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REVIEW ARTICLE

Mapping and linking supply- and demand-side measures in climate-smart agriculture. A review

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Abstract

Climate change and food security are two of humanity's greatest challenges and are highly interlinked. On the one hand, climate change puts pressure on food security. On the other hand, farming significantly contributes to anthropogenic greenhouse gas emissions. This calls for climate-smart agriculture—agriculture that helps to mitigate and adapt to climate change. Climate-smart agriculture measures are diverse and include emission reductions, sink enhancements, and fossil fuel offsets for mitigation. Adaptation measures include technological advancements, adaptive farming practices, and financial management. Here, we review the potentials and trade-offs of climate-smart agricultural measures by producers and consumers. Our two main findings are as follows: (1) The benefits of measures are often site-dependent and differ according to agricultural practices (e.g., fertilizer use), environmental conditions (e.g., carbon sequestration potential), or the production and consumption of specific products (e.g., rice and meat). (2) Climate-smart agricultural measures on the supply side are likely to be insufficient or ineffective if not accompanied by changes in consumer behavior, as climate-smart agriculture will affect the supply of agricultural commodities and require changes on the demand side in response. Such linkages between demand and supply require simultaneous policy and market incentives. It, therefore, requires interdisciplinary cooperation to meet the twin challenge of climate change and food security. The link to consumer behavior is often neglected in research but regarded as an essential component of climate-smart agriculture. We argue for not solely focusing research and implementation on one-sided measures but designing good, site-specific combinations of both demand- and supply-side measures to use the potential of agriculture more effectively to mitigate and adapt to climate change.

Keywords Climate change · Greenhouse gas emissions · Adaptation · Mitigation · Sustainable intensification · Farming systems · Consumer behavior · Food security

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1 Introduction

Global temperature increase is accelerating rapidly (Smith et al. 2015) and casts doubt on the credibility of a 2° target (Peters et al. 2013; Friedlingstein et al. 2014), and even less of a 1.5° target as aspired under the 2015 Paris agreement. In order to mitigate climate change, the Paris agreement introduced intended nationally determined contributions (INDCs)—voluntary country pledges—but it lacks legally binding emission reduction commitments (Clémençon

2016). Over 100 countries have recognized the importance of agriculture for climate change mitigation and have included the sector, especially livestock management (Fig. 1) and land use change, in their INDCs (Richards et al. 2015). However, the irreversibility of climate change (Solomon et al. 2009) and the insufficiency of the INDCs to reach the temperature targets clearly indicate the need for climate change adaptation in addition to climate change mitigation (Fig. 2)

Agriculture does not only affect climate change, but is also affected by climate change. Agricultural yields have stagnated or even decreased in some regions of the world, in part as a response to climate change, such as heat stress (Ray et al. 2012). Besides yield responses to changes in climate means, the often neglected impacts by increased climate variability (Thornton et al. 2014) and responses in cropping frequency and area (Cohn et al. 2016) might further reduce agricultural output. This makes it even more challenging to meet the ever-growing food demand (Godfray et al. 2010). In this regard, climate-smart agriculture aims to achieve food security while simultaneously mitigating and adapting to climate change (FAO 2010). Several authors have indicated that meeting the twin challenge of climate change and food security, however, cannot solely rely on technological efficiency and sustainable intensification, but must be complemented by demand management (Garnett 2011; Smith et al. 2013; Verburg et al. 2013; Bajzelj et al. 2014; Bryngelsson et al. 2016). The necessary interlinkage between supply and demand measures is overlooked in most studies on climate-smart agriculture. Recent reviews on the topic focused on either mitigation (Smith et al. 2008) of or adaption (Anwar et al. 2013) to climate change reviewing measures on the agricultural supply side only, while other studies focused only on the demand side (Hallström et al. 2015).

The objective of this paper is to review both supply- and demand-side measures for climate-smart agriculture and discuss their interlinkages, trade-offs, and context- and site-specific validity. The literature reviewed focuses on studies during the last decade (2008–2017) addressing food- and feed-related measures. Based on the literature review, potentials for different measures are identified and mapped across the globe using representative datasets. Therefore, this paper does not only aim to provide a broad overview of measures but also to identify areas with high opportunities for implementing these measures.

Fig. 1 Livestock is a major contributor to agricultural greenhouse gas emissions. These emissions stem from enteric fermentation and manure. Recognizing this fact, many countries have pledged to improve livestock management as part of the Paris agreement to mitigate and adapt to climate change (photo by: *Bianka Büchner*)

2 Climate change mitigation at the supply side

Climate-smart interventions are numerous (Fig. 3) and can broadly be categorized into three options: (1) reducing emissions, (2) enhancing sinks, and (3) fossil fuel offsetting (Smith et al. 2008). Fossil fuel offsetting by using agricultural fields to produce bioenergy, which can then replace fossil fuels used in any sector, is often seen as a measure for climate change mitigation (Dornburg et al. 2010). However, its potential largely depends on local conditions (Searchinger 2010) and production methods (Pfister and Scherer 2015) and is heavily debated in the literature due to limitations in land availability (Searchinger 2010; Tokgoz and Laborde 2014). Therefore, this topic is not discussed in this study which rather focuses on climate-smart agriculture in food and feed production.

2.1 Reducing emissions

Greenhouse gas emissions from agriculture originate from enteric fermentation, manure (left on pasture and management), fertilized soils (synthetic fertilizer, manure used as organic fertilizer, crop residues), rice cultivation, cultivation of organic soils (Tubiello et al. 2013), land use change (Johnson et al. 2014), and energy use for transport, processing, manufacture of agrochemicals, on-farm machinery, and irrigation (Arizpe et al. 2011; Weiss and Leip 2012). Enteric fermentation of livestock has the largest share among direct agricultural emissions, while fertilized soils are the largest source in cropping systems (Fig. 4). Indirect emissions from land use (further discussed in Section 2.2) also contribute a lot but are recommended to be reported under the separate sector of land use, land use change, and forestry. Likewise, energy use is usually reported under the separate sector of energy (UNFCCC 2014). Below, multiple measures are described to reduce emissions from the different emission origins, following the decreasing order of their total emissions.

Ruminant feed optimization and animal breeding can reduce CH_4 emissions from enteric fermentation. Examples of feed optimization include diets richer in concentrates (Ross et al. 2014) and supplementation with methane inhibitors (Hristov et al. 2015). However, the benefits of concentrate feed remain unclear if the additional land use change for feed

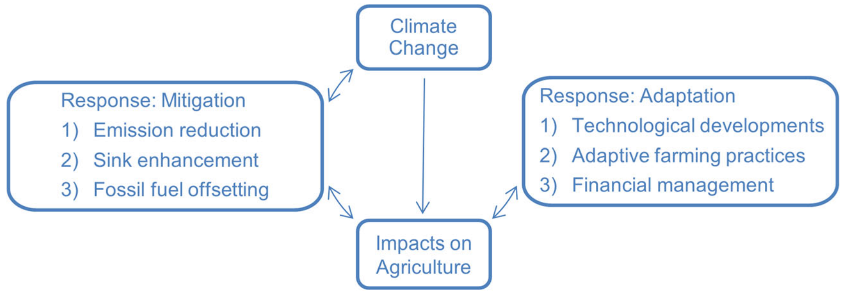

Fig. 2 Climate change response cycles. Climate change negatively affects agriculture, e.g., by causing yield losses. In response, two types of measures can be applied: either mitigation to slow down climate change or adaptation to reduce its impacts. Both involve various possible climate-smart measures

production and its associated emissions are considered (Bellarby et al. 2013). Animal breeding offers some opportunities to reduce emissions from enteric fermentation by selecting genotypes with higher productivity or lower emissions (Ross et al. 2014). Overall, the potential for reducing emissions from enteric fermentation is in a similar range as for measures addressing other agricultural activities despite its higher contribution to total agricultural emissions (Table 1, Fig. 4).

A high technical potential for reducing agricultural emissions lies in manure management (Table 1). Emissions can be reduced by rapidly removing the manure from the field or stable and storing it in a biogas plant for anaerobic digestion. The captured biogas is a source of energy and, as such, additionally offsets emissions from fossil fuels (Cuéllar and Webber 2008).

Agricultural input efficiency is a key to reduce environmental impacts (Clark and Tilman 2017). Globally, less than half of the nitrogen applied as fertilizers to agricultural fields is taken up by crops (West et al. 2014). That points to the potential to increase the use efficiency and, thereby, reduce emissions (Table 1). Reducing nitrous oxide (N_2O) emissions is crucial due to their high global warming potential, but also particularly challenging due to the complexity of transformation pathways and the multitude of influences, including climate and management practices. Therefore, the effectiveness of measures depends on local conditions and varies over time. In experiments, it is essential to also measure other forms of reactive nitrogen, such as nitrate and ammonia, as there might be trade-offs and these other forms might still be converted to N_2O downwind or downstream. Reducing the N application rate might be most reliable to reduce emissions, but it must be balanced with farmers' profits. An excellent review on these challenges and opportunities for mitigating N_2O emissions in agriculture is given by Venterea et al. (2012). In addition, it is important to note that emissions do usually not increase linearly with the N application rate as assumed by the IPCC, but rather exponentially. By using IPCC emission factors, emissions of overfertilized soils but also the emission reductions would, consequently, be underestimated (Philibert et al. 2012; Shcherbak et al. 2014).

Also, numerous options exist to limit the methane and total greenhouse gas emissions from rice cultivation, ranging from cultivar selection to straw and water management (Hussain

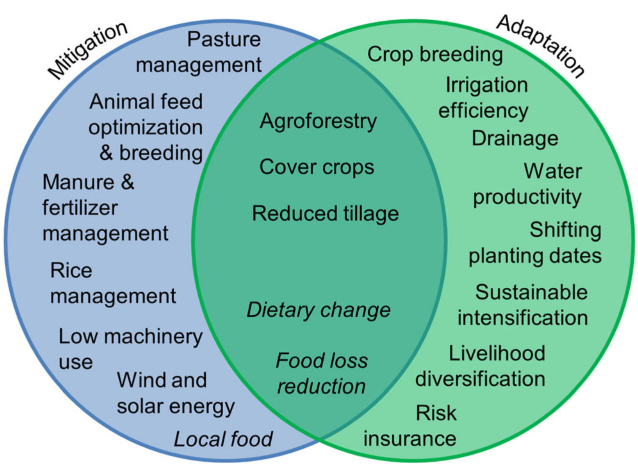

Fig. 3 Climate change mitigation and adaption options at the supply (normal font) and demand side (italic font). Some measures are synergistic in that they simultaneously address mitigation and adaptation (overlapping part of figure). The measures are numerous and the optimal choice depends on the location and context. Measures should not be applied in isolation. Instead of that, it is recommended to apply a set of complementary measures

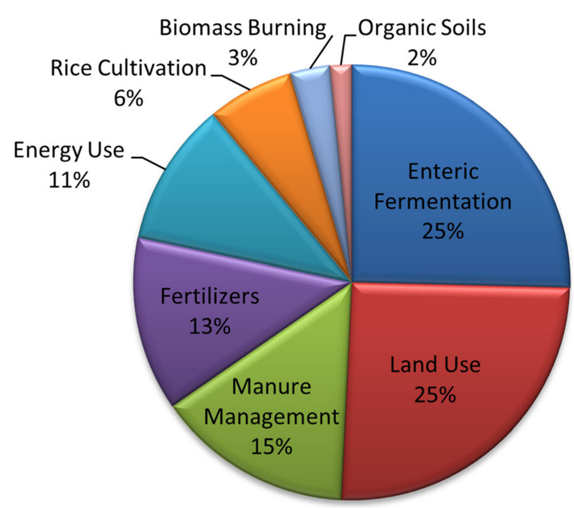

Fig. 4 Share of global agricultural greenhouse gas emissions from different activities. Absolute values were obtained from FAOSTAT for the year 2014, except for energy of the year 2012 (FAO 2015)

Table 1 Emission reduction potential of supply-side measures relative to total agricultural greenhouse gas emissions. The table gives a broad but not comprehensive overview of possible measures. The potentials of the measures are not necessarily additive, as some measures might interact with each other, especially if they address the same agricultural activity. The reduction potential was related to total agricultural greenhouse gas emissions by the shares from different agricultural activities in Fig. 4. Regarding energy use, 0.5% of the global energy consumption could be saved by increasing agriculture's energy efficiency of below-average countries to the global average (Schneider and Smith 2009). It was assumed that agriculture contributes 2% to the total energy consumption across all sectors (EEA 2017)

Agricultural activity	Example measure	Reduction potential (%)	Reference
Enteric fermentation	Feed supplement	7.6	(Hristov et al. 2015)
	Low-forage diet	3.5	(Ross et al. 2014)
	Breeding	2.9	(Ross et al. 2014)
Manure	Anaerobic digestion	18	(Cuéllar and Webber 2008)
Synthetic fertilizers	Nitrification inhibitor	1.0–7.4	(Lam et al. 2017)
	Placement	2.6–4.9	(Drury et al. 2006)
	Fertilizer composition	3.9	(Hasler et al. 2015)
	Reduced application rate	1.8–3.7	(West et al. 2014)
	Timing	2.5	(Phillips et al. 2009)
Rice cultivation	Straw management	2.3–5.1	(Hou et al. 2013)
	Water management	1.0–4.7	(Hussain et al. 2015)
	Cultivar selection	0.4–1.3	(Lyman and Nalley 2013)
Energy use	Energy efficiency	2.7	(Schneider and Smith 2009)

et al. 2015). The net mitigation potential is often lowered by opposing effects on CH_4 and N_2O emissions but is still significant (Hussain et al. 2015).

Furthermore, fossil energy use for machinery and the manufacture of agrochemicals can be reduced by higher energy efficiency, lower input use, and the substitution with renewable energy (Schneider and Smith 2009). While energy-intensive irrigation methods such as drip irrigation might be needed more under climate change (Fader et al. 2016), these can be combined with renewable low-carbon energy use, especially where high irrigation requirements coincide with high solar energy capacity in arid and semi-arid regions.

2.2 Enhancing sinks

The effectiveness of carbon sinks depends on the capacity for carbon storage, which is higher in the tropics than in the temperate or boreal zone (West et al. 2010). Besides carbon stocks that sequester carbon, changes in biophysical factors affect radiative forcing. In boreal forests, warming effects by reduced carbon sequestration upon deforestation might be offset by cooling effects of an increased snow albedo (Alkama and Cescatti 2016; Mykleby et al. 2017). In contrast, the mitigation potential of carbon stocks in tropical forests is enhanced by additional evapotranspiration and cloud cover (Alkama and Cescatti 2016). The combined effects in the temperate zone is also expected to reduce radiative forcing upon afforestation (Alkama and Cescatti 2016; Mykleby et al. 2017). Stand age and fraction cover further influence the mitigation potential by afforestation (Mykleby et al. 2017). Moreover, the sequestration potential of natural vegetation and agricultural land in temperate and boreal regions is expected to increase with climate warming and might turn some carbon sources into sinks (Zhang et al. 2017).

The most effective measure to enhance carbon sinks is land sparing (Table 2), i.e., increasing agricultural yields to spare land for natural habitat restoration (Lamb et al. 2016). In addition, carbon sequestration can be increased on the agricultural land, for instance by agroforestry. Large agricultural areas are suitable for this practice (Ramachandran Nair et al. 2009). Its potential for carbon sequestration depends on site characteristics, management practices, and the tree species (Ramachandran Nair et al. 2009). Crop residues and animal manure added to soils can also increase soil organic carbon if the soil is not saturated yet. However, its benefits depend on the alternative fate of the bio-waste (Powlson et al. 2011). When transforming bio-waste into biochar with more stable carbon, renewable energy is additionally produced and can offset fossil energy (Woolf et al. 2010). The sequestration potential of grasslands can be increased by optimizing grazing intensities, increasing the pasture productivity, and introducing new grass species (O'Mara 2012).

Cover crops and no-till farming can mitigate climate change by both carbon sequestration and an increase in surface albedo (Davin et al. 2014; Kaye and Quemada 2017). The cooling effect of no-till farming due to an increased albedo is especially strong during hot summer days. Therefore, no-till farming is more effective in mitigating heat waves than

Table 2 Sink potential of supply-side measures relative to total agricultural greenhouse gas emissions. Assumptions: General: Global agricultural greenhouse gas emissions are assumed at 5.6 Gt CO_2 equivalents (O'Mara 2012). Currently, 1550 Mha of arable land is used (Eitelberg et al. 2015). Land sparing: Using a medium scenario for yield growth, agricultural emissions in the UK can be reduced by 41% despite the low yield gaps of about 10% (Lamb et al. 2016). The global average yield gap is 57.5% (Mueller et al. 2012). Agroforestry: Currently, agroforestry is practiced on 1023 Mha, and an additional 630 Mha is suitable (Ramachandran Nair et al. 2009). Assuming a global average sequestration rate increase of 0.72 Mg C ha^{-1} a^{-1} (Ramachandran Nair et al. 2009), 4.4 Gt CO_2 equivalents could be saved per year. Cover crops: Cover crops are estimated to mitigate 125 g CO_2 equivalents m^{-2} a^{-1} by carbon sequestration and 29 g CO_2 equivalents m^{-2} a^{-1} by an increased albedo relative to the soil (Kaye and Quemada 2017). Consequently, 2.4 Gt CO_2 equivalents could be saved per year. No-till farming: Assuming a no-till adoption on 70% of the arable land (the current share in some South American countries (Derpsch et al. 2010)) and a sequestration rate increase of 0.57 Mg C ha^{-1} a^{-1} (Abdalla et al. 2013), 2.3 Gt CO_2 equivalents could be saved per year

Measure	Sink potential (%)	Reference
Land sparing	236	(Lamb et al. 2016)
Agroforestry	79	(Ramachandran Nair et al. 2009)
Cover crops	43	(Kaye and Quemada 2017)
No-till farming	41	(Abdalla et al. 2013)
Biochar addition to soils	32	(Woolf et al. 2010)
Pasture management	18	(O'Mara 2012)

reducing mean global temperatures (Davin et al. 2014). The carbon sequestration potential was found to be often overestimated, as organic carbon in the top soil layer increases rather as a result of redistribution over depth than an actual increase (Powlson et al. 2014). Still, on the long term, overall climate change mitigation is achieved as a result of increased soil carbon sequestration (Liu et al. 2014).

Carbon sinks have a large potential, but they are not infinite. The sequestration potential of cover crops, for example, is estimated to reach saturation after 155 years (Poeplau and Don 2015). In both tropical and temperate forests, there are first signs of saturation (Nabuurs et al. 2013; Brienen et al. 2015). In addition, carbon sinks do not guarantee permanent storage. Various biological and non-biological processes contribute to carbon releases (Rey 2015). Part of the emissions from land cover change are offset by erosion and subsequent carbon burial (Wang et al. 2017). Furthermore, subsoils, especially when clay-illuviated, are usually more appropriate for long-term storage of stable carbon than topsoil; however, this constitutes a trade-off with productivity gains of carbon stored in the topsoil (Torres-Sallan et al. 2017). All that shows that carbon sinks are important for climate change mitigation, but we cannot solely rely on them. Carbon sinks cannot replace but should complement emission reductions.

3 Climate change adaptation

Climate change is likely to adversely affect global food security in terms of food availability (yield losses), food stability (supply variability), food utilization (reduced food safety and more diseases), and food access (income losses and price increases) (Schmidhuber and Tubiello 2007; Vermeulen et al. 2012; Wheeler and von Braun 2013). The impacts of climate change vary regionally in magnitude and direction with high risks for food production indicated especially for South Asia and Africa (Knox et al. 2012), but also reported in numerous other regions (Springmann et al. 2016). Such impacts are not only threatening food production itself but may feed forward into countries' economic and political stability (Bellemare 2015). Smallholders, which include some of the world's poorest people, are especially vulnerable to climate change, not necessarily because of the farming system but because of a location bias (Cohn et al. 2017). This indicates the need for climate change adaptation (Fig. 3). Available options can be categorized into (1) technological advancements, (2) adaptive farming practices, and (3) financial management.

3.1 Technological advancements

Substantial progress has been made in plant breeding to tailor crops to new climatic conditions such as heat stress (Driedonks et al. 2016), floods, and droughts (Jez et al. 2016), but still large knowledge gaps prevail. Crop responses to abiotic stresses are highly complex and vary according to species, developmental stage, and environmental conditions (Driedonks et al. 2016; Jez et al. 2016). This highlights major challenges ahead of plant breeding, especially if multiple stresses simultaneously act on crops (Jez et al. 2016).

Various options exist to adapt to changes in the water cycle. In irrigated agriculture, alternative irrigation techniques such as deficit irrigation (Geerts and Raes 2009), drip irrigation (Törnqvist and Jarsjö 2012), and irrigation with treated wastewater (Trinh et al. 2013) can save freshwater. In rainfed agriculture, rainwater harvesting techniques can store some of the surface runoff as soil moisture and, thereby, increase the crop available water and resulting crop yields (Lebel et al. 2015). Improved drainage is an important measure to adapt to climate change in areas affected by increased precipitation, sea level rise, and land subsidence (Ritzema and Stuyt 2015).

3.2 Adaptive farming practices

Adaptive farming practices include shifting planting dates to optimize the timing of crop growth for a changing climate (Dobor et al. 2016) or changing the crop type. Some of the crops that are more resilient to climate change are hitherto hardly used. For example, teff (Cheng et al. 2015), amaranth (Alemayehu et al. 2015), and quinoa (Ruiz et al. 2014) can withstand some abiotic stresses such as high or low temperatures, or droughts. In addition, measures to increase agricultural productivity will be valuable in view of climate-induced yield losses, including nutrient management to close yield gaps (Mueller et al. 2012) and multiple cropping to close harvest gaps (Waha et al. 2013; Wu et al. 2014).

3.3 Financial management

Income diversification can contribute to adapting to climate change, especially in managing risks due to increased climate variability (Antwi-Agyei et al. 2014). Incomes can be diversified by taking up non-farm jobs or by integrating various farming activities. Agroforestry, for example, helps to diversify the farmer's income by combining tree crops with annual crops or pastures for livestock. At the same time, it creates synergies between adaptation and mitigation if it is applied in the tropics where carbon sequestration offers a co-benefit (Mbow et al. 2014).

Insurances can transfer climatic risks and, as such, complement climate change adaptation at low to medium risks. At high risks, donor and government supports remain essential. However, both financial instruments are limited in their effectiveness. While insurances are not accessible and affordable to all farmers, donors and governments fall behind with their financial liabilities (Linnerooth-Bayer and Hochrainer-Stigler 2015).

4 Climate change mitigation at the demand side

While the literature has a strong focus on supply-side mitigation of climate change, also, the demand side of agricultural production can contribute to climate change mitigation. Retailer and consumer demands strongly influence farm management and production decisions, hence impacting on production-related emissions. Measures discussed below mainly concern (1) dietary changes, (2) localism and seasonality, and (3) waste efficiencies.

The role of diets on greenhouse gas emissions is frequently discussed (Stehfest et al. 2009). With the possible exception of vegetables grown in heated greenhouses, plant-based products emit less than animal-based products (González et al. 2011; Clark and Tilman 2017), including wild-caught and farmed fish (Cao et al. 2013). The greenhouse gas emissions of beef are exceptionally high due to enteric fermentation (González et al. 2011; Clark and Tilman 2017). Therefore, a change in diet to less animal-based products and especially to less beef can significantly reduce greenhouse gas emissions (Table 3). Compared to average diets in developed countries, a vegan diet (without any animal products) reduces greenhouse gas emissions by 25–75% (van Dooren et al. 2014; Hallström et al. 2015; Bryngelsson et al. 2016). Even just a shift from ruminant (beef and lamb) to monogastric meat (pork and poultry) could reduce emissions by 18–35% (Hoolohan et al. 2013; Hallström et al. 2015). However, the opposite trend is observed, and worldwide, diets are rather getting richer in meat, leading to an increasing carbon footprint of an individual's diet (Pradhan et al. 2013).

Food consumed in the USA is, on average, transported almost 7000 km (Weber and Matthews 2008), while in other developed regions, similar transport ranges apply. As a result, transportation of food contributes about 11% to the greenhouse gas emissions from agriculture (Weber and Matthews 2008). Reducing the food miles by buying local decreases these emissions. However, some products do not have local substitutes, for example exotic fruits and coffee for European consumers. Therefore, strict localism, even when the entire country is still considered as local, would require a dietary change, including substituting products and decreasing the consumption of products without a substitute. Carbon efficiencies earlier in the supply chain may overcompensate transport emissions (Verburg et al. 2013; Avetisyan et al. 2014). This applies, for example, to developing countries with a

Table 3 Emission reduction potential of demand-side measures relative to total food-related greenhouse gas emissions. The extrapolation of meat consumption to a global estimate is based on the assumption that people in developed countries consume almost double the amount of meat than the world average. The extrapolation of obesity to a global estimate is based on the average share of obese people among different countries. Since transport emissions can be overcompensated by carbon efficiencies earlier in the supply chain, a climate benefit from local food consumption is uncertain. Likewise, the implications of seasonal food are inconsistent

Measure	Reduction potential (%)
Shift from omnivore to vegan diet	13–38
Avoidance of obesity	15
Shift from beef and lamb to pork and poultry	9–18
Food waste reduction	12
Local food consumption	±
Seasonal food consumption	±

beneficial climate and less energy-intensive farming practices compared to many developed countries (Brenton et al. 2009). Therefore, optimizing trade relations could lead to larger emission reductions than strict localism. Furthermore, long-distance transport emissions can be lowered by reducing transport in airplanes in favor of ships despite longer storage and associated energy use for cooling (Stoessel et al. 2012). If buying local is feasible also depends on the food self-sufficiency. Some European countries such as Norway and Portugal require continental trade, and most of East Asia, Africa, and the Arabian Peninsula even require global trade to meet their calorie demand due to insufficient capacity of local agriculture (Pradhan et al. 2014). These analyses do not yet consider the nutritional variety of food production, which might further reduce self-sufficiency. Climate change might increase international trade dependency in 2050 by 4–16% (Pradhan et al. 2014). Historical analysis has shown that food security has improved significantly, but that it was mainly achieved by trade, while self-sufficiency has hardly changed (Porkka et al. 2013).

Eating local food is often perceived as implying to eat seasonal food. While a focus on foods that can be grown locally in the season may reduce food miles, this is not always what is implied with seasonality. The definition is still vague, and, strictly speaking, seasonal food only requires food to be grown outdoors during the natural growing period. As such, it excludes greenhouse production and possibly long-term storage of food, but it can be consumed anywhere, distinguishing it from local food (Brooks et al. 2011). In that case, the environmental benefits are found to be minor (Jungbluth et al. 2012) and inconsistent, and, in practice, it is difficult to identify out-of-season food if it can be produced globally (Brooks et al. 2011).

Globally, over half of the calories from harvested crops and grassland are lost, of which only a part is unavoidable (Alexander et al. 2017). While in developing countries postharvest losses (at the supply side) are high, people in developed countries waste a lot of perishable food at the household level (at the demand side) (Aschemann-Witzel et al. 2015). The high food waste in developed countries can be explained by low food expenditures in high-income countries (USDA 2016). Preventing avoidable food losses would, globally, reduce greenhouse gas emissions from food by about 12% (Hoolohan et al. 2013). Overconsumption can also be considered as food waste (Alexander et al. 2017). Its restriction offers two benefits in terms of climate change: Most importantly, it saves food (and food waste) per capita, and in addition, vehicles need less fuel for transporting a lighter population (Michaelowa and Dransfeld 2008). In a British study, an obese population with an 18% higher body mass index (40% obese people instead of only 3%) had a 6% higher carbon footprint (Edwards and Roberts 2009). Globally, obesity is increasing and its environmental implications deserve more attention in future research (Walpole et al. 2012).

5 Mapping opportunities for climate-smart interventions

Opportunities for the various climate-smart agricultural interventions often depend on the location as a result of varying agricultural practices and environmental conditions, or the production or consumption of a specific product. The variation in these conditions leads to different potential benefits of climate-smart agricultural interventions across the world, and targeting interventions to locations with high potential may lead to efficiency. Using proxies for the different possible groups of interventions, we synthesized available knowledge and data to identify large-scale patterns of opportunities for specific types of climate-smart interventions at both the supply (Fig. 5) and demand side (Fig. 6). Table 4 presents the proxies used to indicate the potentials for the interventions including the spatial databases used to represent those in a map.

Manure emissions (FAO 2015) are especially high in the major meat-producing countries: the USA, Brazil, and China (FAO 2015). Excess nitrogen (West et al. 2014) is especially applied in Asia and Europe, like Bangladesh, India, Belgium, and the Netherlands. These excess applications are partly emitted as N_2O into the atmosphere. The largest rice producers are China, India, and Indonesia (FAO 2015). Consequently, they have a higher potential to reduce CH_4 emissions from rice cultivation (FAO 2015) by measures such as optimized drainage (Kudo et al. 2014). In sub-Saharan Africa where technological development is low, food losses from agricultural production and postharvest handling and storage can be reduced. Carbon sinks have the greatest potential in the tropics where tropical forests can store a lot of carbon and albedo is low (West et al. 2010; Alkama and Cescatti 2016). Countries that stick out with a high carbon storage potential include French Guiana, Gabon, and Malaysia. The need for adaptation is linked to the excess death rate in 2050 due to climate-induced changes in agricultural production (Springmann et al. 2016). Springmann and colleagues modeled changes in bodyweight, red meat consumption, and fruit and vegetable consumption as well as their health effects. The excess death rate is highest in China, Vietnam, and Greece.

Demand-side measures can complement supply-side measures. Therefore, we also map meat consumption, obesity (likely because of overconsumption), and food waste (Fig. 6). The USA, Canada, Australia, and New Zealand rank high in all three categories. Per capita meat consumption is

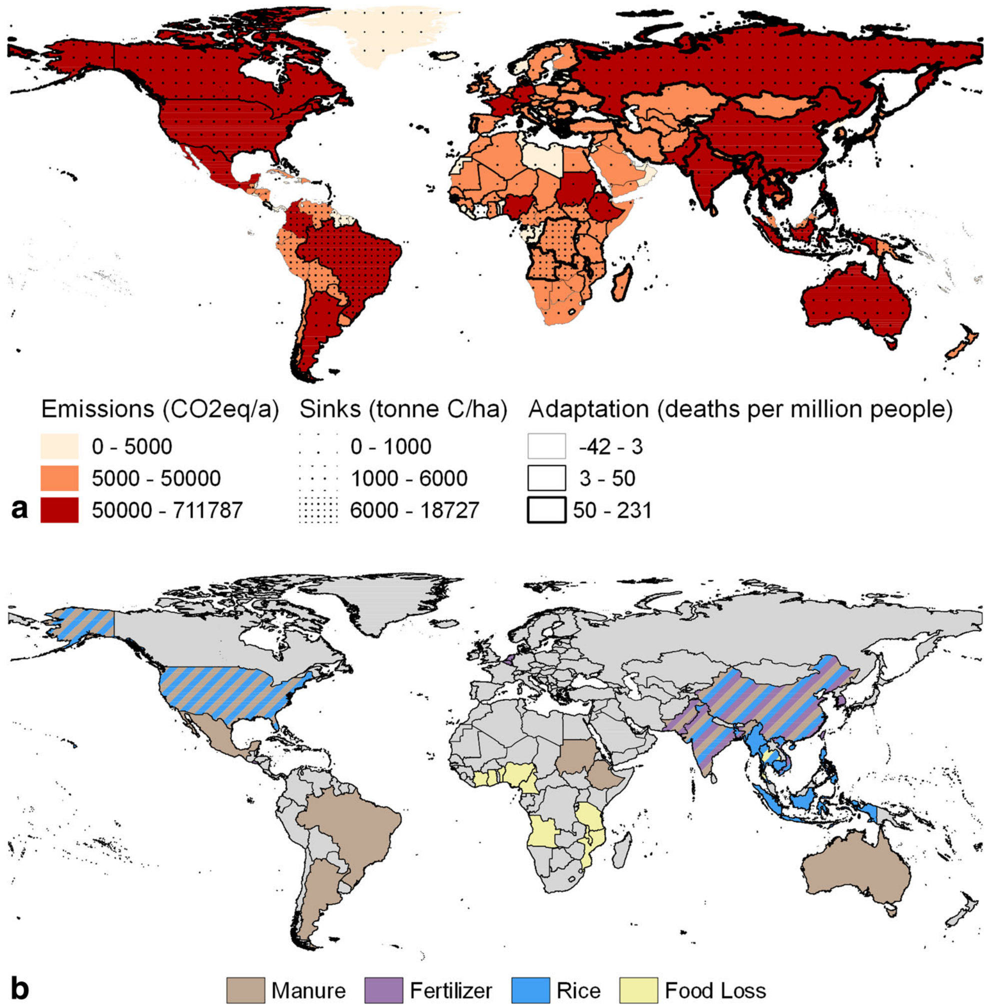

Fig. 5 Country-level opportunities for implementing site-dependent and climate-smart interventions at the supply side. **a** The top map shows potentials for mitigation in terms of emission reduction and sink enhancement and potentials for adaptation. **b** The bottom map shows the top 10 countries for different mitigation options in terms of emission reduction

also high in South America, Europe, and Israel, and the most meat per capita is consumed in Hong Kong (FAO 2015). These countries have a wide scope for dietary change contributing to climate change mitigation, which benefits both their health and the environment. Likewise, reducing overconsumption and obesity benefits both, and there is also a large

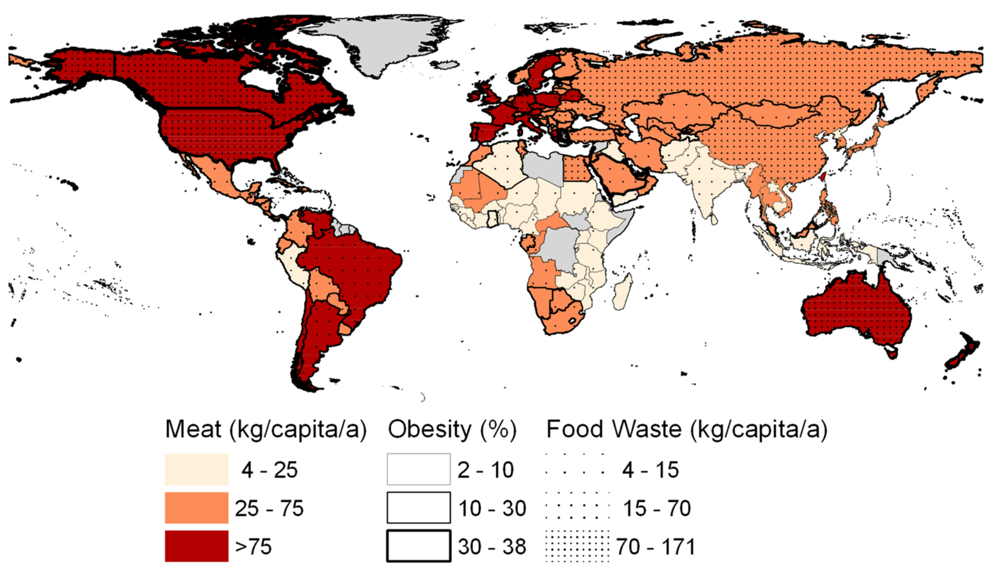

Fig. 6 Country-level opportunities for implementing site-dependent and climate-smart interventions at the demand side. Consumers can reduce greenhouse gas emissions by reducing their meat consumption, overconsumption (obesity), and food waste. Only countries with a population of at least one million people are assessed. Countries with smaller populations or missing data are displayed in a light gray color

Table 4 Spatial proxies indicating opportunities for various climate-smart interventions. Food loss and waste percentages given for seven food groups and world regions (Gustavsson et al. 2011) were translated to absolute values by means of food supply data (FAO 2015). For food losses, the average rank of absolute and relative losses was used

Intervention	Proxy	Reference
Emission reduction	Total agricultural emissions	(FAO 2015)
	Emissions from manure	(FAO 2015)
	Emissions from fertilizers	(FAO 2015)
	Emissions from rice cultivation	(FAO 2015)
	Food losses	(Gustavsson et al. 2011)
Sink enhancement	Biomass carbon storage	(Ruesch and Gibbs 2008)
Adaptation	Climate-induced mortality	(Springmann et al. 2016)
Mitigation (demand)	Meat consumption	(FAO 2015)
	Obesity	(CIA 2015)
	Food waste	(European Commission 2016; Gustavsson et al. 2011)

room for improvement in Europe and the Middle East (CIA 2015). Moreover, more food waste could also be avoided in Europe (European Commission 2016).

Mapping of such opportunities enables to identify hotspots and to set priorities of where to implement which measures. We further analyzed the Pearson correlation among opportunities for different climate-smart interventions, and between the opportunities and the human development index (HDI) in 2015 (UNDP 2016). At the supply side, correlations with the HDI are low and most pronounced for carbon sinks. Carbon sinks tend to be higher in countries with a lower HDI, as many carbon sinks are in tropical, developing countries. At the demand side, all correlation coefficients exceed 0.5. This confirms that consumers in developed countries have larger environmental footprints, while at the same time often having multiple opportunities for more climate-smart consumption, especially with regard to meat consumption and obesity (Fig. 7).

6 Interlinked supply and demand changes

While most of the literature reviewed in this paper focused on either supply-side or demand-side measures, changes on both sides are often interlinked. In most cases, changes at either side necessitate changes at the other side (Table 5). We can categorize the processes underlying interlinkages between supply- and demand-side changes into (1) prize effects, (2) demand-supply relations, and (3) efficiency impacts.

Some of the measures at the supply side entail higher costs for capital (e.g., installations of new technology) or labor (e.g., less mechanization). Unless they are fully subsidized, these costs will likely translate into higher selling prices the consumer must be willing and able to pay for the measures to be economically viable. Without regulation, in absence of subsidies, or without some sort of certification, it is unlikely that farmers will adopt such supply-side measures, as it will affect their competitive advantage as compared to other producers. Rueda et al. (2017) present a framework for analyzing how sustainable practices at the supply side can be selected in using the supply chain. Note that the passage through the food value chain moderates the effect of increased production costs on consumer prices (García-Germán et al. 2016). Still, if consumers can afford higher prices largely depends on their food budgets relative to their incomes. It ranges from 6% of their total expenditure US Americans spend on food to 56% Nigerians spend on food (USDA 2016). On the one hand, with such a high budget share in low-income countries, higher food prices inevitably lower food intake, thus decreasing food security (Regmi and Meade 2013). In addition, food aid also reduces with rising prices, as donor countries often have a fixed annual budget allocated to food aid (Rosen and Shapouri 2008). On the other hand, since farm incomes might rise and agricultural employment is high in food insecure low-income countries (World Bank 2017), the higher income might improve food security (Antle et al. 2015), which does

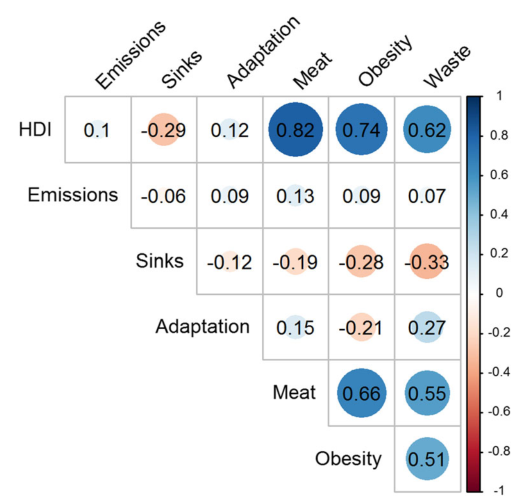

Fig. 7 Pearson correlation matrix of the human development index (HDI) and country-level opportunities for implementing site-dependent and climate-smart interventions at the supply and demand sides

Table 5 Interlinkages between supply- and demand-side changes

Supply-side change		Demand-side change
Supply-side driven measures		
Manure management	→	Higher consumer prices due to increased labor costs
Low machinery use	→	Higher consumer prices due to increased labor costs
Wind and solar energy	→	Higher consumer prices due to increased capital costs
No-till agriculture	→	Reduction in consumption in case of yield losses
Agroforestry	→	Higher consumption of food from trees and of shade-resistant crops; reduction in consumption in case of yield losses
Plant breeding	→	Consumer acceptance of genetic engineering
Heat- and drought-resistant crop production	→	Higher consumption of underutilized crops; reduction in consumption in case of lower yields
Demand-side driven measures		
Decrease in meat production, increase in processing of meat analogs	←	Diet change, especially reduced meat consumption
Diversification of local food production, supply chain management changes	←	Local food consumption
Complementary measures		
Postharvest food loss reduction	↔	Food waste reduction

not only depend on food availability but also on food access (Schmidhuber and Tubiello 2007; Vermeulen et al. 2012; Wheeler and von Braun 2013).

Price elasticities are higher for animal than for plant-based products (Cornelsen et al. 2015). Since a reduction in meat consumption is a key leverage for climate change mitigation by consumers (Table 3), the price increases necessary to mitigate climate change at the supply side might also contribute to mitigating climate change at the demand side. However, meat consumption is especially high in high-income countries (Pradhan et al. 2013), where food price elasticities are lower (Cornelsen et al. 2015). In addition, in high-income countries, where food consumption is typically saturated and a significant share of the income is spent on luxuries like recreation and cultural activities (Regmi and Meade 2013), consumers can afford to spend more money on food, thus compensating for higher production costs of climate-smart agriculture. If potential price increases are not accepted by consumers, the implementation of climate-smart practices would require enforcement by law to create equal opportunities for farmers on the market. However, resulting price effects could lead to strong public resistance. Still, increasing environmental regulation economically challenges farmers who, even in developed countries, can often hardly eke out a living (Rodriguez et al. 2009; Selfa et al. 2010). The high perceived economical risks and uncertainties associated with adopting sustainable agricultural practices (Dumbrell et al. 2016) indicate that financial incentives, from subsidies to higher profit margins, might motivate farmers to change practices. For example, price premiums in organic agriculture have been shown to be an effective motivator for changes (Serra et al. 2008) and also agri-environmental schemes have been widely adopted (Lastra-Bravo et al. 2015). Labeling or certification would be needed to justify increased consumer prices. Although hypothetical studies on consumer behavior are likely to be biased by social desirability towards overstatements (Costanigro et al. 2011), it seems that consumers are willing to pay more, especially for greenhouse gas minimization (Tait et al. 2016).

Demand-supply relations are related to matching changed production to changes in consumption and vice versa. When supply-side measures involve the production of different crops (better adapted to climate change or with less emissions), the consumer must be willing to consume these crops as a substitute for the original produce. Agroforestry, for example, requires trees and shade-resistant crops. It is only feasible if the food they provide—such as nuts and fruits from trees or potatoes as a shade-resistant crop (DBU 2010)—are consumed more. This requires to break eating habits which influence food choices much more than attitudes and intentions (Köster 2009). Crop breeding and the use of different crops might both improve resilience to climate-induced natural hazards such heat and droughts. While the acceptance of genetically modified crops could be fostered by informing consumers about risks and benefits and by building trust through governmental regulations (Ishii and Araki 2016), changing consumption patterns, especially traditional staple crops, requires to overcome food neophobia (our reluctance to try out novel food) and cultural attachment to specific crop types (Hoek et al. 2011).

In reverse, some of the changes at the demand side must also be accompanied by changes at the supply side. First, a reduction in meat consumption requires some livestock farmers to seek alternative income sources and an increased processing of crops to meat analogs or other protein-source alternatives. Wheat and soya beans, for example, can be texturized to resemble meat (Asgar et al. 2010), but also other crops, previously not cultivated at large scale, may substitute for protein demand, such as lupins (Mercedes Lucas et al. 2015). Second, local food consumption entails changes in supply chain management and diversification of local food production to ensure a nutritional balance and good health of the consumers. To achieve a reduction of food miles, supply chain management needs to avoid that consumers have to drive to various nearby farm shops to collect different food products (Coley et al. 2009). Also, diversity is an important aspect of food consumption and is more challenging to achieve at the local scale where soil and climatic conditions resemble each other and production of specific crops is far from efficient (Clancy and Ruhf 2010).

Climate-smart practices differ in agricultural productivity from conventional practices. Where productivity is reduced, this creates trade-offs with land use changes or changes in supply-demand matches. Efficiency differences in using land often depend on the location and context. No-till farming, for example, can produce higher yields (especially in dry climates and in combination with residue retention and crop rotation), but, when looked from a global perspective, it mostly reduces yields compared to conventional tillage with an average of 6% yield loss (Pittelkow et al. 2015). Likewise, agroforestry can produce higher and lower yields compared to sole cropping, and high tree densities are favored in temperate regions (Sereke et al. 2015). When replacing common staple crops with underutilized crops, the productivity losses might be more significant, most importantly because breeding has not yet been exploited for theses crops (Mercedes Lucas et al. 2015). Losses in production would have to be compensated by agricultural expansion which is limited by land availability (Eitelberg et al. 2015) and associated with carbon losses (Chaplin-Kramer et al. 2015). As a result, agricultural expansion due to productivity losses might nullify the climate benefits of the above measures. To avoid such negative rebound effects, climate-smart measures would best be accompanied by changes on the demand side, e.g., by reducing food waste or consumption. Similar linkages through the land system are apparent for changes in the consumption of animal products. Ruminants can be raised on land unsuitable for crop production and additionally fed by co-products from food production, which are not edible for humans (van Kernebeek et al. 2016). Therefore, the consumption of animal proteins (within these limits) could be an efficient means to use land resources.

7 Pathways for implementing climate-smart agriculture

Under the United Nations Framework Convention on Climate Change, full producer responsibility is assumed (Jiang et al. 2017), while in life cycle assessments, typically all the responsibility is allocated to consumers. Both viewpoints influence each other: consumer-driven changes will affect the supply side, while supply changes will either lead to prize effects or require consumer acceptance. Given these interactions and the possible synergies arising, responsibilities should be shared between producers, consumers, and intermediaries (Rodrigues and Domingos 2008). An obstacle shared by both the producer and consumer side is the resistance to behavior changes (Rodriguez et al. 2009; Hoek et al. 2011). Even in case of awareness of environmental problems and intention to change behavior, it still requires additional efforts to translate the intention into action and to maintain that behavior.

Barriers to production change by farmers include risk-averse attitudes, lack of knowledge and skills, lack of financial resources, and low expected economic returns from new practices (Rodriguez et al. 2009; Fleming and Vanclay 2011). The breadth of influencing factors shows that a low adoption of sustainable practices is not necessarily a result of intrinsic reluctance of farmers, but often rather stimulated by external circumstances that heavily reduce the opportunities for change (Rodriguez et al. 2009). This applies especially to poor smallholder farmers in developing countries whose contributions are important but require innovative solutions (Cohn et al. 2017). Furthermore, individual behavioral change is not directly related to results in a complex field like climate change (Fleming and Vanclay 2011), and farmers might not be aware of the risks of climate change, or they might not know which measures are appropriate in their case to adapt to climate change. Informing farmers on benefits and risks is a key to facilitate the adoption of climate-smart practices. For doing so, extension services play a crucial role (Iglesias et al. 2012). Likewise, change agents must provide much more than just general technical assistance. They must be able to provide farm-specific advice on suitable sustainable practices (Rodriguez et al. 2009).

However, when markets are not conducive to change, the main factor in farmer decision making is not addressed. Financial incentives can stimulate the adoption of climate-smart practices. Subsidies are motivating farmers to change their agricultural practices (Serra et al. 2008), but few subsidies exist for climate-smart practices. In the EU, for instance, subsidies are, to some extent, steered towards extensive agriculture and production on marginal land with the aim to compensate farmers for adverse conditions and to promote biodiversity (Merckx and Pereira 2015). From a climate and food perspective such policy may not be optimal and other, better targeted incentives may be more beneficial and effective to reach climate and food security targets (Rodriguez et al. 2009). Alternatively, carbon credits for mitigating emissions or sequestering carbon might also offer an additional income to farmers, but the inclusion of agriculture on the carbon market faces multiple challenges. First, carbon prices fluctuate and the associated uncertainty discourages farmers from adopting climate-smart practices (Dumbrell et al. 2016). Second, it is difficult to measure and verify carbon emissions from agriculture (Sirohi 2015). Contrariwise, communicating potential co-benefits, such as improved soil quality, is more likely to convince farmers to switch (Dumbrell et al. 2016), although the benefits can only be realized in the long term (van Apeldoorn et al. 2011). At the same time, simple tools to estimate on-farm emissions and their reductions need to be developed (Sirohi 2015), and intermediaries could bridge the gap between farmers at the micro-level and credit buyers at the macro-level (Clements and Moore 2015).

Obstacles that consumers face to change their diets or minimize food waste include unfamiliarity with alternatives (Hoek et al. 2011; Schösler et al. 2012), inappropriate packaging (Aschemann-Witzel et al. 2015), convenience, such as buying ready meals (Schösler et al. 2012) and buying fewer times but in excess (Graham-Rowe et al. 2014), the belief that meat is important for a healthy diet (Verbeke et al. 2010), expiration dates, and the lack of knowledge on how to store and handle food (Aschemann-Witzel et al. 2015). The obstacles point again to the opportunities for motivating sustainable consumption. Changes in consumer behavior may be achieved by improved access to climate-smart alternatives (Hoek et al. 2011; Schösler et al. 2012), raising awareness about the health benefits (Appleby and Key 2016), and taxing emissions from food, especially food items with high emissions, such as beef (Wirsenius et al. 2011; Edjabou and Smed 2013). Minimizing food waste can be facilitated by educating consumers, removing discounts on large purchases, different date labeling, and innovating packaging that allows to withdraw smaller amounts during a longer period (Aschemann-Witzel et al. 2015). By contrast, food eco-labels as an incentive for consumers to buy more sustainable food products are so far of limited use because consumers have difficulties in understanding the meaning of the many different labels on the market and distrust them. Therefore, some have argued for more regulation on labeling (Horne 2009).

Next to the mentioned opportunities and constraints, two factors are important two consider for both the producers and consumers: (1) the power of retailers and (2) the scale of change. First, retailers mediate between farmers and consumers. Especially in the EU, the USA, and Australia, the retail sector is very concentrated, and as such, they have a large influence on what farmers produce (Sutton-Brady et al. 2015) and citizens consume (Dawson 2013). This situation provides a potential to stimulate the adoption of supply-chain measures: within the bounds of countries of origin, supply chain arrangements, and end markets' characteristics (Rueda et al. 2017), retailers can demand more sustainable products from the farmers and make them easily accessible to consumers. Second, compared to big changes of a few, such as niche markets and meat-less diets, larger gains are expected by moderate changes of many, such as raising the baseline for all farmers (Smith et al. 2008b) and reducing meat consumption of many consumers (Laestadius et al. 2016).

8 Conclusions

Considering the large competition for land (Wu et al. 2014), severe water scarcity (Scherer and Pfister 2016), and other environmental pressures, achieving productivity gains (or compensation for productivity losses) is challenging without strong externalities or higher greenhouse gas emissions and energy use. Meeting the twin challenge of climate change mitigation and food security requires a portfolio of interventions at both the supply and demand side. Such portfolio is needed because the potential of measures is context-specific and there are strong interlinkages between the supply and demand sides. However, also the feasibility of adoption and regulation are site-specific, sometimes excluding high-potential regions due to low governance and other constraints to implementation. Generally, emissions can rather be reduced in developed countries with high fertilizer application and energy use and especially in meat-producing countries with high emissions from enteric fermentation and manure, while productivity can be improved in developing countries to reduce emissions from land use change especially in the tropics.

In achieving climate-smart agriculture, the supply and demand sides are interlinked and targets are only reachable by action on both sides. This makes implementation of such measures challenging. The higher food prices related to agronomic climate-smart measures require willingness of the consumers to pay more or reduce their consumption to avoid burden shifting to another location. In contrast, a higher demand for local food or meat analogs requires changes in the supply chain. Besides climate mitigation, adaptation is important due to the irreversibility of climate change. Also here, optimizing agricultural production is insufficient and must be interlinked with demand management such as reduced food waste and diet changes.

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