manure breakdown take time and are influenced by soil temperature and water. In relation to crop nutrient demand, manure is a more effective supplier of P than of N, because excess P is stabilized in the soil, while excess N is lost (e.g. Conijn and van Dijk, 2018). In this respect, processing of manure to alter its composition can offer a solution (Velthof, 2015). Effects of application methods, roughly ranging from incorporation to broadcasting, have been investigated in several studies, but findings on emissions do not all point in the same direction and trade-offs between N_2O and NH_3 emissions require further research (Chadwick et al., 2011).

2.2.2 Mitigation through carbon (C) sequestration

The soil carbon stock is the result of carbon inputs (from roots, crop residues and external organic amendments) and carbon losses through mineralization, making these two mechanisms the main levers for C sequestration (Debaeke et al., 2017). Soil fertility management strategies that benefit C sequestration (for overviews see e.g. Ogle et al., 2005; Powlson et al., 2011; Smith, 2008) include the application of organic amendments and the inclusion of cover crops or green manures in rotations. With respect to the application of organic amendments, mineralization of the organic material after incorporation in the soil results in much of the carbon being lost again to the atmosphere as CO_2. Yet, in the long run, these amendments are observed to positively affect the build-up of the soil carbon stock (Autret et al., 2016; Johnston et al., 2009).

The '4 per 1000' initiative (http://4p1000.org/understand), launched in 2015 at the COP21 in Paris, has attracted a lot of political and scientific attention to the potential of C sequestration in agricultural soils. The initiative aims at increasing global soil organic carbon stocks by 0.4% per year to halt the increase of CO_2 in the atmosphere. However, whereas recent studies (e.g. a multi-country overview by Minasny et al. (2017) and a global gridded modelling study by Zomer et al. (2017)) paint optimistic pictures of the offsetting potential, the reality is likely less rosy due to a number of biophysical caveats (Baveye et al., 2018; Poulton et al., 2018) and socio-economic realities (Amundson and Biardeau, 2018). Firstly, when C sequestration measures are implemented, the carbon sequestration rate may be fast at first, but quickly drops down as the soil saturates with C and reaches a new equilibrium at which point the soil will no longer function as a C sink (Johnston et al., 2009). Secondly, to maintain the C stock, the addition of organic material needs to be continued over time, otherwise the sequestration will be reversed (Smith, 2012). This organic material needs to be produced, thus requiring nutrients and potentially leading to more emissions. Thirdly, with global warming, increasing temperatures will fuel microbial activity leading to a faster decomposition of soil organic matter and release of CO_2 in the atmosphere (Crowther et al., 2016). Fourthly, some of the management practices aimed at increasing the soil C stocks (e.g. manure use) may increase the emissions of other, more potent, GHG like CH_4 and N_2O, as explained in the previous section. Also, increased N input (with associated N_2O emissions) is needed to counteract the lower N availability associated with suboptimal soil stoichiometry of C and nutrients resulting from the process of increasing SOC (van Groenigen et al., 2017; Kirkby et al., 2013). Finally, leakage or displacement issues have been described where the organic amendments applied to a certain area for C sequestration come from another area where losses in carbon are incurred due to the displacement. This is especially problematic in areas of low biomass availability (e.g. in Burkina Faso, as described by Félix et al. (2018)). The above caveats caution against overly optimistic claims, resulting from ignoring scientific evidence. These claims may decrease the sense of urgency, which is badly needed for the implementation of climate-smart solutions (Baveye et al., 2018). In addition, the stipulations point to the importance of holistic and multi-scale analyses to understand the true potential of proposed solutions.

2.2.3 Mitigation through land sparing – a result of sustainable intensification?

Land use change and forestry are responsible for the largest share of the annual GHG emissions from the Agriculture, Forestry and Other Land Use (AFOLU) sector (Smith et al., 2014). In their review of a range of natural climate solutions, Griscom et al. (2017) point to avoided forest conversion as a pathway with an enormous mitigation potential, second only after the reforestation pathway. However, worldwide and throughout human history, the opposite trend has been the most dominant: the conversion of land for agricultural practices has allowed production increases in response to increasing demands for food, feed and fuel (Pretty and Bharucha, 2014; Mandemaker et al., 2011). But, as suitable land is becoming scarce and the conversion leads to ecosystem degradation and GHG emissions, intensification of agricultural production on existing agricultural land is claimed as the way forward (van Ittersum et al., 2016; Tilman et al., 2011). Yet, as agricultural intensification has led to environmental, health and social problems (Kerr, 2012; Stoate et al., 2001; Matson et al., 1997), calls for SI have come to the fore. Even though the SI concept and its meaning are debated (Struik and Kuyper, 2017; Garnett et al., 2013), the principle of producing more output from the same (or less) area of land while reducing negative environmental externalities (Pretty et al., 2011) is appealing in its simplicity. Not surprisingly, next to genetic improvements, soil fertility measures that manage the trade-offs between maximizing productivity and minimizing environmental externalities are high on the SI agenda (for an overview, see Weltin et al., 2018). Extensive information on what constitutes SI in different contexts is available. In high-input systems, there is often scope to maintain good yields while reducing input levels, thus improving efficiency and reducing environmental impact (see e.g. Silva et al. (2017) for a study on Dutch arable farming systems). In low-input systems, emphasis is placed on improving yields by environmentally sound increases in (nutrient) input use, for example through integrated soil fertility management (Vanlauwe et al., 2014, 2015). This will require a so-called 'tunnelling through' of the environmental Kuznets curve through management and technological practices that enable high nutrient-use efficiency and avoid surpluses that may degrade the environment (Zhang et al., 2015).

In summary, by improving agricultural productivity and efficiency, SI may not only reduce the emission intensity of agricultural production, it may also contribute to reforestation and avoiding forest degradation through land sparing (Rounsevell et al., 2005; Schröter et al., 2005). This premise relies on the assumption that with improved resource-use efficiency (e.g. land productivity or yield), the use of that resource (i.e. the land) will decline. However, as described in 'Jevons Paradox', often the opposite is observed due to an increased demand for that resource. This paradox points to the important role of policies and land use legislation to achieve the land sparing effect (Ceddia et al., 2013; Mandemaker et al., 2011; Rudel et al., 2009).

2.2.4 Adaptation

From the previous sections, it is clear that soil fertility management has direct impacts on the first productivity pillar of CSA and on many mechanisms related to the third pillar of mitigation. For adaptation, however, effects are not always straightforward and may even be counteracting. An indirect positive effect is that as a result of soil fertility management, soil organic carbon content and general soil health may improve, leading to better soil functioning (Bos et al., 2017). Indeed, associated increased water-holding capacity and infiltration rates (Franzluebbers, 2002) may help crops to better bridge dry spells in the growing season, which may become more frequent in the future. Reduced soil erodibility is another effect of soil management that helps cropping systems to be more resilient against more intense and larger storm events. Mulching as a form of crop residue management protects the soil not only against raindrop effects, but also creates a micro-climate by buffering temperature amplitudes and heat, which is a useful feature in a warming climate.

With respect to nutrient input, the evidence points in different directions depending on the context and scale of analysis. In general, crops that are not nutrient-limited can take better advantage of CO_2 fertilization effects (Masikati et al., 2019) and cope with pests and diseases (Dordas, 2008). Also, higher fertilizer use generally reduces yield variability (Reidsma et al., 2009). Yet, increasing the nutrient input may also turn out to be risky, especially in low-input systems, typical of smallholder agriculture in Africa. In variable climates, these systems are usually managed to minimize downside risk and characterized by no or very little fertilizer input (Tittonell and Giller, 2013). Resulting crop yields are low on average, mainly due to nutrient limitations, but relatively constant from year to year and relatively insensitive to climate change (Masikati et al., 2019). With increased nutrient input, average yields would improve, but the year-to-year variability would also increase (Keating et al., 2010), as crop production would now be less constrained by nutrients and more determined by seasonal variations in the climate. With investments in inputs not sure to pay off, this increased risk may be a serious barrier preventing the uptake of improved soil fertility management by smallholders. Similarly, the larger sensitivity to climate change (Traoré et al., 2017; Rurinda et al., 2015) would reduce rather than enhance resilience of the crops. At the larger farm level, however, increased nutrient input may improve farmer incomes on average and in good years more substantially. With good financial management and storage facilities (Milgroom and Giller, 2013), this may help to buffer losses in poor years and create possibilities for further re-investment in farm management, thus benefiting the farmer's adaptive capacity.

2.2.5 Trade-offs and constraints

Soil fertility management may entail important trade-offs between the three pillars of CSA. These can be assessed either from the level of the mechanisms or with a specific practice as a starting point. As an example of the first type, N_2O emissions can be reduced by cutting N input to cropping systems, with potential repercussions on crop yield (Debaeke et al., 2017). A good example of the second type is cover crops, which have the potential to increase C sequestration and reduce N_2O emissions, but consume water, which may lead to poorer adaptation to drying climates (Kaye and Quemada, 2017).

As soil fertility management influences the C and N dynamics in the soil, which in turn influence the soil carbon stock and the emissions of GHG from the soil, it is not surprising that trade-offs between the various mitigation mechanisms exist. For example, applying manure may increase carbon stocks, but at the same time increase N_2O emissions from the soil or from downstream denitrification of leached nitrate, thus partially offsetting the benefits of C sequestration (Bos et al., 2017). In the same vein, it is important to be aware of pollution swapping. For example, the use of (imported) manure may lead to savings in mineral fertilizer use, but this is counteracted by the emissions during manure storage and due to enteric fermentation. Another example is that the decrease in ammonia emissions through incorporating slurry may stimulate N_2O losses in some cases (Chadwick et al., 2011).

Whether to apply manure and/or mineral fertilizer is a question that strongly depends on the scale of the analysis, the context and the diversity of CSA objectives and trade-offs taken into account. At field and farm level, using manure may lead to a higher emission intensity compared to using mineral fertilizer, because the slow decomposition of manure complicates the exercise of matching crop demand with N supply, leading to losses in various forms. The fact that the increase in N_2O emissions outweighs the gains in C sequestration from manure application (Bos et al., 2017) is another argument for using mineral fertilizers. In addition, contrary to common beliefs, a meta-analysis by Hijbeek et al. (2017) showed that in Europe, increased soil organic matter does not on average lead to higher yields, if sufficient nutrients are applied by mineral fertilizers. However, at a larger regional level, a different conclusion could be reached. For example, in areas with large livestock densities such as the Netherlands, it makes perfect sense to deal with manure surplus problems by using the available manure on arable fields. Also in a different context the evidence could be in favour of using manure. For example, in low-input systems characterized by poor soil fertility, manure not only helps in building soil organic matter, but also provides a range of other (micro-)nutrients, the lack of which limits crop yield and response to mineral fertilizer (Rusinamhodzi et al., 2013).

Soil fertility management influences (both positively and negatively) a range of agricultural and environmental issues and broader sustainability dimensions beyond the three pillars of CSA that may strongly affect its relevance and attractiveness for farmers. For example, increased nitrogen-use efficiency in agricultural systems may also benefit water and air quality through reduced nitrate leaching and ammonia volatilization, as well as below- and above-ground biodiversity (Debaeke et al., 2017; Zhang et al., 2015). In the social dimension, equity is an important sustainability perspective, particularly in the smallholder context. Better-endowed farmers are often those who own cattle producing manure and have capital to buy fertilizers. Hence, these farmers are more likely to adopt soil fertility management practices that enhance their productivity and resilience (Zingore et al., 2007), thus enlarging the gap with the less-endowed farmers in a community and increasing inequity. On the positive side, co-benefits of including leguminous crops can be found in the economic domain, as the legumes diversify the farmers' income portfolio and hence increase resilience. Another synergy is that legumes diversify the human diet, thus improving the food security of subsistence farmers.

Incremental and transformational change

Anticipated drastic changes in the future climate and resulting changes in ecosystems may exceed thresholds beyond which human actors and natural systems cannot adapt by incremental adjustments (Klein et al, 2014). Such small adaptations in technologies and farm management, including changing crop cultivars, shifting planting dates or water harvesting, have, in the past, allowed farmers to adapt continuously to gradual changes in their environment. Growing evidence for substantial changes in future climate, for which these incremental adaptations will not suffice, has underscored the need for more drastic adaptation (Panda, 2018; Rickards and Howden, 2012). In other words, when the current system is not able to adapt within its biophysical, economic and technological limits, a transformation of the system is needed. For example, climate change is likely to exclude the cultivation of particular crops in certain places due to a shortening of the growing season, or exceeding various suitability thresholds related to temperature and rainfall (e.g. Rippke et al., 2016; Jones and Thornton, 2009). In such cases, transformational change comprises shifts in the production location of crops or shifts to new crops or production systems for a particular location (Rippke et al., 2016).

Transformational adaptation is a relatively new concept in the literature, which still suffers from ambiguity in its definition and the numerous perspectives on its dimensions and required degree of change (Panda, 2018; Klein et al., 2014). Perhaps as useful as a clear definition is the realization that boundaries between types of adaptation are fluid and that adaptation is a continuum from coping through incremental changes, over systemic adaptations (e.g. major changes in the interaction between crops and livestock, the introduction of new technologies such as precision agriculture, the inclusion of shade trees), to transformational change (Rickards and Howden, 2012). Panda (2018) distinguished five types of transformational adaptation, including (a) adaptation actions adopted at a larger scale, (b) shifting crops and changing agricultural systems, (c) changing business scale, structure and location, (d) creating new croplands/irrigation and (e) forced farm abandonment and migration.

Furthermore, in many agricultural systems globally, it is not climate change but other drivers, for example in demography, environmental degradation, or markets and trade, that put most pressure on the current system and coerce it to transform (Reidsma et al., 2015). Hence, the transformation towards a climate-smart agricultural system will require changes in interdependent socio-economic, institutional and political aspects of society (Wise et al., 2014), as well as in the behaviour of consumers. As such, the change in the agricultural sector towards better productivity, resilience and reduced GHG emissions needs to be considered within a larger food systems context (UNEP, 2016).

So far, most research efforts on CSA have been directed at assessing effects of incremental options through empirical and modelling studies (Challinor et al., 2014). The resulting lack of information on the effects of more radical changes is a challenge for decision makers. Visioning and scenario analyses conducted with stakeholders and linked to integrated agricultural models can help fill that knowledge gap (Antle et al., 2018; Meuwissen et al., 2019; and Section 4.2).

3 Gaps and problems in our current understanding of the climate-smart agriculture (CSA) concept and its potential

The number of scientific studies on CSA has expanded rapidly since the concept was launched in 2010. The number of journal papers rose from less than 10 per year in 2012–2014, to over 50 in 2017 and 82 in 2018 (based on papers indexed by Web of Science, accessed 7th of January 2019). Journal papers dealing with both adaptation and mitigation in relation to agriculture, but without necessarily mentioning CSA specifically, are more numerous, with numbers starting to rise quickly from over 20 in 2010 to more than 100 in 2017 and over 140 in 2018. However, from a review of journal articles, Locatelli et al. (2015) concluded that empirical and quantitative information is lacking for many options and contexts. They concluded that CSA assessments are often qualitative and based on generalized statements. Systematic reviews and meta-analyses of effects of specific CSA options on the different CSA pillars are indeed not common. A good exception is the study by Kaye and Quemada (2017) that deals with effects of cover crops on seven mitigation-related mechanisms and adaptation to climate change aspects of drought, extreme rainfall and increased temperatures. For CA, Thierfelder et al. (2017) summarize information for southern Africa. For other CSA options, the quantitative evidence is biased towards one CSA pillar, such as C sequestration for the case of agroforestry (e.g. Mbow et al., 2014; Verchot et al., 2007). On yet other options that claim to be climate-smart (e.g. soil fertility management), empirical information on the effects on the CSA pillars is scattered in papers targeted to a specific pillar or to a specific technology or practice, without systematic gathering of the current knowledge. This knowledge gap complicates decision-making for agricultural practitioners and for policy makers in terms of which CSA options to prioritize in which context, and how to underpin the uptake of the CSA options with adequate policies. Related to this, the CSA concept is often interpreted so broadly that almost all good agricultural practices fit under it (see e.g. FAO, 2013). As such, CSA runs the risk of becoming an empty signifier, amenable to any kind of political intervention. In addition, it is a common problem that many studies refer to the same few sources, where values may have been reported based on rough assumptions. Particularly in relation to the C sequestration potential of agricultural soils, this has led to overly optimistic claims when the uncertainties associated with original values were ignored (Powlson et al., 2011). Related to this, standard IPCC Tier 1 values are often used as if they are true everywhere, while much scientific evidence already indicates that these values vary and may differ from earlier suggestions.

The CSA literature often mentions trade-offs and the three-pillar concept lends itself very well to considering trade-offs between productivity, adaptation and mitigation objectives. Yet, CSA assessments often mention trade-offs in qualitative or general terms without quantification (Bos et al., 2017), and there could be a bias in reporting win-wins and ignoring trade-offs (Locatelli et al., 2015). For example, with respect to mitigation, studies on soil fertility management focus mostly on either carbon sequestration or N losses, whereas options that increase soil C stocks often lead to larger N_2O emissions. With a modelling study, Bos et al. (2017) quantified these trade-offs for specific soil fertility management options in the Netherlands, but were the first to do so for arable land. They also studied the trade-offs in profits associated with reducing emissions and found that with current carbon prices, C credits could not compensate the expected financial losses. Whether a practice leads to a win-win or a trade-off may also depend on the unit of analysis, as illustrated next for the tension between food security and mitigation objectives. As discussed before, meeting future global food requirements will have to rely on increased productivity per area of land, in particular in currently low-yielding areas. This will require increased input use. Hence, whereas the GHG emissions on a product basis may go down, the GHG emissions on a land basis may increase. Contrary to this, organic agriculture and agricultural extensification, with overall lower yields, may lead to lower emissions per hectare, but larger emissions per unit of produce (Carlson et al., 2016; Bos et al., 2007). Globally, with more food being produced it will be very hard to bring down the absolute amounts of GHG emissions (Smith, 2017).

Beyond the three CSA pillars, trade-offs associated with the implementation of CSA options may occur in other environmental domains and in the social and human well-being domains of sustainability. Taking these trade-offs into account in ex-ante impact assessments is important for addressing unintended side effects (Klapwijk et al., 2014). With respect to the environmental domain, a narrow focus on mitigation may lead to so-called pollution swapping, as described previously for the specific case of manure use. With respect to the social domain, side effects of CSA options on the gender balance within households may occur if the implementation leads to shifts in the crop mix or other management practices, resulting in disproportionally more labour or more cash for a specific gender group (Jerneck, 2018). Social equity in communities may be adversely affected if the promotion of certain CSA practices mostly benefit the better-endowed farmers who can afford the investment or are able to implement the change in management. However, the social dimension in the impact of CSA options remains largely understudied (Karlsson et al., 2018).

The potential bias towards win-win and risk of overlooking or underestimating trade-offs may be aggravated when constraints and barriers to adoption are not carefully considered, resulting in an overestimation of the CSA potential and thus an underestimation of the future impacts of climate change. The potential effect of CSA options on mitigation and adaptation is usually derived from experimental or modelling studies. Very often, the CSA options tested also have the potential to increase the productivity in the current climate and system configuration. However, the contrast between the theoretical benefits and the fact that farmers are not currently using the options points to barriers in the current system that prevent adoption. An example from sub-Saharan Africa is the often advocated shift from maize to so-called climate-robust crops such as millet and sorghum. Given the fact that we currently see the exact opposite trend in many countries and that maize yields more than sorghum and millet under virtually all but the very driest climates (Rurinda et al., 2014; Traoré et al., 2014), this seems very unlikely to happen. Taste, ease of processing and markets are further factors for what seems an inexplicable trend if assessed from only a climate perspective. Another example from the Netherlands illustrates the importance of prices and income. A shift to wheat is often advocated because it is more robust in climate extremes than potato and it better stimulates soil organic matter build-up. However, compared to potato, wheat is a lower value crop, which discourages farmers to grow it (Mandryk et al., 2017). It is naive to think that the constraints (or drivers) may simply disappear in the future, and a thorough understanding is needed as a basis for their alleviation (or bending). For this, the well-developed literature on adoption of agricultural technologies and practices (for overview papers, see e.g. Kassie et al., 2015; Knowler and Bradshaw, 2007; Doss, 2006; Feder and Umali, 1993) can shed light on possible constraints and barriers limiting the adoption of CSA options. A common conclusion from these studies is that the adoption potential of a certain option depends on its fit with the farmer's context, which is determined by combined agro-ecological, sociocultural, economic and institutional dimensions at scales varying from the farm to landscape, regional and national level (Descheemaeker et al., 2019; Ojiem et al., 2006). At the farm level, poor access to natural, human and financial capital restricts the incentives and possibilities for farmers to invest in technologies or alter their farm management. In particular, small farm sizes prevent investments in improved technologies or practices to be economically viable (Harris and

Orr, 2014). Farm diversity in resource endowment may thus explain why CSA options could be interesting for some and unfeasible for other farmers in the same community or agro-ecological zone, which is why tailoring of options and providing farmers with baskets of options is advocated for improved adoption (Descheemaeker et al., 2019). Factors at larger spatial and organizational scales beyond the farm, such as community organization or extension services, may influence information flows, knowledge and skills, which have been observed to influence adoption (Kassie et al., 2015). Cultural norms and beliefs are also important determinants of adoption factors such as motivation, perception and attitude towards risk (Meijer et al., 2015; Peterson et al., 2012). Finally, common institutional determinants include market infrastructure and organization, price settings (levels, uncertainty, decision-making, information) and the presence/absence of payment (e.g. for environmental services) and insurance schemes (Mullins et al., 2018; Mandryk et al., 2015; Garbach et al., 2012).

Besides the bias from ignoring adoption constraints, other factors related to modelling capabilities may cause an overestimation of the CSA potential. These include the limitations of models to include factors interacting with climate such as weeds, pests and diseases, future changes in water resource availability and effects of climate extremes and increased variability (Challinor et al., 2014; Schaap et al., 2013). However, also the opposite trend of underestimating the true adaptation potential may occur as crop models can only simulate a limited set of CSA options (e.g. planting dates, cultivars, certain soil fertility management options) and mostly exclude systemic and transformational adaptations by focussing on current system configurations (Mandryk et al., 2012; Reidsma et al., 2010). Additionally, there are still huge uncertainties with respect to the climate predictions themselves, and more work is required to understand the interactions and feedbacks between climate, crop growth and soil biogeochemical processes under elevated CO_2 concentrations, especially in tropical soils and climates. Besides uncertainty in the climate predictions, there are various sources of crop model uncertainty which may cause either over- or underestimates of climate change impacts on crops (e.g. Asseng et al., 2013; Müller et al., 2011).

4 Operationalizing climate-smart agriculture (CSA)

Moving towards CSA requires sound decision and policy making from farm to landscape and from national to regional and global levels. CSA prioritization tools (e.g. Andrieu et al., 2017; Mwongera et al., 2017) are designed to support the decision-making process. Yet, to be effective, these tools need quantitative information on the likely effects of a range of options on the different CSA pillars; and this information needs to be specific for the context where the decisions are made. Besides that, quantitative information is also needed on the associated effects in other sustainability dimensions and on the potential constraints to adoption by diverse farmers. Furthermore, as agricultural systems are constantly changing, information is needed on likely effects in future system settings.

This section mainly focuses on two case studies from the Netherlands and Zimbabwe, where researchers in collaboration with stakeholders aimed to fill the above-mentioned knowledge gaps. The cases represent contrasting farming systems and environments in terms of the likely impact of climate change and the institutional setting determining the adaptive capacity of the agricultural sector. Despite the contrasting setting, a similar modelling approach was used, integrating climate, farm component (crop and/or livestock) and whole farm models. The modelling exercises were embedded in a broader farming systems analysis and stakeholder engagements. The case studies illustrate how farming systems analysis can assist in operationalizing CSA tools by generating contextualized and quantitative evidence on the effects of options on the CSA pillars and by integrating stakeholders' views to carve out climate-smart pathways to a sustainable future.

4.1 Climate-smart agriculture (CSA) in Flevoland, The Netherlands

The Netherlands exhibits a mild maritime climate with mean temperatures varying between 3°C in January to 18°C in July. Rainfall averages 832 mm per year. Warming is expected more so in winter than in summer, but summer variability is expected to increase. Precipitation has increased by 14% annually since the 1950s; all seasons have become wetter except summer. Winter rain will continue to increase at similar rates, summers will likely become drier.

The province Flevoland is an important agricultural area in the Netherlands, as its marine clay soils are very fertile (Janssen, 2017). Arable farming is the dominant land use (75% of the area) and is one of the major drivers of the economy (Schaap et al., 2013). Most of the farms are characterized by a substantial share of seed and ware potatoes in the rotation that are both high-value crops. Other high-value crops are seed onions and sugar beet. Winter wheat is a relatively low-value crop, used mainly for feed, and it is merely grown to improve soil quality and to keep disease pressures down.

Three related integrated assessments were performed for arable farming in Flevoland, to assess impacts of climate change towards 2050 (Mandryk et al., 2017; Reidsma et al., 2015; Wolf et al., 2015). These studies all combined a crop model, bio-economic farm model and participatory approaches. In addition, Bos et al. (2017) specifically focussed on mitigation in relation to soil fertility management.

Reidsma et al. (2015) illustrated that (1) crop models cannot account for all relevant climate change impacts and adaptation options, and (2) changes in technology, policy and prices have had and are likely to have larger impacts on farms than climate change. While crop modelling indicated positive impacts of climate change on yields of major crops in 2050, a semi-quantitative and participatory method assessing impacts of extreme events (Schaap et al., 2013) showed that there are nevertheless several climate risks. A range of adaptation measures were, however, available to reduce possible negative effects at crop level.

Potential yield improvement due to climate change simulated by WOFOST ranged between 2% (ware potato) and 29% (sugar beet) in the different scenarios (Reidsma et al., 2015). For ware potato, the main crop, a change in cultivar (higher temperature sum and longer life span) and an earlier sowing date, further improved the yield increase to 11%. In the driest scenario, water-limited yield reduced from 77% to 67% of the potential, so more irrigation was also an adaptation option. Five main climate risks were identified, which had the largest economic losses. For heat waves, causing second-growth in seed and ware potato, drip irrigation was identified as the best adaptation measure in most scenarios. To reduce the impact of warm winters inducing early sprouting in seed and ware potato, air-conditioning seemed the best adaptation measure, and to protect seed onions against fungi infections during warm and wet conditions, chemical protection was identified as the best measure. However, a portfolio of adaptation measures was available, and costs and benefits depended on the scenario (Schaap et al., 2013).

In addition to crop-level measures, at farm level, farmers can change cropping patterns, and adjust inputs and outputs. Optimal adaptation depended on objectives and constraints of farmers. If farmers can cope with extreme events, increasing the share of high-value crops such as potato improved their gross margins (Mandryk et al., 2017; Wolf et al., 2015). However, within the current rotation constraints this was only possible if arable farms cooperated with dairy farms, and rented land to rotate their high-value crops with grass or maize. As climate change had less impact on wheat, increasing the share of wheat was a more robust option, wheat prices allowing. Wheat also helped to improve the organic matter balance, and was therefore more climate-smart from a mitigation perspective (Bos et al., 2017; Mandryk et al., 2017).

In terms of mitigation, doubling the winter wheat area combined with the cultivation of cover crops to increase soil organic carbon accumulation resulted in a net GHG emission benefit, but it was associated with a financial trade-off (Bos et al., 2017). With regard to the use of organic fertilizers, only the use of compost resulted in net mitigation benefits, with larger relative soil organic carbon increases compared to N_2O emissions. When using cattle or pig slurry, the increase in N_2O emissions was higher than the emission offset through soil organic carbon accumulation. Wolf et al. (2015) projected increases in

N_2O emissions under future adaptation scenarios, but these may be reduced by increasing nitrogen-use efficiency, as nitrogen application can be reduced while maintaining yields (Silva et al., 2017).

Finally, it should be noted that farm structural change will influence productivity, adaptation and mitigation. Larger farms have more potential to adopt adaptation and mitigation options, but whether they do so depends on their objectives. The Dutch government envisions a more circular agriculture, which should lead to more cooperation among farms, increased resource-use efficiency at the regional level, and an agricultural sector, which is more climate-smart.

4.2 Transforming mixed cereal–livestock farming systems in semi-arid Zimbabwe

Semi-arid Zimbabwe is characterized by variable rainfall and poor soil fertility. Mixed crop-livestock systems predominate with crop residues used as dry-season feed, and livestock providing draft power and manure to crop production (Homann-Kee Tui et al., 2015). Current crop yields are low, with maize yielding on average 0.7 t ha^{-1} and other crops such as sorghum, millet and groundnut even less. Also, livestock productivity is poor and constrained by high mortality rates. With more than 76% of the rural population below the poverty line (ZimVAC, 2013) and food self-sufficiency achieved for only 3–10 months per year, rural households are extremely vulnerable to the adverse effects of climate change.

To assess the likely impacts of climate change and design more resilient systems, the Agricultural Model Intercomparison and Improvement Project (AgMIP) Regional Integrated Assessment (RIA) approach (Antle et al., 2018) was applied, embedded in an iterative process of stakeholder engagements. The RIA links climate, crop, livestock and economic data and models for impact assessment in heterogeneous farm populations (AgMIP, 2015). During stakeholder consultation workshops, scenarios, called 'Representative Agricultural Pathways' (RAPs; Valdivia et al., 2015) describing future socio-economic and biophysical settings, and adaptation options were conceived and consecutively refined based on modelling results. Mitigation options and effects were not considered.

Results from 29 climate models, run for the mid-century period for two representative concentration pathways, showed consistent increases in temperature, and more variable rainfall projections. Here, we highlight results contrasting a relatively 'hot-dry' with a 'hot-wet' future. A total of 160 households were surveyed and stratified into three types (extremely poor, poor and non-poor) based on resource endowments (Homann-Kee Tui et al., 2013). The modelling framework was run with specific farm structure and management settings per household. The crop growth model APSIM (Holzworth et al., 2014) and the livestock model LIVSIM (Rufino et al., 2009) simulated field- and herd-level productivity and fed into the TOA-MD model, which estimated economic performance at the farm level (Antle et al., 2014).

In the current agricultural systems, crop sensitivity to climate change was relatively small, due mainly to poor soil fertility and low fertilizer application rates, causing severe nutrient stress. The observed small decline was attributed to increased temperature accelerating phenological development, and exacerbated by drought stress in the hot-dry climate. As non-poor farms cultivated maize on better soils and with more fertilizer input, their maize was more sensitive to yield loss compared with the less-endowed farms. Livestock productivity was affected through altered production of crop residue and rangeland biomass, influencing feed intake, ranging from a positive to a negative effect in the hot-wet and the hot-dry climate, respectively. Non-poor farms, typically with larger stocking density, were more sensitive to feed gaps, and more strongly impacted by climate change than poor farms (Descheemaeker et al., 2018). At the farm level, the simulated change in farm net returns depended on the climate and the farm type. Ninety-five per cent of the extremely poor households was currently below the poverty line. Their low-input production system was not sensitive to climate change, and only 40–50% of these farmers would lose (a little). In the group of best-endowed farmers, who cultivate better soils and keep more cattle, about 75% faced reduced returns, which increased the poverty rate from 60% to 70% of the households.

During a first round of stakeholder meetings, these expected impacts were discussed and a package of adaptation options was proposed for testing. This consisted of a drought-tolerant maize variety, rotation with the forage legume mucuna (*Mucuna pruriens* var. *utilis*) and fertilizer application on maize (Masikati et al., 2015). The effects of the adaptation package were evaluated in the context of a likely future system of the mid-century, conceived with stakeholders in a first RAP. In this future system, the performance of the crop and livestock components improved due to increased nutrient input for maize and high-quality feed for the cattle. However, at the farm and community levels, improvements were disappointing with no reduction in poverty rates for the extremely poor and poor. Only the better-endowed households considerably increased their farm net returns and the poverty rate in this group dropped from 60% to 40%.

Researchers and stakeholders discussed these results in a second round of workshops and decided to design RAPs and adaptation packages that would transform the agricultural system and generate truly positive impacts on farmer livelihoods. Two contrasting RAPs were developed: a 'sustainability' pathway (RAP4) and a 'fast-economic growth' pathway (RAP5). In RAP4, improved access to technologies, markets and services enabled intensification, diversification and crop-livestock integration. Farms would increase in size by up to 40%.

RAP5 supported the better-off farms, who would increase their size by 80% and rely more heavily on external inputs. The extremely poor farms would shrink and rely more on off-farm income. Within both RAPs, the adaptation options consisted of heat-tolerant cereal varieties able to retain life cycle, and drought-tolerant legume varieties.

Crop yields in the future agricultural systems of RAP4 and RAP5 were better but also more sensitive to climate change as compared to current agricultural systems, because increased fertilizer use alleviated nutrient limitations. Contrastingly, livestock production was less sensitive, because feeding concentrates mitigated the feed gaps. At the farm level, the net returns were much higher and poverty rates much lower in the future than today, with RAP4 resulting in more profitable and less vulnerable farms compared to RAP5. As in the current system, the least endowed farm group was least sensitive to climate change. This was explained by their stronger reliance on the more robust groundnut in RAP4 and on off-farm income in RAP5. Better-adapted crop varieties effectively improved yield under climate change, particularly in RAP4 where manure use enabled more stable production compared to RAP5 where crop production relied solely on inorganic fertilizers.

However, even with the drastically better agricultural productivity in the RAPs and the reduced climate vulnerability with the adaptations, poverty rates remained high, at about 40% overall, and particularly in the less-endowed groups. This highlights the limited capability of agricultural development to lift people out of poverty and the farm size as a binding constraint for generating a decent income from agriculture. Hence, job opportunities outside agriculture will be needed to provide a living for the poorest groups and allow farms to grow bigger in area and/or economic size. By upscaling findings from field and herd to farm level, seemingly positive effects due to incremental adaptations evaporated, with virtually no impact on poverty rates. With this insight, the approach of co-designing transformative change by relaxing current binding constraints (e.g. farm size, input access) showed potential ways forward and underscored the required institutional and policy change to enable sustainable development. The role of local stakeholders was essential in contextualizing the (modelling) work and incorporating local realities in future pathways.

4.3 Lessons learnt from farming systems analysis in the case studies

Despite the large contrasts, the case studies illustrate the importance of (1) stakeholder involvement, (2) integrated, multi-criteria and cross-scale assessment and (3) consideration of farm diversity for a holistic understanding of the CSA potential. The participatory nature of the studies allowed to reveal risks and options that were not captured by the model and to co-design transformative pathways for future development. By taking on board multiple criteria, beyond the CSA pillars, trade-offs were revealed that need to be addressed for improving the adoption potential of options. By scaling from field and herd level to farm and larger levels, important limits and constraints, such as farm size, came to the fore. Likewise, this revealed why choices that seemed obvious at the field level, worked out differently at the farm level. Interestingly, in both studies, larger farms showed a larger potential to adopt and benefit from options. This illustrates the importance of taking farm diversity into account when trying to understand the true impact and potential of CSA options.

Global studies on climate change impact and CSA options (e.g. van Meij et al., 2018; Rosenzweig et al., 2014) need to be complemented with contextualized information at smaller scales to account for locally varying factors that determine crop productivity (e.g. soil fertility, crop management) and limit adaptation and mitigation (Challinor et al., 2014). The two case studies in this chapter show the strength of such contextualized research for unravelling the complexity in expected impacts of climate change and for illustrating what matters and what is feasible. In the Netherlands' example of highly productive agriculture, the pillars of adaptation and mitigation are of high priority. Nevertheless, the economic consequences of CSA options determine their uptake by farmers. In this context, input levels and related GHG emissions can be cut without a penalty on crop productivity. In contrast, in smallholder systems, represented here by the Zimbabwean case, only food security and adaptation are on the minds of farmers. One can argue whether it is even ethical to promote climate change mitigation (Doelman et al., 2018; Page, 2008) in smallholder agriculture, where amounts of input need to rise from the currently low levels in order to meet future food requirements.

5 Conclusion

The agricultural sector is both a culprit and a victim of climate change. Hence, there is a strong need for adapting to climate change and mitigating agriculture's contribution to GHG emissions. At the same time, agriculture will have to meet demands for food that are expected to sharply increase in the coming decades. The CSA concept offers scope to analyse this three-pronged challenge of food security, resilience and mitigation in an integrated way.

Numerous cropping options are claimed to be climate-smart, with agroforestry and the incorporation of legume crops as powerful examples. Yet, many claims of triple-wins do not withstand detailed scrutiny, as benefits for one CSA pillar often go hand in hand with drawbacks for another pillar or compromises in terms of social or economic sustainability. In addition, constraints to the adoption of CSA options limit the adaptation and mitigation capacity of the current system. Policies to underpin pathways towards CSA must take account of the possible trade-offs and synergies between the CSA pillars. This chapter shows that these interactions depend on the context and the scale of the analysis. To understand this complexity and find holistic solutions, integrated, cross-scale analyses that look beyond the binding constraints of the current system are necessary. We therefore argue that the quest for climate-smart cropping options is best conducted within a farming and food systems perspective.

The '4 per 1000' initiative illustrates the risk of hyping a strategy without a sound scientific basis. Unrealistic expectations of the capacity of the agricultural sector to curb emissions may reduce the sense of urgency of policy makers to invest and promote effective solutions that may be more costly. That same risk must be avoided by the science community when it comes to promoting CSA. There is an urgent need to strengthen the qualitative and generalized statements on CSA with quantitative and contextualized information on the effects of options and their feasibility for farmers. Besides decision and policy makers looking for evidence-based information, also science would benefit from systematic reviews and meta-analyses allowing the identification of knowledge gaps and new areas of research.

Finally, our contrasting case studies illustrate that context matters. Developing countries require an intensification of agricultural production to close yield gaps and meet sharply rising food demands. In this context, there are less possibilities to reduce GHG emissions, and it makes perfect sense to target efforts to food security and resilience. In contrast, for developed countries with intensive agriculture, it is not a priority to increase production, but to reduce emissions, while also adapting to climate change. Climate-smart cropping options tailored to the context can help achieving these targets.

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