Adaptation and development pathways for different types of farmers

Working Paper No. 270

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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RESEARCH PROGRAM ON
Climate Change, Agriculture and Food Security

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Correct citation:
Stringer LC, Fraser EDG, Harris D, Lyon C, Pereira L, Ward CFM, Simelton E. 2019. Adaptation and development pathways for different types of farmers. CCAFS Working Paper no. 270. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Available online at: www.ccafs.cgiar.org.

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The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is a strategic partnership, led by the International Center for Tropical Agriculture (CIAT). The Program is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For details please visit https://ccafs.cgiar.org/donors.

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Abstract

One of the greatest challenges humanity faces is feeding the world's human population in a sustainable, nutritious, equitable and ethical way under a changing climate. Urgent transformations are needed that allow farmers to adapt and develop while also being climate resilient and contributing minimal emissions. This paper identifies several illustrative adaptation and development pathways, recognising the variety of starting points of different types of farmers and the ways their activities intersect with global trends, such as population growth, climate change, rapid urbanisation dietary changes, competing land uses and the emergence of new technologies. The feasibility of some pathways depends on factors such as farm size and land consolidation. For other pathways, particular infrastructure, technology, access to credit and market access or collective action are required. The most viable pathway for some farmers may be to exit agriculture altogether, which itself requires careful management and planning. While technology offers hope and opportunity, as a disruptor, it also risks maladaptations and can create trade-offs and exacerbate inequalities, especially in the context of an uncertain future. For both the Sustainable Development Goals and the 2015 Paris Agreement to be achieved, a mix of levers that combine policy, technology, education and awareness-raising, dietary shifts and financial/economic mechanisms is required, attending to multiple time dimensions, to assist farmers along different pathways. Vulnerable groups such as women and the youth must not be left behind. Overall, strong good governance is needed at multiple levels, combining top-down and bottom-up processes.

Keywords

Development; adaptation; farmers; climate change; agriculture; food security.

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Acknowledgements

This paper was written as part of the *Transforming Food Systems Under a Changing Climate* initiative, led by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). The authors would like to thank their respective organizations as well as the reviewers who provided feedback on this paper.

Transforming Food Systems Under a Changing Climate:

About the initiative

Transforming Food Systems Under a Changing Climate is an initiative led by CCAFS that aims to realize a transformation in food systems by mobilizing knowledge and catalyzing action. The initiative brings together leaders in science, business, farming, policy and grassroots organizations to identify pathways for transformation. To find additional publications in this series and for more information, please visit: http://bit.ly/TransformingFood.

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Acronyms

GDP	Gross Domestic Product
SDGs	Sustainable Development Goals
UBI	Universal Basic Income

Introduction

Global demand for food is expected to grow by 70% from 2009 levels by 2050 (Foley et al. 2011). At the same time, projected climate change impacts threaten to make food more difficult and more expensive to produce and distribute (Foley et al. 2011), while huge amounts go to waste. The burden of these challenges is likely to fall disproportionately on the poorest and most vulnerable farmers, many of whom already suffer from hunger (Holt-Gimenez et al. 2012; Gregory et al. 2005). To keep the planet's mean annual temperature within 1.5 °C of pre-industrial times, agriculture's carbon intensity must be radically and urgently reduced, as food production is already contributing significantly towards the overstepping of planetary boundaries (Gordon et al. 2017). Changes are required against the backdrop of global trends in population growth, rapid urbanization, dietary changes, the emergence of new technologies and pressures from competing (non-food) land uses. Impacts of these trends are unequally distributed between the global north and the global south, affecting different types of farmers in different ways.

'Business as usual' agriculture is not an option for meeting basic human needs on a planet with 2 billion more people compared to 2018 by 2040, and with intensifying climate change impacts. If countries' commitments under the 2015 Paris Agreement and the Sustainable Development Goals (SDGs) are to be achieved, transformation becomes vital. Transformative change towards a future in which food security, climate change and livelihood aspirations are met requires radical, systemic shifts in values and beliefs, patterns of social behaviour, and governance (Olsson et al. 2014). Haberl et al. (2011) estimate the magnitude of transformation required is akin to that from hunter-gatherer societies to agrarian and then industrial societies, constituting nothing less than the "fourth industrial revolution" (World Economic Forum 2016). No single transformation pathway will be appropriate in all situations, and it is difficult to generalize from one farmer to another (Fraser et al. 2006; Stringer et al. 2006; Scoones et al. 2018). Interventions that help to leverage progress along different pathways need also to address the needs and aspirations of the farmers themselves if they are to pursue a meaningful livelihood. Pathways further need to ensure that environmental, economic and social-cultural benefits are not compromised, now or into the future.

This paper explores possible pathways for different types of farmers, considering where they might be in 2040. It outlines some of the necessary interventions, risks and trade-offs associated with different pathways, for farmers operating in a variety of agricultural systems globally, including cropping, livestock and tree (silvopasture) systems. It also considers the impacts of different disruption scenarios that could radically alter anticipated pathways and offers a menu of possible interventions.

Adaptation and development pathways for different types of farmers

Different types of farmers need different adaptation and development pathways: they are starting from different points, and are affected by global trends in different ways. In some cases, farm size is important in shaping decisions and options; in others, possible pathways reduce the role of income from agriculture within overall livelihood strategies, require greater action on environmental concerns, or suggest an exit from farming altogether. This section presents a range of different farmer types and possible indicative pathways.

Conventional large-scale, commercial farmers

Average farm sizes are generally larger in countries with higher average per capita GDP (Lowder et al. 2016). Large-scale commercial farmers' decision-making is currently overwhelmingly driven by the markets they can access to sustain and enhance their profitability. Land management practices are often environmentally insensitive, requiring agrochemicals, large machinery, transportation infrastructure, and irrigation (Pereira et al. 2018). Consequences of this include the eutrophication of water bodies, aquifer depletion, soil degradation, increases in greenhouse gas emissions, declines in pollinator abundance and diversity, as well as negative impacts on off-farm ecosystem and human health (Schindler et al. 2016; Dalin et al. 2017; Smith et al. 2016; Ramankutty et al. 2018; Goulson et al. 2015). The power of large-scale commercial farming can reinforce inequalities, which in the global south includes a loss of local livelihoods and food security, as larger commercial farms negatively disrupt established local income generation patterns (Shete and Rutten 2015; Mellor and Malik 2017). Large multinational and supermarket purchasing models, driven by consumer demands for cheap food, also favour larger scale producers (Stringer et al. 2008). Both large-scale private companies and quasi-governmental agricultural enterprises are involved in transnational land and water "grabbing". Such actions reflect specific modes of development that favour economically-driven capitalist approaches (e.g. economies of scale efficiencies) with often negative effects on local livelihoods and land rights (Dell'Angelo et al. 2017; Lambin et al. 2001).

Pathways for conventional large-scale commercial farmers need to support development of markets for more sustainably created produce by 2040 in order to meet food security and climate change challenges. From a regulatory perspective, regional, national and international governance processes must establish a coherent framework to ensure that sustainable practices are prioritised, emphasising environmental and social-cultural aspects. This could include pricing mechanisms on carbon and payment for ecosystem services programmes that incentivize creation/maintenance of biodiversity and ecosystem services. The logic behind these kinds of schemes has been well articulated, and experts, industry and policymakers have been aware of these possibilities for decades (Redford and Adams 2009). In parallel to supporting farmers, work needs to be done on the consumer side of the food system, through awareness-raising and education programmes, to ensure that consumers, especially in wealthier parts of the world where disposable income is more abundant, demand food that has been produced to the highest environmental and ethical standards.

Another pathway of particular relevance to large-scale farmers who have easy access to capital for investment is based on harnessing the power of technology. Digital technology has been proposed as a 'quick-fix' (Falk et al. 2018), offering hope as a route both to attract new farmers and keep some people in farming, especially in the global north. Robotics, artificial intelligence and big data analytics all offer potential to produce more food on less land and with fewer inputs (Lindblom et al. 2017; Parizat and Strubenoff 2018). However, these technologies are not a panacea, and concerns have been raised about e.g. the effect of automation and robotics on rural labour, particularly in locations where youth unemployment is already high (Fraser 2016). The development of technology further presumes some level of investment capacity, literacy and infrastructure, excluding some farmers from the outset (Trace 2016). Consequently, the development and application of specific technologies in local contexts needs to be guided by local stakeholders, with farmers themselves playing a key role.

In summary, pathways for large-scale commercial farmers demand legal frameworks and regulations pertaining to the environment, supported by necessary policy, financial and economic mechanisms; consumer advocacy around sustainably produced products, grounded in long-term awareness raising and education programmes; and technological interventions. In reality, all these pathways and many more will be required, in order to ensure that the environmental impact of conventional large-scale farming is reduced, production levels are sustained and enhanced and social and cultural conditions are improved, especially where large-scale agricultural corporations lack connection to the land.

Conventional smallholder farmers

Farmers of this type span a very large spectrum, with those farming for subsistence at one end and those generating a small surplus for market at the other. Income generated by conventional smallholder farms is seldom adequate to ensure a meaningful livelihood (Homann Kee-Tui et al. 2015; Harris and Orr 2014). There are an estimated 570 million farms in the world (Lowder et al. 2016) and around 85% of these (480 million) comprise 2 ha or fewer. While large numbers of people operate these small farms, they occupy only around 12% of global agricultural land area. Even using best-practice farming methods, such small farms are not financially viable (Harris 2019), with land users relying on other sources of income, particularly where fragmentation reduces the effective land area available for cultivation. Farmers with less than 2 ha of land are unlikely to become prosperous, no matter how productive they become (Harris 2019), and meaningful poverty reduction will never be achieved from increasing crop and livestock productivity alone (Wichern et al. 2017). Rare exceptions are capital-intensive enterprises such as glasshouses producing high-value crops, and intensive livestock production.

Although most smallholder households sell a proportion of their produce at some time, this is not really ‘commercial’ market agriculture. They are not selling a surplus for profit but a means to generate cash to pay for goods and services that cannot be provided by a subsistence lifestyle. Significant sustainable intensification on these very small farms - the majority - will be difficult to achieve and it is unlikely that most conventional smallholders will make a major contribution to increased global food security (Thornton et al. 2018). Very small farms cannot be commercial in any real sense unless they gain access to more land, which would allow them to focus more on producing surpluses for sale. They should then respond to the same incentives as large conventional farms. Thus the pathways from subsistence to commercial farming are predominantly a function of farm size, with these types of smallholder farmers viewed on a continuum.

The traditional model of agricultural transition, whereby people leave land that is then consolidated into larger and more capital-intensive farms, is not happening quickly in regions such as sub-Saharan Africa, where rural households are strongly attached to their land (Tafira 2015). At the same time, there is mounting evidence of environmental degradation, while yield gaps reinforce existing poverty (Tittonell and Giller 2013), in combination with population growth and high levels of rural youth unemployment. Many smallholder households diversify their livelihoods by engaging in non-farm income generating activities, although many of these are currently seasonal and/or precarious (Harris and Orr 2014). Whether or not developing countries can generate enough economic opportunities for people to leave farming completely remains questionable. The current situation, where households operate small land units as low-cost, low-risk, 'safety net' enterprises alongside other income generating activities, is a perfectly reasonable social system and can be relatively durable given enough support (despite that environmental aspects are often somewhat neglected). However, it is not readily amenable to agricultural intensification.

Decarbonising agriculture could potentially hit smallholders disproportionately hard, especially considering their greenhouse gas emissions are comparatively small to those of intensive large-scale commercial farms. Boosting or sustaining productivity through e.g. climate-smart agricultural practices offers one feasible option. For instance, integration of *Faidherbia* with grain crops on nutrient-poor African soils can both sequester more carbon in soils and trees while increasing yields. However polycultures are not popular in mitigation schemes requiring rigorous monitoring and reporting. Despite local climate and food production 'wins', potential gains on very small farms will always be small and represent poor incentives for investment (Harris and Orr 2014; Harris 2019). Given that smallholder households already rely on multiple income sources, an important pathway for conventional farmers with the smallest, least viable farms may be to develop more secondary or tertiary economic opportunities in the rural environment. This may include improving the post-harvest value chain and other ancillary economic activities. These efforts require institutional support, education and training, as well as resourcing and investment. They also necessitate consideration and mitigation of greenhouse gas emissions from new sources as novel opportunities emerge.

Another pathway, involving reform of tenure rights and enabling land ownership, could help those households with agricultural ambitions to access extra land, creating larger viable, profitable farms oriented more firmly towards markets (Collier and Dercon 2014). This pathway is equally relevant to small commercial farmers who wish to expand their enterprises. Widespread ownership could support a vibrant and effective land rental market. If owners were better able to rent out their land they could obtain some income from this asset while effectively removing themselves from direct involvement in agriculture. Urbanisation trends offer an opportunity for this pathway as millions of people are likely to exit from smallholder agriculture altogether (see section 2.5). At the same time, agricultural re-engagement efforts are needed to help the 65 million refugees and displaced people in the world (UNHCR 2018), many of whom live in camps, to derive their own food security at a small scale. This is vital if the post-2015 development aspiration to 'leave no one behind' is to be achieved. Positive examples of refugees striving to become food self-sufficient while keeping emissions low are found in countries such as Kenya (FAO 2018a).

Traditional extensive farmers

Traditional extensive farmers start from a point of strong environmental and socio-cultural emphasis but are not always profitable, so pathways to 2040 need to attend to this. One example of a traditional extensive farmer operates in a silvopasture system. Silvopasture systems are characterized by agroforestry and the co-location of animals or crops and trees, often, but not always, in extensive systems (Mosquera-Losada et al. 2009, 2012; Cubbage et al. 2012). Silvopastoral activities can be found in landscapes around the world (Maia et al. 2007), but their scale and potential varies hugely from region to region. For example, in South America, small-scale systems can be classified as 20-50 ha; medium scale from 90-800 ha and large-scale >1100 ha (Frey et al. 2007), while in other regions more extensive systems are found (Cubbage et al. 2012).

The traditional extensive farmer type faces challenges and constraints, particularly relating to knowledge, initial capital and labour costs, operational issues, resource tenure, niche markets and incentives (Thevasthasan et al. 2012; Hernandez-Morcillo et al. 2018). However, in general, land management practices deliver a wide range of ecosystem services, and hold high socio-cultural values for human populations that live in and manage these areas (Atanga et al. 2014; Simelton and Dam 2014). Possibilities for profit are challenged by the often remote, extensive nature of these systems, which stifles market access; while smaller plots offer limited opportunities for the movement of livestock (Mirzarbaev et al. 2016).

Traditional, extensive farmers suffer from a lack of economic profitability. Yet, diverse, traditional extensive systems such as silvopasture offer at least two opportunities for income generation for both small and large farmers as pathways seek to better harness economic, environmental and socio-cultural benefits: i) money from the sale of trees/shrubs and their products, and ii) income from the sale of livestock. Some types of trees (e.g. *Gliricidia sepium* in Nigeria) also provide secondary resources such as fodder and browse, while products such as berries, nuts and mushrooms can be gathered for subsistence and/or sale (Vandermeulen et al. 2018; Rousseau et al. 2015). Overall, decision making about the types and numbers of animals in these systems plus the types and numbers of trees creates opportunities and limits relating to both food production capabilities and opportunities to mitigate and adapt to climate change. Trees on farms can further aid faster economic recovery after natural disasters (Simelton et al. 2015).

In general, larger extensive farms offer greater opportunity for economic gain while maintaining environmental and socio-cultural values purely because of their larger land area, compared to smaller farms. One trade-off is that with a bigger area to manage, it can be more difficult for a single farmer given the sometimes lower economic returns per ha compared with other systems (Antonini and Arguilés-Bosch 2017; Duffy 2009; Woodhouse 2010). Larger farms are nevertheless more likely to be able to gain market access, especially in locations such as the USA and Australia, where extension and other agricultural learning institutions are more easily accessible (Jin and Huffman 2016). These opportunities and resources can combine to help to generate higher returns than smaller farms.

While small silvopastoralists may be hampered by their land size, collective action can be stimulated to pool both input resources (land, knowledge, infrastructure etc) and outputs, supporting marketing of diverse products from smaller scale systems. For example, in Romania following the collapse of Communism, owners of degraded, fragmented plots united to harness World Bank funding for tree planting via the Government. This enabled access to funding which was only available for land areas of a certain (larger) size (Stringer et al. 2007). Other collective options include cooperative grazing (Lesorogol 2008) or engagement in land rental, although these may result in economic changes or create environmental degradation if not carefully managed (Sklenicka et al. 2014). Other pathways include microfinance to provide upfront capital to invest in the system (e.g. use microfinance to support set up of a cooperative), while learning platforms can provide an opportunity to share knowledge between different small farmers—an important gap in many regions (Djanibekov et al. 2016)—facilitating collective action. These pathways can be supported by rebalancing subsidies and improving market access, marketing and the opening up of new markets (Frey 2007). Viable levers may also include innovations such as payments for ecosystem services (PES), certification of niche products; or diversification of income streams into cultural/eco-tourism (Tew and Barbieri 2012; Heikkinen et al. 2012).

Artisanal farmers

Artisanal farmers start from a point of profit-orientation, with an environmental emphasis. This type of farmer responds to the increasing disconnection between food consumers and producers (Goodman 2011; Schneider and McMichael 2010). Artisanal farmers short-cut industrial supply chains by reconstructing the producer-consumer interface, emphasizing the locality/region or provenance of the food they grow (Goodman 2011). While some commentators consider that this allows for better environmental and social outcomes, the ability of “alternative” networks to deliver these win-wins may be overstated (Hodgins and Fraser 2018). At the same time, niche food production is more expensive than conventional agriculture because it incorporates environmental externalities of the production process, so it can be unaffordable for many. In order to improve food security while keeping emissions low, enhanced access to products developed by this kind of farmer is necessary.

The evolution of food resistance through, for example, vegetarian choices, brand choices and avoidances, provides a trend through which alternative food networks are entering the mainstream (Cronin et al. 2014). Such networks and practices present opportunities for climate-smart production and consumption, offering trendy alternatives to unsustainable options in the current dominant food system. They also present a market that is willing to pay an increased price for a higher quality product that is more climate-smart and agro-ecological. One example of a food movement centred on the artisanal farmers is the Slow Food Movement: a recent gastronomy that endorses the principles of taste and pleasure whilst at the same time defining food as a thoroughly cultural product linked to issues of quality, sustainability, biodiversity, and social justice (Scheider 2015; Fraser and Rimas 2010). Emphasising the quality of produce, connecting to specific farmers and their practices has important environmental outcomes, as people are sometimes willing to pay more for what they see as premium food and drink. However, ‘small batch’ mentality means that this produce is often accessible only to a small consumer base and excludes the majority. Enabling transformative pathways for artisanal farmers requires them to make their products more accessible to wider society, but also for wider society to value and demand the products that they are offering (Guerrero Lara et al 2019).

The success that gastronomic movements have in shifting perceptions of food and what can be considered as good food, offers a starting point for moving taste preferences towards more sustainable produce, such as alternative proteins to ruminant-based meat. A classic example is how high-end restaurants like Noma in Copenhagen opened the door for entomophagy—the eating of insects—that offers a viable alternative protein source to meat (Ceurstemont 2013; Cressey 2014; Vantomme 2015; Halloran and Flore 2018). Insects provide a viable alternative to meet protein demands of a growing world population (Van Huis, 2016; Hanboonsong et al. 2013), yet attitudes remain a barrier in certain cultures and countries. Private companies in USA and Europe continue to develop products using insects at a small scale, but research is exploring how to increase appeal to a wider market. Studies have shown that strategies such as processing insects into familiar products and promotion via ‘celebrity chefs’ and well-known restaurants, can help to shift attitudes (Van Huis 2016). Education and awareness-raising are key here. The implication is that there is a growing demand for insects that requires a shift towards their cultivation and away from foraging, in order to prevent over-harvesting as demand increases (Vantomme 2015). There is also technological potential for insect farming to become less labour intensive via use of robotics (Aspire 2016).

Foraging enables individuals, restaurants or small companies to promote local ingredients, however, it can lead to sustainability issues if demand is too high (Lindow 2017). The seaweed industry provides examples of how foraging can move towards cultivation, enabling wider market access and increasing supply without threatening wild populations. There is a growing market for seaweed (Rebours et al. 2014), but issues with seasonality and over-harvesting present barriers to scaling up (Hasselstrom et al. 2018; Hafting et al. 2012). There is nevertheless potential for on-land cultivation which still allows for the quality, traceability and availability that is preferred by the current premium market (Hafting et al. 2012). There are already examples of this happening successfully in USA and Europe via improvements in technology and knowledge sharing between companies and countries such as Japan and China, where seaweed farming has been established for longer (Rebours et al. 2014).

Bread is a staple food for many people and can be made with various different grains. In South Africa perceptions about the link between increased diabetes and the consumption of highly processed white bread made from wheat flour, has become a concern to some (Markey 2016). Artisanal bread, made from biologically-grown wheat, stone-ground into coarse flour, has become a conventional product for the middle classes in Cape Town. Being able to harness a premium price for higher quality produce offers an incentive to artisanal farmers to use more sustainable farming practices and to grow a greater variety of crops (e.g. indigenous grains or landraces). The impact of improved soil health and biological farming methods affects the taste and nutritional value of the food produced on the farm. By widening the societal base that can access these higher quality products, farmers are offered markets to which they can tailor bespoke produce. However, this healthier bread alternative, that supports artisanal small-scale wheat farmers, is not affordable for the majority of South Africans, especially those living in informal settlements. Innovative business models by bakers that include cross-subsidisation of produce by those who can afford it for those who cannot is one intervention that can enlarge the customer base for these niche products. This model allows processors to support farmers to grow more organic and speciality grains, whilst ensuring it results in improved accessibility of these products for a larger proportion of the population (Markey 2016).

Pathways out of agriculture

An exit pathway away from agriculture is possible for all the farmer types considered above as we move towards 2040. For large-scale commercial conventional farmers, an exit pathway looks more likely when e.g. technology changes production, or low profit margins or natural disasters put enterprises out of business. In many ways, this is a process that has been underway for generations and is linked to what is known as the "cost price squeeze". In particular, stagnant commodity prices have suppressed farm incomes while rising input prices (including land values and property tax) have increased the cost of farming. The vast majority of farmers have simply exited farming while those that remain have, in general, adopted a high-volume low-margin approach that is extremely capital-intensive (Troughton 1989). Insurance also plays a key role for those who remain.

Exiting agriculture offers a very real possibility for smallholder farmers facing situations where livelihoods are increasingly marginal, in areas of the global south with few/no other on-farm livelihood options and where vulnerability to civil unrest and extremism is high (Fraser and Rimas 2011; Sneyd et al. 2013). An exit pathway presents knock-on impacts for migration and movement as people seek jobs outside of the agricultural sector. This kind of pathway is particularly critical given high levels of youth unemployment in many rural regions (White 2012). Deagrarianization also feeds urbanisation trends and can exacerbate already widening inequalities, both within and between countries. In some regions, an exit from agriculture is fuelled by civil unrest and extremism, which could further increase numbers of refugees and internally displaced people (Suckall et al. 2015; Suckall et al. 2017), as seen, for example, in Nigeria, where people have been driven away from their land by Boko Haram (Enobe 2016). Smallholders in the global north are not immune from the exit pathways either. The blight *Xylella fastidiosa* affected olive groves across southern Europe since 2013, and has put small specialised farms out of business, despite that for hundreds of years they successfully lived off producing olive oil (Strona et al. 2017). Similar push factors could easily emerge over short- medium- and long-terms.

Traditional and extensive farmers could exit agriculture when viable and desirable alternative livelihoods and robust transition supports (e.g. training programmes and income support) are available. Without such supports, farming households that exit agriculture face substantial obstacles in terms of relocation and establishing new livelihoods (Anderson and McLachlan 2012). For more traditional hunter-gatherer societies who turned to farming (e.g. the Kalahari San people), exiting agriculture becomes a much more likely pathway when their rights to access land alter. In many parts of Africa in particular, designation of land for conservation purposes has caused populations to move to urban centres and seek livelihoods outside of farming.

Artisanal farmers are likely to take an exit pathway when there is no viable demand for their higher priced goods. This could occur, for instance, during an economic downturn when people have less disposable income and start cutting down on luxuries. If these producers are focussing on specific markets, for example tourists or for export, then they would be hit hard by changes in tourist numbers (e.g. resulting from security alerts or damage to transport infrastructure) as well as changes in trade regulations (e.g. new import tariffs to a market they rely on). These types of shocks may result in these farmers having to exit farming altogether.

For all farmer types, exiting farming may bring mental health and well-being challenges independent of transition support mechanisms. Farming, like other rural livelihoods, provides a deep sense personal identity and meaning to rural lives and communities that links with strong attachment to place and landscapes (Parkins and Reed 2013; Tafira 2015). Being pushed out of farming may cause gendered psychological harm with higher suicide risks for men in the global north and south (Hogan et al. 2012; Alston 2010a,b, Carleton 2017). Such disruptions of rural livelihoods in male-dominated rural economies may also result in higher rates of domestic abuse and family dissolution (Alston 2010b; Whittenbury 2013). Depending on local cultural orientations, rural communities also may resist exit (Lyon 2014, Lyon and Parkins 2013). Thus, well-resourced engagement and transition measures for exiting farm households should form part of any climate and agricultural transition policy (Bourque and Cunsolo Willox 2017). Cultivating a link between place attachment (i.e. the emotional links between people and places), local social capital, and environmental values (the things that people appreciate and put in high regard in a place) may help to mitigate the need to exit farming or its risks to well-being (Lincoln and Ardoin 2016; Cradock-Henry et al. 2018). For example, local livelihood diversification interventions can support this, which include expanding local or household assets, improving literacy, and training through extension services, all of which can soften exit hardships (Martin and Lorenzen 2016; Asfaw et al. 2017). In turn, these measures could help to slow urbanisation rates and reduce some of the tensions associated with migration as people seek alternative jobs.

Towards transformation

Given the diversity of starting points and the different challenges faced by each type of farmer, it is clear there is no silver bullet for transformation. In reality there are many more possible pathways than we have space to address, but focusing on a selection for different farmer types allows us to identify the kind of levers and interventions, along with some of the risks that would need mitigation. Table 1 summarises possible situations that each farmer type might be in by 2040 if they take the pathways we have considered and if they remain within agriculture.

Table 1. Transformation matrix for different types of farmers (present-2040) and the necessary levers and risks

Farmer type T_1 (2019)	Farmer type T_2 (2040)	Interventions for each pathway	Risks to be mitigated along each pathway
Conventional large-scale commercial e.g. 300 ha industrial monoculture maize farm	Big commercial farmer with greater focus on environmental externalities e.g. 300 ha maize farm with hedgerows, wild flower and pollinator	Novel technology	Unequal access, energy intensive, environmentally damaging, increased social inequality, marginalisation of women, reduction/change in rural employment opportunities, loss of farmer control, technology lock-in, hackability and use of novel technologies to disrupt other technologies
		Payments for Ecosystem Services	Unclear or ill-defined cost & benefit sharing mechanisms
		Coherent regulatory framework, platforms,	Unenforced or unevenly enforced laws and regulations that exacerbate inequality

	areas and certified organic status	and enforcement	
		Removal of perverse subsidies	Unintended consequences such as economic disruption and continued or worsening environmental degradation
		Consumer awareness & education	Social upheaval
Conventional smallholder subsistence e.g. 0.5 ha, low input, experiences food shortages at certain times of year	Smallholder market producer with land consolidation and increased market access due to urbanisation	Increased access to credit, technology, and infrastructure	Increased environmental externalities and potential trap of becoming the next generation of industrialised farmers in a different location, increased exposure to market fluctuations
		Tenure reform, land rental markets	Conflict between traditional & formal authorities, land-grabbing
Conventional smallholder market oriented e.g. 5 ha growing a little excess for market	Smallholder market producer with increased supply chain security	Increased access to credit	Increased debt and economic vulnerability
		Access to appropriate technology	Unequal access, energy intensive, environmentally damaging, increased social inequality, marginalisation of women, reduction/change in rural employment opportunities, loss of farmer control, technology lock-in, hackability
		Expansion of 'Fairtrade' style certification schemes	Unequal access, inequality, marginalisation of women, reduction/change in rural employment opportunities, high compliance costs
Traditional extensive farmer e.g. silvopastoral farmer or coastal mussel forager	Increased diversification of income streams	Certification	Lack of buy-in, greenwashing, increased inequality due to higher costs of artisanal foods
		Payments for ecosystem services	Unclear or ill-defined cost & benefit sharing mechanisms
		Infrastructure investment	Unequal access, energy intensive, environmentally damaging, increased social inequality, marginalisation of women, reduction/change in rural employment opportunities, loss of farmer control, technology lock-in, hackability
		New market opportunities e.g. ecotourism	Reduction in food production due to non-agricultural incomes due to land-use change to conservation, increased carbon emissions from tourism (flights etc.)
		Improve credit access	Increased debt and economic vulnerability
		Collective action	Failure of collective action due to fragmentation, conflict, or lack of interest

Artisanal e.g. urban roof greenhouse or niche livestock producers (organic, free range)	Increased market share	Urban horticulture	Increased debt and economic vulnerability, competition in a niche market, regulatory resistance or hesitance
		Certification	Lack of buy-in, greenwashing, increased inequality due to higher costs of artisanal foods
		New business models enabling equitable consumer access	Social upheaval, lack of implementation, class conflict
		Increase social movements	Failure of social movements, increased conflict within and between movements, lack of critical mass
		Chef-farmer alliances	Cartels, inequality, competition-price issues, lack of buy-in, greenwashing, increased inequality due to higher costs of artisanal foods

The range of pathways in Table 1 are illustrative and necessarily partial given the great diversity of farmer types globally. Some pathways tackle single trends; others attempt to target multiple trends. All the pathways require a mixture of interventions to help address the innovation, social and economic challenges associated with each. To deliver transformation requires fundamental shifts in how food and agriculture are understood and governed, meaning that each pathway comes with a suite of caveats, uncertainties, challenges, trade-offs and limitations. All pathways require policy and behavioural changes involving one or more types of actor, making education, awareness raising and learning central to the process. It is also clear that top-down governance interventions need to be met by bottom-up solutions that fully appreciate the variety of contexts in which they are deployed. Understanding context requires engagement with the farmers themselves to appreciate their decision-making, uncertainties and motivations, and to co-develop appropriate pathways and the necessary levers to advance along them. The components of the enabling environment do not operate in isolation either. All interventions and levers depend on appropriate governance, knowledge and education, resourcing and finance, and the support of legal and regulatory frameworks and their enforcement.

Considering the feasibility of different pathways in terms of sustaining food production while minimising climate change impacts suggests that overall there would be a convergence towards smallholder and traditional farmers becoming more like artisanal farmers with a greater market share by 2040. This would be coupled with substantially improved connectivity between producers and consumers, shorter supply chains and larger areas under production as a result of rental markets and consolidation, potentially through cooperatives and supported by collective action. At the same time, technology would need to evolve to support the different farmer types.

No new technology is without risk. Innovations are often implemented under high uncertainty where the degree of unwanted side-effects are unknown. These ‘unknown unknowns’ demand some degree of caution. For instance, from an equity perspective, technological change impacts diverse social classes and gender differently (Taylor 2018). Most importantly, the transition towards food system digitalization will introduce a host of “behind-the-scenes” actors including national and supra-national level regulators, technical standard bodies, private corporations, and potential hackers into everyday agriculture/fisheries practices (Greenfield 2018; Bronson and Knezevic 2016). On the extreme side, this may create the potential for the weaponization of agri-food data, system hacking, and the fear of our food data falling into the wrong hands. As Taylor (2018) cautioned, the failure to address the underlying inequalities in the food system will impact who is rendered vulnerable and insecure by new technologies. Some technological solutions are currently only feasible at small scale and if large scale adoption takes place, adaptations could shift towards being maladaptations; similarly, some innovations are more suitable in some contexts, being maladaptive in others. Indeed, the application of less radical innovations such as climate insurance in agriculture illustrates how sometimes strategies designed to help farmers in the global north end up causing unintended consequences, especially when they are transferred to the global south. Müller et al. (2017) found that under traditional practice, farmers spread their risks, growing several crops in the hope that at least one can withstand climate extremes such as drought. Conversely, climate insurance in agriculture is often set up to target specific crops and therefore acts as an incentive for farmers to specialize. If crop insurance is targeted only at key staple crops, this strategy can undermine risk spreading, as well as contributing to biodiversity loss, land degradation and other challenges. Insurance can have social impacts too, reducing farmer to farmer assistance when insured farmers no longer come to the aid of those who are not insured.

Careful planning and coordination will be vital, especially if co-benefits are to be harnessed while reducing risks. Institutionalised mechanisms for rapidly remedying trade-offs in months, as opposed to the years and decades that high-level political decision making requires, is necessary and involves a wide range of actors beyond those in the food and climate system. Nevertheless, even with the best laid plans, disruptions could take things in new (unexpected) directions, both singly and in combination. Disruptions could speed up or slow down progress along the various pathways or call their entire feasibility into question by e.g. altering transport routes, disrupting existing markets and creating new opportunities. For example, the New Silk Road Economic Belt (One Belt, One Road) project which is connecting Asia and Europe via new infrastructure could disrupt agriculture and markets in novel ways. A selection of five disruption scenarios is presented in section 3.

Disruption scenarios

We first present the various disruption scenarios before exploring their impacts on different types of farmer and the pathways.

Box 1 considers the possible impacts that a global carbon pricing mechanism might have on the agricultural production model that is most responsible for environmental degradation: large-scale, industrialised monocultures (Gordon et al. 2017; Pereira et al. 2018). Although to date there is limited evidence that current carbon pricing schemes have resulted in any substantial reductions of greenhouse gases, there is a consensus in the literature that while market mechanisms on their own may not be sufficient, they are still needed (e.g. Campiglio 2016), despite their social unacceptability, even in richer countries. To avoid exacerbating inequalities, clear mechanisms are needed to make sure polluting practices are not outsourced to poorer countries, that taxes are high enough to adequately compensate for damages and that development activities in the developing world are not put in jeopardy. Addressing these challenges means uncomfortable conversations and actions are needed around equity and fairness, as opposed to equality, such that different abilities to pay are reflected in the tax system, and top-down and bottom up governance are brought together.

Box 1 Disruption via a global carbon pricing mechanism

One reason for environmental degradation is the failure of the market to adequately cost externalities such as pollution or soil erosion. Regulations are needed to internalize the negative environmental costs associated with farming. Any such strategy would best be instituted at international level or included in multilateral trading agreements. Leaving aside the political feasibility and social acceptability of achieving this, there is widespread consensus that policies to internalize environmental costs are needed to promote sustainable pathways for agriculture and food (Jaffe et al. 2005). Carbon pricing mechanisms stand as an illustrative example and include "cap and trade" programmes where economic actors are given a maximum amount of greenhouse gas emissions they are allowed to produce [the cap] and then allowed to trade with other economic agents, selling surplus carbon credits or purchasing more as needed.

Another carbon pricing mechanism would include a carbon tax on the amount of greenhouse gas emissions created by an economic agent. Applying such policy instruments to food and farming systems would have transformative impacts in at least four areas. First, farmers would receive a huge incentive to adopt farming practices such as conserving nitrogen fertilizer (fertilizer is a major source of greenhouse gas emissions as the creation of nitrogen fertilizer is extremely energy intensive). It should be noted, however, that area-based payments to smallholder farmers for environmental services entail very high transaction costs. Second, carbon pricing would likely have a significant impact on the technology used to transport food. In particular, it is likely that trucking and shipping companies would shift to an electric fleet. Similarly, it is likely that the compressors used to keep shipping containers refrigerated would also shift from diesel to electricity-based systems. Third, protein, and in particular conventional livestock, are amongst the most energy intensive aspects of our diet. However, alternative proteins based on ingredients such as algae, fungus, legumes, or insects can be produced at a fraction of the greenhouse gas emissions when compared with most conventional forms of livestock protein. A carbon pricing mechanism would have the likely effect of making alternative proteins more competitive in the marketplace and would create an incentive for industry to make greater use of these ingredients. A fourth potential impact of a carbon pricing mechanism would be to slow the rate of land-use conversion from forest to agriculture. In particular, if high carbon land uses, such as forests, were given carbon credits under a cap and trade program, then there would be a financial incentive to reforest marginal

Box 1 Disruption via a global carbon pricing mechanism (continued)

agricultural land as well as an incentive to protect forested land from being converted into farms.

Taken together, therefore, the anticipated impact of a universal carbon pricing mechanism could have transformative impacts on food and agricultural systems. It would create incentives for farmers to use management practices that result in fewer inputs, create an incentive for firms to invest in a low greenhouse gas emission transportation infrastructure, be instrumental in creating a market opportunity for alternative proteins, and provide a catalyst for reforestation while preventing forest areas from being cleared for farming.

Box 2 considers the impact of the fourth agricultural revolution which might use genetics to accelerate photosynthesis, in line with the development of new technologies. As noted earlier, such technologies are not without risk.

Box 2 The fourth agriculture revolution

Averting the food crisis through technology has the potential to radically change food and farming systems. In particular, gene editing, robots, artificial intelligence and the Internet of Things lead many experts to believe that food and farming systems are on the cusp of the "4th agricultural revolution" that will be as significant for the 21st century as the Green Revolution was in the 20th century (Pretty and Bharucha 2018, World Economic Forum 2018). These new technologies offer precision agriculture's "smart tractors" that help farmers boost profitability while reducing inputs by giving them the tools to plant the right seed in the right place within a field (Capmourteres et al. 2018). Similarly, there are now robotic milking parlours that maintain the health and welfare of the animals while reducing potentially harmful inputs such as antibiotics (Weersink et al. 2018). Other major areas of potential innovation include the use of data analytics to help monitor and prevent zoonotic diseases (Astill et al. 2018).

One area of technological innovation that may prove to be particularly disruptive relates to the genetics of photosynthesis. In general, yields of our major food crops rose by over 100% since 1950, and approximately 50% of these increases can be attributed to genetic improvements while the other 50% relate to farm management and inputs (Long et al. 2006). One fixed limit on plant productivity has been the extent to which plants are capable of turning solar energy into

Box 2 The fourth agriculture revolution (continued)

biomass. While estimates vary, depending on the crop and the weather conditions, generally plants utilize <5% of the solar energy they receive and reengineering crops so that they convert more solar energy into biomass represents a kind of "holy grail" amongst plant geneticists (Santini 2012). As a result, the Gates Foundation has poured $70M into the "Realizing Increased Photosynthesis Efficiency" project. This involves using cutting edge genomic technologies to change the 170-step process that plants undergo when they convert sunlight and carbon dioxide into biomass (RIPE 2018). One way to do this would be to engineer rice and wheat so that it uses the same photosynthetic pathways as do maize and sugar cane. Briefly, maize and sugar cane have an extra carbon molecule in the chloroplasts, and this enables these crops to be more efficient and able to remain productive under hot and dry conditions. Researchers estimate that if they were ever able create rice and wheat cultivars that use this "extra-carbon" (or "C4") form of photosynthesis, then they would be able to boost yields by 50% (Bullis 2018).

If genetic engineers are able to develop germplasms that are able to boost production by over 50%, the context of global food and farming systems will fundamentally change. So long as these technologies are made accessible to small scale producers across the Global South, then hundreds of millions of people could be lifted out of poverty and the spectre of a global food crisis provoked by population growth will recede. Of course, creating plants with more productive photosynthetic pathways may also provoke additional problems, and super productive plants will also need huge amounts of water and nitrogen to fully develop. However, it is undeniable that developing more efficient crops may fundamentally alter the nature of food security debates over the next century.

Box 3 picks up on the idea of engaging more people in small-scale agriculture through a vertical farming disruption scenario. This approach has been taken in refugee camps in Syria with a view to moving the displaced from a situation of 'surviving' to 'thriving' (Verner 2016). Though currently unviable for many without access to electricity, other infrastructure and training, it can be a more environmentally friendly option as it takes up less land area than conventional surface cropping, and in many of these systems, water use is minimised and clean energy is used. Furthermore, it is feasible in the urban contexts that many smallholder farmers are migrating to in search for better economic opportunities.

Box 3 Disruption via increased engagement in agriculture through vertical farming

An interesting technological innovation with potential to enable a pathway towards small-scale, but profitable production systems, with lower environmental impacts, is that of vertical farming (Despommier 2013). This includes a broad suite of approaches that move production indoors into highly controlled environments. The potential of this is huge and proponents argue that vertical farms will, in future, be found in and around all major cities and support a significant proportion of urban residents' diets. Small-scale vertical farms, which may be built in shipping containers, offer remote communities promises of year-round produce, supporting nutritional security in areas that are not well serviced by major trading routes. Ultimately, proponents argue that large multiscale facilities will integrate horticulture and aquaculture production in a way that is safe, nutritious and economically efficient (Thomaier et al. 2015; Specht 2014).

Current technologies however, are too immature to realize this vision. To date, vertical farming has made huge inroads into creating both hydroponic growth solutions as well as utilizing LED lighting systems, removing both soil and sun from the farm equation. The current generation of vertical farms waste very little water while sophisticated robotics mean that low levels of human labor are needed to plant, tend or harvest crops. However, most vertical farms only produce green leafy vegetables such as basil, spinach and lettuce and are still highly energy intensive. Consequently, outputs of vertical farms typically result in very high-quality salads, sold at relatively high-end supermarkets and do not, yet, represent a viable food security strategy for the world's poor. However, their contribution to micro-nutrient deficiencies (rather than calorific content) could be significant. Looking into the future there are a number of horticultural challenges to overcome specifically to develop systems so that major vegetable crops like tomatoes, peppers and cucumbers can be produced in vertical farms. Equally, it may be possible to situate vertical farms adjacent to manufacturing facilities and engineer infrastructure to use waste heat from the manufacturing to heat and power the farm. A host of social and cultural issues would need to be overcome too in order to ensure that small vertical farms could produce culturally appropriate food for more remote communities.

Box 4 considers a major socio-economic disruption that would alter the pathways of millions of farmers, in the form of universal basic income. Universal Basic Income (UBI) is a simple idea that entails unconditionally providing every resident (child and adult) of a particular geographic location with a regular subsistence wage. Although a simple concept, it has potentially game-changing implications for how the world would operate in the future.

Box 4 Disruption via Universal Basic Income

Giving every member of society a regular sum of money as a right has been posited as a tool for transformation towards a more egalitarian and ecologically sustainable economic order (Perkio 2015). This idea has garnered support over the centuries from scholars and intellectuals, including Thomas More, Abraham Lincoln, Henry George, Bertrand Russell, and Franklin Roosevelt (Klein 2016). UBI is currently being discussed in the United Kingdom, Greece and Spain, and trials are under way in India, Italy, Finland, Brazil, Kenya and the Netherlands (Klein 2016; Lowrey 2018). In terms of the impact of such a policy on indigenous and smallholder farmers, this sort of programme would mitigate the economic stresses and vulnerabilities that prevent farmers from adopting or experimenting with approaches such as climate-smart innovations.

UBI has already been proposed as an innovative food policy tool to further the transition towards fairer and more sustainable food systems (see, for example https://www.ubie.org/project/agrarian- basic-income/). The arguments underlying this financial intervention include that it would reduce the vulnerability of farmers to food price volatility and climate hazards, and that a basic income given individually, unconditionally and automatically to all food producers could considerably enhance the bargaining power of farmers vis-à-vis commodity buyers, food processors and retailers. UBI may complement or replace the numerous and often contentious agriculture subsidy schemes around the world, which may be of uncertain social-ecological benefit depending on context and application (Annan and Schlenker 2015; Minviel and Latruffe 2017). This would allow farmers to experiment with climate-friendly practices with reduced risk in terms of loss of income or viability.

To put the potential costs of UBI in perspective, giving each member of the 470 million smallholder farms (assuming an average of four members per household) $1.90 per day would cost around $1.3 trillion per year. This is around twice the

Box 4 Disruption via Universal Basic Income (continued)

proposed 2018 defence budget of the USA ($640 billion, https://comptroller.defense.gov) or roughly 10 times the global official development aid budget of $146 billion (OECD 2017). One potential trade-off here is that some farmers receiving UBI may not necessarily remain in farming. If so, what happens to their land is crucial.

Box 5 considers a global dietary shift as a possible disruptor that could further change consumer behaviours linked to the development of alternative protein sources.

Box 5 Disruption alternative protein sources

The literature often assumes that everyone in the world is transitioning to a diet similar to that of current North American consumers. There are at least two important factors that may change these projections. The first factor is sociocultural and relates to the rising interest in vegetarian-based diets specifically amongst young Westerners. This trend seems to be spreading (Statista 2018; Askew 2017; Kenward 2017; Cornish 2018; Poore and Nemecek 2018). The second factor is technical, linked to the sharp rise in the number of non-traditional protein products available to consumers. Protein based on algae, fungus, legumes or insects can be produced at a fraction of the financial and environmental costs, of conventional livestock (Alexander et al. 2017). In addition, so-called "clean meat", which is a highly contested term that refers to meat substitutes produced using stem cell technology, seems poised to enter the market in the next five years (Flink 2018). Regardless of whether the claims around synthetically manufactured meat prove accurate, this combination of new protein alternatives, along with the perception that there is a growing segment of the population who is experimenting with diets low in livestock products, has led to a flurry of interest by major players in the North American food industry. Companies such as Nestlé and Tyson have both made major acquisitions in non-meat protein products while Maple Leaf Foods, Canada's largest food processor, has recently purchased two plant-based and one insect-based protein companies. Maple Leaf now positions itself as on a trajectory to become the most sustainable protein company on Earth, a goal that they will accomplish in part by reducing the amount of conventional livestock in their portfolio (Maple Leaf Foods 2018). This shows potential for producers to support both food security and sustainability. However, while the emerging interest in alternative proteins is fascinating, it is too early to ascertain with any confidence whether this is simply yet another consumer fad or a durable trend that will extend in the long term and become mainstream.

Box 5 Disruption alternative protein sources (continued)

Nevertheless, it is clear that if the shift towards alternative protein continues to grow this will have transformative and unpredictable effects on food system sustainability in the long term.

Table 2 synthesises the possible impacts of the disruptors on the different farmer types and the possible pathways, potentially changing what they will look like in 2040.

Table 2. Impacts of the various disruptors on different types of farmers

	Global carbon pricing mechanism	**Genetic engineering of photosynthesis**	**Vertical agriculture**	**Universal basic income**	**Dietary shift towards new protein sources**
Large-scale commercial conventional farmer	Initial negative impact as the price of conventional production increases, but as farmers adjust to lower carbon intensive production mechanisms, over the long-term, this will ensure more climate smart agriculture. If they are unable to remain financially viable with the pricing mechanism, these farmers may have to exit agriculture	This could substantially increase the productivity and hence profitability of commercial farmers	Unlikely to have an impact beyond offering new investment opportunities	Unlikely to have an impact as farms already have high labour and financial inputs	This could result in an exit from farming of many large-scale livestock producers and farmers of grain and soy for feed
Small-scale subsistence farmer	Farmers with lower carbon intensive agriculture could receive payments for carbon sequestering production	Unlikely to have an impact as they are not likely to have access to the technology, which would be aimed more	Unlikely to have an impact given high energy and technology demands, need for re-skilling and	This will allow subsistence farmers space to continue to grow food for subsistence without having to shift to excess	Unlikely to have an impact as farmers are not linked to markets and therefore unlikely to be affected by

	that could help meet their financial needs over the long term, especially if they restore degraded land	at cash crops. Could exacerbate inequalities with larger farmers	high upfront investment costs	production to generate cash income. It should lead to improved food security as basic needs can be met	shifts in demand
Small-scale market farmer	If they are already producing with minimal carbon emissions, over the short term, these farmers would have a competitive advantage over conventional farmers that are more carbon intensive	If these farmers were able to access the technology, it could increase their viability in the long-term as they would be more productive per hectare and therefore more profitable	This could enable a diversification of these small-scale farmers into peri-urban and urban areas where they would be able to produce higher value crops from small pieces of land	This would provide a financial buffer for farmers during periods of stress, such as those expected under climate change, as they would still be able to buy basic goods. It could also provide a market for their produce closer to home as there would be more disposable income in poorer areas. Over the long-term, this could lead to financially viable smaller farming operations	Unlikely to have an impact unless diversification into e.g. black soldier fly larvae production has low entry costs
Traditional extensive farmer	The carbon pricing mechanism will make this type of farming more competitive against conventional farming and over the long term help to meet the financial needs of these farmers	Unlikely to have an impact as farmers may have greater focus on traditional methods and are unlikely to have access to technology	Unlikely to have an impact given farmers may have greater emphasis on traditional/ cultural methods of farming	As with subsistence farmers, this would enable a financial safety net for these farmers so that they could continue to farm traditionally without focussing on having to produce for markets	Unlikely to have an impact, unless dietary shifts focus on more extensively farmed protein sources. Alternatively a shift away from meat consumption could have negative impacts on some farmers

Artisanal farmer	As these farmers are already internalising their carbon costs in their pricing mechanisms, this would have little effect other than to make their produce more affordable compared to the produce from conventional farmers with an added carbon price	Unlikely to have an impact as it would likely not fulfil niche criteria, which is a key part of artisanal farming	This would enable a diversification of artisanal producers as they would be able to produce more efficiently and closer to their markets, therefore cutting the costs of their operations	Unlikely to have an impact although as for small-scale and extensive farmers, it could act as a buffer if demand for artisanal produce temporarily decreases (e.g. during economic downturn)	As with the vertical farming, this disruptor would enable more artisanal farmers focussing on alternative protein sources like insects to find markets for their goods. If they are no longer having to compete with industrial meat production, these alternative products are likely to become mainstream over time, thus strengthening the viability of these types of farmers

Transformation pathways to 2040 are unlikely to be smooth. The disruption scenarios above illustrate how changes in policies, technology and consumer behaviour may impact upon farmer pathways, how these impacts may be positive or negative, and how they may vary between farmer types. These are only a range of examples; there are many more potential disruptors and even more that may be difficult to predict. Policy makers will need to take into account the possibilities of these disruptors when designing interventions to encourage trajectories along certain pathways, ensuring that that farmers are able to adapt to any changes that disruptions may cause and are not unintentionally pushed into maladaptive practices. Figure 1 illustrates the potential routes towards 2040. Adaptive (green area) and maladaptive (red area) pathways are shown here to graphically reflect the pathways for transformation in agriculture for all farmer types. Disruptors (! signs) and key decision points (intersection signs) reflect different combinations of options and levers (intersections) and varying levels of uncertainty (blind summit, fog signs). Farmers and agricultural systems at any level may be leveraged toward maladaptive directions, some of which may be difficult or impossible to recover from (no U-turn, cul-de-sac signs). The aim of farmers, governments, and other stakeholders as they navigate pathways to 2040 is to carefully facilitate interventions and mitigate risks to keep from straying into maladaptive space, evidenced by measures of farm household socio-economic well-being, climate impacts, and overall food security.

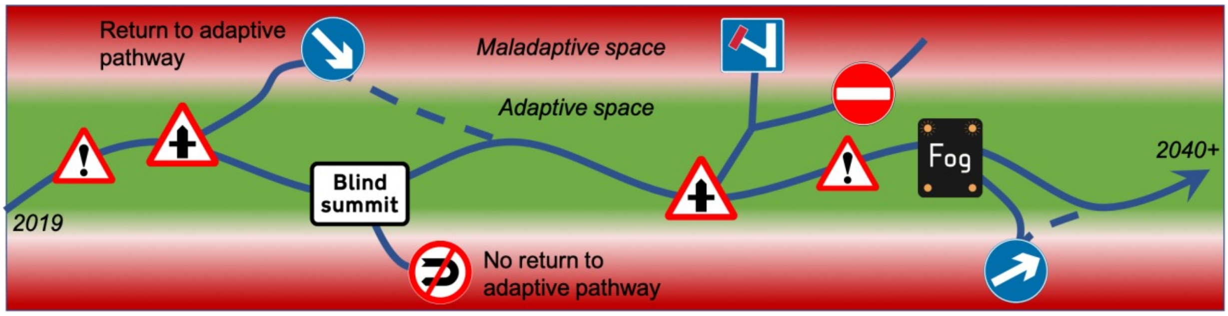

Figure 1. Adaptive and maladaptive pathways, decision points, and disruptors.

Modified from Fazey et al. 2016; traffic signs are used with UK Crown Copyright, Open Government Licence.

Conclusion and recommendations

The consequences are severe if we do not meet the challenge of sustainably and nutritiously feeding the world's population both now and in the future. The spectre of worsening food insecurity, political and economic instability and the possibility of new waves of migrants and conflict as people move in search of food, water and livelihoods remains very real (Fraser et al. 2016), especially as nations become more inward-looking. We may already be at the beginning of the crisis: for the last 10 years, food prices have been both high and volatile. Dozens of food riots occurred between 2008 and 2011 when food prices reached levels (in real terms) that had not been seen since the 1970s (FAO 2017; Lagi 2011). In addition, after decades of declines, the number of undernourished people (in both absolute and proportional terms) has risen for each of the last three years (FAO 2018) while the world has become increasingly turbulent, uncertain, novel and ambiguous (MOD 2018).

There is a global imperative to quickly embark on pathways that will protect biodiversity, decarbonize the economy and keep humanity within a safe operating space. There is an equally strong imperative to ensure equity in these efforts. The clock is ticking and there is urgent time pressure for multi-level governance to deliver the kinds of policies that support lower income countries and the social movements that create and push demand for sustainable food value chains. Voluntary transformations and market solutions have thus far shown not to deliver fast enough action. With increasing nationalism, governance options of the past will not suffice for the future. Techno-optimists might point to organisations, industries and countries that have set standards and targets to help ensure agricultural technology is deployed to protect the environment, enhance environmental impacts and social development, but the challenge is great in the context of continued population growth and increasing consumption. While the population issue is stark in some areas meaning uncomfortable conversations need to be had, efforts that address other SDGs by empowering women, improving access to education and healthcare could also support improved family planning. Interventions to date have largely centred on understanding and supporting the distribution of resources rather than the distribution of people in meeting increasing food demands. Migration patterns are starting to address this gap in a somewhat haphazard way as people seek their own redistributions. Migration from rural areas to the cities tends to remain within states and thus freedom of movement is upheld. However, migration from poorer countries to richer ones is limited by immigration policies and border controls, which may be revised as an as yet under-utilised, but currently contentious, adaptive pathway. Importantly, even where population growth has stabilised or started to decline, consumption levels remain high, diets remain poor and the food systems in place fail to deliver the necessary balance of nutritious food. Business as usual is not an option if the world is to equitably, ethically and nutritiously feed its human population while meeting its sustainable development aspirations in a climate resilient way with minimal emissions. A seismic shift in both production and consumption sides of the global food system is necessary.

Global leaders have a suite of options that offer possibilities for action over different time frames that can help food producers and consumers across the spectrum. Immediate actions include those that:

- Build on alliances that foster change through peer pressure and cooperation, to push others in the same direction. Examples of this are regional trade agreements and policies that can push towards implementing good practices and standards through national, international or national laws and their enforcement. This option will require a strategy for removing corruption in institutions that control export, import, sales and transport of prohibited goods
- Incentivise cooperation at local levels, to support small-scale farmer cooperatives to help them meet the costs and requirements of certification schemes, as a lever towards sustainability

- Invest in education, technology and research to improve the quality, quantity and nutritional value of raw products and plants; to facilitate more efficient use of environmental and human resources; to reduce overall consumption post-harvest losses, energy, transport and waste; and to empower women on their reproductive choices
- Remove subsidies for monocultures and other perverse incentives that undermine environmental quality, replacing them with subsidies that reward pro-sustainability behaviours in a substantial way. This needs to take place alongside more stringent implementation of polluter-pays principles and carbon taxes within the food system
- Develop national environmentally sustainable food security strategies for 2020-2050 that set out context-specific pathways and levers for different types of farmers and which promote land rental markets and consolidation

Longer-term actions include:

- Policies that support populations not just to develop secondary and tertiary industries in rural areas, but also so they have the necessary support to exit rural agriculture and engage with urbanization should they choose. Ensuring food production does not decline requires parallel investments in agricultural niches and re-skilling of the workforce so they can engage in e.g. vertical agriculture, urban agroforestry, small-scale processing, in line with dietary shifts and the implementation of sustainable food security strategies
- Develop new technology to monitor environmental impacts and exert polluter-pays principles, making it easier and cheaper to punish those companies and countries who extract environmental values and functions without returning them

Overall, strong good governance is needed at multiple levels to support transformations of different kinds as there is no one-size-fits-all pathway or single solution. Such governance needs to be both equitable and inclusive, in its processes and outcomes, over multiple time frames. Concurrent action is required urgently across the realms of technology, policy, finance, and consumer behaviour around dietary choices, tackling the key underlying trends both individually and in combination. Trade-offs will be inevitable: spatially, temporally and across different groups in society. Some changes will also turn out to be maladaptive with hindsight. However, careful tailoring of adaptation and development pathways to the specific context in which they are enacted can offer some degree of risk mitigation and also offer opportunities to harness co-benefits. Understanding the context requires engagement with farmers themselves from the outset, so as to better understand their values, motivations and desired outcomes, along with the interaction of competing pressures that shape their decisions and practices.

References

Alexander P, Brown C, Arneth A, Dias C, Finnigan J, Moran D and Rounsevell MDA. 2017. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Global Food Security* 15:22–32.

Alston M. 2011. Gender and climate change in Australia. *Journal of Sociology* 47(1):53–70.

Alston M. 2012. Rural male suicide in Australia. *Social Science & Medicine* 74(4):515–522.

Anderson CR and McLachlan SM. 2012. Exiting, enduring and innovating: Farm household adaptation to global zoonotic disease. *Global Environmental Change* 22(1):82–93.

Annan F and Schlenker W. 2015. Federal Crop Insurance and the Disincentive to Adapt to Extreme Heat. *American Economic Review* 105(5):262–266.

Antonini C and Argilés-Bosch JM. 2017. Productivity and environmental costs from intensification of farming. A panel data analysis across EU regions. *Journal of Cleaner Production* 140:796–803.

Asfaw A, Simane B, Hassen A, Bantider A. (2017). Determinants of non-farm livelihood diversification: evidence from rainfed-dependent smallholder farmers in northcentral Ethiopia (*Woleka* sub-basin). *Development Studies Research* 4(1):22–36.

Askew K. 2017. Europe leads in innovation as meat-free demand grows. *Food Navigator*. (Available from: https://www.foodnavigator.com/Article/2017/08/24/Europe-leads-in-innovation-as-meat-free-demand-grows) (Accessed 25 November 2018)

Aspire 2016. Edible Insect Technology | Farming Automation | Agricultural Robotics. *Aspire Food Group*. (Available from: http://www.aspirefg.com/technology.aspx) (Accessed 23 November 2018)

Astill J, Fraser E, Dara R, Sharif S. 2018. Detecting and Predicting Emerging Disease in Poultry With the Implementation of New Technologies and Big Data: A Focus on Avian Influenza Virus. *Frontiers in Veterinary Science* 5:263.

Atangana A, Khasa D, Chang S, Degrande A. 2014. Socio-Cultural Aspects of Agroforestry and Adoption. *Tropical Agroforestry*. Dordrecht: Springer Netherlands, p 323–332.

Bourque F, Cunsolo Willox A. 2014. Climate change: The next challenge for public mental health? *International Review of Psychiatry* 26(4):415–422.

Bronson K, Knezevic I. 2016. Big Data in food and agriculture. *Big Data & Society* 3(1).

Bullis K. 2018. Supercharged Photosynthesis. *MIT Technology Review*. (Available from: https://www.technologyreview.com/s/535011/supercharged-photosynthesis/) (Accessed 19 December 2018)

Campiglio E. 2016. Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics* 121:220–230.

Capmourteres V, Adams J, Berg A, Fraser E, Swanton C, Anand M. 2018. Precision conservation meets precision agriculture: A case study from southern Ontario. *Agricultural Systems* 167:176–185.

Carleton TA. 2017. Crop-damaging temperatures increase suicide rates in India. *Proceedings of the National Academy of Sciences of the United States of America* 114(33):8746–8751.

Ceurstemont S. 2013. Inevitable insectivores? Not so fast. *New Scientist* 219(2924):34–37.

Collier P, Dercon S. 2014. African Agriculture in 50 Years: Smallholders in a Rapidly Changing World? *World Development* 63:92–101.

Cornish C. 2018. Could we save the world if we all went vegan. *Financial Times*. (Available from: https://www.ft.com/content/3b210ddc-bba0-11e8-8274-55b72926558f) (Accessed 25 November 2018)

Cressey D. 2014. Time to eat insects. *Nature*.

Cronin JM, McCarthy MB, Collins AM. 2014. Covert distinction: how hipsters practice food-based resistance strategies in the production of identity. *Consumption Markets & Culture* 17(1):2–28.

Cubbage F, Balmelli G, Bussoni A, Noellemeyer E, Pachas AN, Fassola H, Colcombet L, Rossner B, Frey G, Dube F, de Silva ML, Stevenson H, Hamilton J, Hubbard W. 2012. Comparing silvopastoral systems and prospects in eight regions of the world. *Agroforestry Systems* 86(3):303–314.

Dalin C, Wada Y, Kastner T, Puma MJ. 2017. Groundwater depletion embedded in international food trade. *Nature* 543(7647):700–704.

Daw TM, Hicks CC, Brown K, Chaigneau T, Januchowski-Hartley FA, Cheung WWL, Rosendo S, Crona B, Coulthard S, Sandbrook C, Perry C, Bandeira S, Muthiga NA, Schulte-Herbrüggen B, Bosire J, McClanahan TR. 2016. Elasticity in ecosystem services: Exploring the variable relationship between ecosystems and human well-being. *Ecology and Society* 21(2).

Dell'Angelo J, D'Odorico P, Rulli MC. 2017. Threats to sustainable development posed by land and water grabbing. *Current Opinion in Environmental Sustainability* 26–27:120–128.

Djanibekov U, Khamzina A. 2016. Stochastic Economic Assessment of Afforestation on Marginal Land in Irrigated Farming System. *Environmental and Resource Economics* 63(1):95–117.

Duffy M. 2009. Economies of size in production agriculture. *Journal of Hunger and Environmental Nutrition* 4(3–4):375–392.

Enobe AL, Johnson-Rokosu SF. 2016. Terrorism Financing. The Socio-Economic and Political Implications of Boko Haram Insurgency in Lake Chad Basin. *Academic Journal of Economic Studies* 2(1):25–41.

Falk J, Gaffney O, Bhowmik A, Borgström-Hansson C, Pountney C, Lundén D, Pihl E, Malmodin J, Lenhart J, Jónás K, Höjer M, Bergmark P, Sareen S, Widforss S, Henningsson S, Plitt S, Shalit T. 2018. *Exponential Climate Action Roadmap*.

[FAO] Food and Agriculture Organization of the United Nations 2017. FAO Food Price Index | World Food Situation | Food and Agriculture Organization of the United Nations. (Available from: http://www.fao.org/worldfoodsituation/foodpricesindex/en/) (Accessed 30 October 2018)

[FAO] Food and Agriculture Organization of the United Nations 2018a. In a Kenyan refugee camp, farming is the path to self-sufficiency | FAO Stories | Food and Agriculture Organization of the United Nations. *Food and Agriculture Organization of the United Nations*. (Available from: http://www.fao.org/fao-stories/article/en/c/1151312/) (Accessed 23 November 2018)

[FAO] Food and Agriculture Organization of the United Nations 2018b. SOFI 2018 - The State of Food Security and Nutrition in the World. *Global Food Insecurity Report*. (Available from: http://www.fao.org/state-of-food-security-nutrition/en/) (Accessed 30 October 2018)

Fazey I, Wise RM, Lyon C, Câmpeanu C, Moug P, Davies TE. 2016. Past and future adaptation pathways. *Climate and Development* 8(1):26–44.

Flink T. 2018. Memphis Meats to Bring Clean Duck and Chicken Meat to Stores by 2021. *LiveKindly*. (Available from: https://www.livekindly.co/memphis-meats-bring-clean-duck-chicken-meat-stores-2021/) (Accessed 25 November 2018)

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West ZC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockström J, Sheehan J, Siebert S, Tilman D, Zaks DPM. 2011. Solutions for a cultivated planet. *Nature* 478(7369):337–342.

Fraser E, Charlebois S. 2016. Automated farming: good news for food security, bad news for job security? | Guardian Sustainable Business | The Guardian. *The Guardian*. (Available from: https://www.theguardian.com/sustainable-business/2016/feb/18/automated-farming-food-security-rural-jobs-unemployment-technology) (Accessed 23 November 2018)

Fraser E, Rimas A. 2011. The Psychology of Food Riots. *Foreign Affairs*. (Available from: https://www.foreignaffairs.com/articles/tunisia/2011-01-30/psychology-food-riots) (Accessed 23 November 2018)

Fraser EDG, Dougill AJ, Mabee WE, Reed M, McAlpine P. 2006. Bottom up and top down: Analysis of participatory processes for sustainability indicator identification as a pathway to community empowerment and sustainable environmental management. *Journal of Environmental Management* 78(2):114–127.

Frey N. 2007. The effect of responsible tourism management practices on business performance in an emerging market (master's thesis). University of Cape Town. (Available from https://open.uct.ac.za/handle/11427/8910)

Goodman D, DuPuis EM, Goodman MK. 2011. *Alternative Food Networks: Knowledge, Practice, and Politics*. 1st ed. London: Routledge.

Gordon LJ, Bignet V, Crona B, Henriksson PJG, Van Holt T, Jonell M, Lindahl T, Troell M, Barthel S, Deutsch L, Folke C, Haider LJ, Rockström J, Queiroz C. 2017. Rewiring food systems to enhance human health and biosphere stewardship. *Environmental Research Letters* 12(10):100201.

Goulson D, Nicholls E, Botias C, Rotheray EL. 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347(6229):1255957–1255957.

Greenfield A. 2018. *Radical Technologies: The Design of Everyday Life*. Verso.

Gregory PJ, Ingram JSI, Brklacich M. 2005. Climate change and food security. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 360(1463):2139–48.

Guerro Lara L, Pereira LM, Ravera F, Jiménez-Aceituno A. 2019. Flipping the *Tortilla*: Social-Ecological Innovations and Traditional Ecological Knowledge for More Sustainable Agri-Food Systems in Spain *Sustainability* **2019**, *11*(5), 1222.

Haberl H, Fischer-Kowalski M, Krausmann F, Martinez-Alier J, Winiwarter V. 2011. A socio-metabolic transition towards sustainability? Challenges for another Great Transformation. *Sustainable Development* 19(1):1–14.

Hafting JT, Critchley AT, Cornish ML, Hubley SA, Archibald AF. 2012. On-land cultivation of functional seaweed products for human usage. *Journal of Applied Phycology* 24(3):385–392.
Halloran A, Flore R, Vantomme P, Roos N. 2018. *Preface* (A. Halloran, R. Flore, P. Vantomme, & N. Roos, eds.). Cham: Springer International Publishing.
Hanboonsong Y, Jamjanya T, Durst PB. 2013. *Six-legged livestock: edible insect farming, collection and marketing in Thailand*. Bangkok, Thailand.
Harris D, 2019. Intensification Benefit Index: How much can rural households benefit from agricultural intensification? *Experimental Agriculture*, 55 (2), 273-287.
Harris D, Orr A. 2014. Is rainfed agriculture really a pathway from poverty? *Agricultural Systems* 123:84–96.
Hasselström L, Visch W, Gröndahl F, Nylund GM, Pavia H. 2018. The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden. *Marine Pollution Bulletin* 133:53–64.
Heikkinen HI, Sarkki S; Nuttall M. 2012. Users or producers of ecosystem services? A scenario exercise for integrating conservation and reindeer herding in northeast Finland. *Pastoralism: Research, Policy and Practice* 2(1):11.
Hernández-Morcillo M, Burgess P, Mirck J, Pantera A, Plieninger T. 2018. Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science & Policy* 80:44–52.
Hodgins KJ, Fraser EDG. 2018. We are a business, not a social service agency: Barriers to widening access for low-income shoppers in alternative food market spaces. *Agriculture and Human Values* 35(1):149–162.
Hogan A, Scarr E, Lockie S, Chant B, Alston S. 2012. Ruptured Identity of Male Farmers: Subjective Crisis and the Risk of Suicide. *Journal of Rural Social Sciences* 27(3):118.
Holt-Giménez E, Shattuck A, Altieri M, Herren H, Gliessman S. 2012. We Already Grow Enough Food for 10 Billion People … and Still Can’t End Hunger. *Journal of Sustainable Agriculture* 36(6):595–598.
Homann-Kee Tui S, Valbuena D, Masikati P, Descheemaeker K, Nyamangara J, Claessens L, van Rooyen A, Nkomboni D. 2015. Economic trade-offs of biomass use in crop-livestock systems: Exploring more sustainable options in semi-arid Zimbabwe. *Agricultural Systems* 134:48–60.
van Huis A. 2017. Edible insects: marketing the impossible? *Journal of Insects as Food and Feed* 3(2):67–68.
Jaffe AB, Newell RG, Stavins RN. 2005. A tale of two market failures: Technology and environmental policy. *Ecological Economics* 54(2–3):164–174.

Jin Y, Huffman WE. 2016. Measuring public agricultural research and extension and estimating their impacts on agricultural productivity: New insights from U.S. evidence. *Agricultural Economics (United Kingdom)* 47(1):15–31.

Kenward E. 2017. Special Report: The Rise in "Flexitarian" Lifestyles. *Food ingredients 1st*. (Available from: https://www.foodingredientsfirst.com/news/special-report-the-rise-in-flexitarian-lifestyles.html) (Accessed 25 November 2018)

Klein E. 2016. Universal basic income. *Arena Magazine (Fitzroy, Vic)* 142:6–8.

Lagi M, Bertrand KZ, Bar-Yam Y. 2011. *The Food Crises and Political Instability in North Africa and the Middle East*. Cambridge, MA: New England Complex Systems Institute.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, George PS, Homewood K, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skånes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* 11(4):261–269.

Larson LR, Conway AL, Krafte KE, Hernandez SM, Carroll JP. 2016. Community-based conservation as a potential source of conflict around a protected area in Sierra Leone. *Environmental Conservation* 43(03):242–252.

Lindblom J, Lundström C, Ljung M, Jonsson A. 2017. Promoting sustainable intensification in precision agriculture: review of decision support systems development and strategies. *Precision Agriculture* 18(3):309–331.

Lindow M. 2017. Exploring resilience capacities through the art of storymaking: the case of food innovators in the Western Cape (master's thesis). Stellenbosch University. (Available from https://scholar.sun.ac.za/handle/10019.1/102910) (Accessed 7 June 2019)

Long SP, Zhu XG, Naidu SL, Ort DR. 2006. Can improvement in photosynthesis increase crop yields? *Plant, Cell and Environment* 29(3)315–330.

Lowder SK, Skoet J, Raney T. 2016. The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide. *World Development* 87:16–29.

Lowrey A. 2018. Give People Money: How A Universal Basic Income Would End Poverty, Revolutionize Work, and Remake the World. p.263.

Lyon C, Parkins JR. 2013. Toward a Social Theory of Resilience: Social Systems, Cultural Systems, and Collective Action in Transitioning Forest-Based Communities. *Rural Sociology* 78(4):528–549.

Maia SMF, Xavier FAS, Oliveira TS, Mendonça ES, Araújo Filho JA. 2007. Organic carbon pools in a Luvisol under agroforestry and conventional farming systems in the semi-arid region of Ceará, Brazil. *Agroforestry Systems* 71(2):127–138.

Maple Leaf Foods 2018. Sustainability – Maple Leaf Foods. (Available from: https://www.mapleleaffoods.com/sustainability/overview/) (Accessed 19 November 2018)

Markey E. 2017. Bread and Beer for a Better Biosphere—The Transformative Potential of the Eco-gastronomic niche in the Greater Cape Town Area. (MSc Thesis, Stockholm Resilience Centre, Stockholm University).

Martin SM, Lorenzen K. (2016). Livelihood Diversification in Rural Laos. *World Development* 83:231–243.

Mellor JW, Malik SJ. 2017. The Impact of Growth in Small Commercial Farm Productivity on Rural Poverty Reduction. *World Development* 91:1–10.

Minviel JJ, Latruffe L. 2017. Effect of public subsidies on farm technical efficiency: a meta-analysis of empirical results. *Applied Economics* 49(2):213–226.

Mirzabaev A, Ahmed M, Werner J, Pender J, Louhaichi M. 2016. Rangelands of Central Asia: challenges and opportunities. *Journal of Arid Land*. 8(1),pp.93–108.

MOD 2018. *Global Strategic Trends: The future starts today (sixth edition)*.

Mosquera-Losada MR, McAdam JH, Romero-Franco R, Santiago-Freijanes JJ, Rigueiro-Rodróguez A. 2009. Definitions and Components of Agroforestry Practices in Europe *In*: *Agroforestry in Europe*. Dordrecht: Springer Netherlands p. 3–19.

Mosquera-Losada MR, Moreno G, Pardini A, McAdam JH, Papanastasis V, Burgess PJ, Lamersdorf N, Castro M, Liagre F, Rigueiro-Rodríguez A. 2012. Past, Present and Future of Agroforestry Systems in Europe. Springer, Dordrecht p. 285–312.

Müller B, Johnson L, Kreuer D. 2017. Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change* 46:23–33.

OECD 2017. Launch of ODA Figures 2017 - OECD. (Available from: http://www.oecd.org/development/launch-of-oda-figures-2017-france-april-2018.htm) (Accessed 19 December 2018)

Olsson P, Galaz V, Boonstra WJ. 2014. Sustainability transformations a resilience perspective. *Source: Ecology and Society* 19(4).

Parizat R, Strbenhoff H-W. 2018. Using big data to link poor farmers to finance. *Future Development*. (Available from: https://www.brookings.edu/blog/future-development/2018/05/03/using-big-data-to-link-poor-farmers-to-finance/) (Accessed 19 December 2018)

Parkins JR, Reed MG. (eds). 2013. Social transformation in rural Canada: community, cultures, and collective action. Vancouver: UBC Press.

Pereira L, Wynberg R, Reis Y. 2018. Agroecology: The Future of Sustainable Farming? *Environment: Science and Policy for Sustainable Development* 60(4):4–17.

Perkio J. 2015. Universal Basic Income: a cornerstone of the new economic order - Perkiö Johanna 2015 *In*: *The Politics of Ecosocialism : Transforming Welfare*. London: Routledge. p. 137–147.

Poore J, Nemecek T. 2018. Reducing food's environmental impacts through producers and consumers. *Science (New York, N.Y.)* 360(6392):987–992.

Pretty J, Bharucha ZP. 2018. Sustainable intensification of Agriculture. *Sustainable Intensification of Agriculture: Greening the World's Food Economy*. p.196.

Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M, Rieseberg LH. 2018. Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annual Review of Plant Biology* 69(1):789–815.

Rebours C, Marinho-Soriano E, Zertuche-González JA, Hayashi L, Vásquez JA, Kradolfer P, Soriano G, Ugarte R, Abreu MH, Bay-Larsen I, Hovelsrud G, Rødven R, Robledo D. 2014. Seaweeds: an opportunity for wealth and sustainable livelihood for coastal communities. *Journal of Applied Phycology* 26(5):1939–1951.

Redford KH, Adams WM. 2009. Payment for ecosystem services and the challenge of saving nature. *Conservation Biology* 23(4):785–7.

RIPE 2018. Our Story | RIPE. *Realising Increased Photosynthetic Efficiency for sustainable increases in crop yield*. (Available from: https://ripe.illinois.edu/objectives/our-story) (Accessed 19 December 2018)

Rousseau K, Gautier D, Wardell DA. 2015. Coping with the Upheavals of Globalization in the Shea Value Chain: The Maintenance and Relevance of Upstream Shea Nut Supply Chain Organization in Western Burkina Faso. *World Development* 66:413–427.

Santini J-L. 2012. 'Artificial leaf' eyed as holy grail in energy research. *Phys.org*. (Available from: https://phys.org/news/2012-02-artificial-leaf-eyed-holy-grail.html) (Accessed 19 December 2018)

Schindler J, Graef F, König HJ, Mchau D, Saidia P, Sieber, S. 2016. Sustainability impact assessment to improve food security of smallholders in Tanzania. *Environmental Impact Assessment Review* 60:52–63.

Schneider S. 2015. Good, Clean, Fair: The Rhetoric of the Slow Food Movement. *College English* 70(4):384–402.

Schneider M, McMichael P. 2010. Deepening, and repairing, the metabolic rift. *Journal of Peasant Studies* 37(3):461–484.

Scoones I, Stirling A, Abrol D, Atela J, Charli-Joseph L, Eakin H, Ely A, Pereira L, Priya R, Van Zwanenberg P, Yang L. 2018. *Transformations to Sustainability*.

Shete M, Rutten M. 2015. Impacts of large-scale farming on local communities' food security and income levels – Empirical evidence from Oromia Region, Ethiopia. *Land Use Policy* 47:282–292.

Simelton E, Dam BV, Catacutan D. 2015. Trees and agroforestry for coping with extreme weather events: experiences from northern and central Viet Nam. *Agroforestry Systems* 89(6):1065–1082.

Simelton E, Viet Dam B. 2014. Farmers in NE Viet Nam rank values of ecosystems from seven land uses. *Ecosystem Services* 9:133–138.

Sklenicka P, Janovska V, Salek M, Vlasak J, Molnarova K. 2014. The Farmland Rental Paradox: Extreme land ownership fragmentation as a new form of land degradation. *Land Use Policy* 38:587–593.

Smith P. 2016. Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology* 22(3):1315–1324.

Sneyd LQ, Legwegoh A, Fraser EDG. 2013. Food riots: Media perspectives on the causes of food protest in Africa. *Food Security* 5(4):485–497.

Specht K, Siebert R, Hartmann I, Freisinger UB, Sawicka M, Werner A, Thomaier S, Henckel D, Walk H, Dierich A. 2014. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values* 31(1):33–51.

Statista 2018. Meat consumption and vegetarianism in Europe - Statistics and Facts | Statista. *Statista: The Statistics Portal*. (Available from: https://www.statista.com/topics/3345/meat-consumption-and-vegetarianism-in-europe/)

Stringer LC, Dougill AJ, Fraser EDG, Hubacek K, Prell C, Reed MS. 2006. Unpacking "Participation" in the Adaptive Management of Social–ecological Systems: a Critical Review. *Ecology and Society* 11(2):39.

Stringer LC, Twyman C, Gibbs LM. 2008. Learning from the South: Common challenges and solutions for small-scale farming. *Geographical Journal* 174(3):235–250.

Stringer LC, Twyman C, Thomas DSG. 2007. Combating Land Degradation through Participatory Means: The Case of Swaziland. *Ambio* 36(5):387–393.

Strona G, Carstens CJ, Beck PSA. 2017. Network analysis reveals why Xylella fastidiosa will persist in Europe. *Scientific Reports* 7(1):71.
Suckall N, Fraser E, Forster P. 2017. Reduced migration under climate change: evidence from Malawi using an aspirations and capabilities framework. *Climate and Development* 9(4):298–312.
Suckall N, Fraser E, Forster P, Mkwambisi D. 2015. Using a migration systems approach to understand the link between climate change and urbanisation in Malawi. *Applied Geography* 63:244–252.
Tafira K. 2015. Why land evokes such deep emotions in Africa. *The Conversation*. (Available from: http://www.tandfonline.com/doi/abs/10.1080/13648470.2011.591197) (Accessed 19 December 2018)
Taylor M. 2018. Climate-smart agriculture: what is it good for? *The Journal of Peasant Studies* 45(1):89–107.
Tew C, Barbieri C. 2012. The perceived benefits of agritourism: The provider's perspective. *Tourism Management* 33(1):215–224.
Thevathasan NV, Gordon AM, Bradley R, Cogliastro A, Folkard P, Grant R, Kort J, Liggins L, Njenga F, Olivier A, Pharo C, Powell G, Rivest D, Schiks T, Trotter D, Van Rees K, Whalen J, Zabek L. 2012. *Agroforestry Research and Development in Canada: The Way Forward*. Springer, Dordrecht p. 247–283.
Thomaier S, Specht K, Henckel D, Dierich A, Siebert R, Freisinger UB, Sawicka M. 2015. Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renewable Agriculture and Food Systems* 30(01):pp.43–54.
Thornton PK, Kristjanson P, Förch W, Barahona C, Cramer L, Pradhan S. 2018. Is agricultural adaptation to global change in lower-income countries on track to meet the future food production challenge? *Global Environmental Change* 52:37–48.
Tittonell P, Giller KE. 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research* 143:76–90.
Trace S. 2016. *Rethink, Retool, Reboot: Technology as if people and planet mattered*. Practical Action Publishing.
Troughton MJ. 1989. The role of marketing boards in the industrialization of the Canadian agricultural system. *Journal of Rural Studies* 5(4):367–383.
UNHCR 2018. UNHCR - Figures at a Glance. *UNHCR - The UN Refugee Agency*. (Available from: https://www.unhcr.org/figures-at-a-glance.html) (Accessed 23 November 2018)

Vandermeulen S, Ramírez-Restrepo CA, Beckers Y, Claessens H, Bindelle J. 2018. Agroforestry for ruminants: a review of trees and shrubs as fodder in silvopastoral temperate and tropical production systems. *Animal Production Science* 58(5):767.

Vantomme P. 2015. Way forward to bring insects in the human food chain. *Journal of Insects as Food and Feed* 1(2):121–129.

Verner D. 2016. Could a livelihood in agriculture be a way for refugees to move from surviving to thriving? | Voices and Views: Middle East and North Africa. *The World Bank*. (Available from: http://blogs.worldbank.org/arabvoices/livelihood-in-agriculture-refugees) (Accessed 25 November 2018).

Weersink A, Fraser E, Pannell D, Duncan E, Rotz S. 2018. Opportunities and Challenges for Big Data in Agricultural and Environmental Analysis. *Annual Review of Resource Economics* 10(1):19–37.

White B. 2012. Agriculture and the Generation Problem: Rural Youth, Employment and the Future of Farming. *IDS Bulletin* 43(6):9–19.

Whittenbury K. 2013. Climate Change, Women's Health, Wellbeing and Experiences of Gender Based Violence in Australia. *Research, Action and Policy: Addressing the Gendered Impacts of Climate Change*. Dordrecht: Springer Netherlands, p. 207–221.

Wichern J,van Wijk MT, Descheemaeker K, Frelat R, van Asten PJA, Giller KE. 2017. Food availability and livelihood strategies among rural households across Uganda. *Food Security* 9(6):1385–1403.

Woodhouse P. 2010. Beyond industrial agriculture? Some questions about farm size, productivity and sustainability. *Journal of Agrarian Change*. 10(3):437–453.

World Economic Forum 2016. The Fourth Industrial Revolution: what it means and how to respond | World Economic Forum. (Available from: https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/) (Accessed 30 October 2018)

World Economic Forum 2018. The Fourth Industrial Revolution must not leave farming behind | World Economic Forum. (Available from: https://www.weforum.org/agenda/2018/08/the-fourth-industrial-revolution-must-not-leave-farming-behind/) (Accessed 19 December 2018)

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