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Review

An innovation perspective to climate change adaptation in coffee systems

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ABSTRACT

Climate change is expected to have strong implications for smallholder coffee farmers and implementing adaptation measures would lessen their vulnerabilities. Adaptation measures have been identified in literature, but how these can be implemented remains unclear. Current certification programmes have the potential to provide guidance on how sustainability criteria can be addressed and taken up by farmers. We identify climate change adaptation options, their scale of application, and the necessary implementation steps. We show that implementation complexity strongly increases with the degree of climate change. With modest climatic changes, incremental adaptations might suffice, but more substantial climatic change will require radical social-institutional changes for adaptation uptake and interventions. For the majority of smallholders the implementation of any measure is largely constrained by a lack of access to knowledge networks and training material, organisational support, and (mainly financial) resources. A landscape approach that encompasses collective action and coordinated cross-sector planning can overcome some of these barriers. Certification approaches can facilitate a move in this direction. Yet, the implementation of transformative adaptations requires visioning, realignment of policies and incentives, and new market formations. This entails a repositioning and revision of certification schemes to allow for more effective adaptation uptake for the benefit of smallholders and the environment.

1. Introduction

Coffee production is an important livelihood for millions of smallholders across the tropics (Läderach et al., 2017). Climate change is expected to increase the temperature in coffee growing areas, change precipitation patterns and enhance climate variability with severe impacts expected on coffee yield and quality if no adaptation takes place (Läderach et al., 2017; Ovalle-Rivera et al., 2015). Climatic suitability for Arabica coffee (*Coffea arabica)*is projected to decrease strongly in Meso-America and East Africa. The decrease in Arabica is likely to be offset by increases in areas suitable for Robusta coffee *(Coffea canephora)*, particularly in Meso- and South America, Indonesia, and West and East Africa (Magrach and Ghazoul, 2015; Ovalle-Rivera et al., 2015). Besides the direct effects of increasing temperature and altered rainfall patterns on coffee plant growth, climate change may also increase the risks of pest and disease incidence (Avelino et al., 2015; Jaramillo et al., 2011; Magrach and Ghazoul, 2015), although empirical evidence is still scarce (Ghini et al., 2011).

Various adaptation options and measures have been identified in literature, but it is not always clear to what extent these can minimize the impacts of climate change (Harvey et al., 2014; Läderach et al., 2017; Rahn et al., 2014). Some adaptation options may only require incremental modifications in current farming practices, others may need radical changes in production system structures (Rickards and Howden, 2012). The existing coffee systems are part of larger, so-called, sociotechnical (agricultural) systems, defined as relatively stable configurations of institutions, rules, practices and knowledge networks (Smith et al., 2005). Techniques and practices are highly intertwined within value chains, organisational structures, regulations and policy (Markard et al., 2012), and continuously evolve to produce commodities more efficiently (Smith et al., 2005). Climate change will similarly put pressure on the coffee value chain and may lead to larger fluctuations in coffee supply and therefore higher volatility of coffee prices received by smallholders. Measures therefore need to be developed and implemented to make smallholder systems more resilient to climate change (Lipper et al., 2014).

Beyond developing adaptation measures, a better understanding is needed on how their implementation is organised (Tittonell et al.,

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2012). New types of socio-institutional changes are likely to be required (Salvini et al., 2016), and this may depend on the degree of climate change, which will also determine appropriate adaptation measures. Smallholders thus may face several barriers in the implementation of adaptation options, both intrinsic to their system as well as extrinsic to it. The expansion of knowledge networks and organisational structures that span value chain and organisational sectors are likely to be important (Hekkert and Negro, 2009) in integrating smallholders into cross-scale adaptation solutions.

One approach through which society can begin to build such organisational structures is that of certification. Certification programmes include sustainability criteria supported by various organisational aspects. Certified farmers gain improved access to discerning markets, from which they might also receive premium prices. Certification programmes also offer avenues to communicate information about sustainability and good practice, which is also amenable to introducing ideas on adaptation (Montagnini and Kanninen, 2005). Indeed, it is valuable to explore the extent to which current certification criteria have already included climate change adaptation measures, as well as the extent to which existing standards provide opportunities for, or barriers to, further adaptation measures.

We address these issues by responding to the following questions: 1) can existing adaptation options confer useful responses to various degrees of climate change; 2) have certified coffee programs already implemented adaption options; 3) what (additional) implementation steps are required to adapt coffee production to climate change; and 4) which social-institutional changes are additionally required to enable smallholders to adapt to climate change at farm and landscape scales.

We start with a short review on the effectiveness of adaptation measures for climate change adaptation at farm and landscape scale and we evaluate the extent to which existing certification criteria provide opportunities for climate adaptation. We then describe possible implementation steps using the technical innovation system framework (Hekkert and Negro, 2009). Finally, we discuss the implementation of adaptation options in relation to possible social-institutional changes that might be required.

2. Adaptation measures

A number of climate adaptation measures for coffee systems exist (Table 1). In this section we elaborate on each measure by reviewing their effectiveness in adaptation to climate change. Most common among these is management of shade tree cover, which is known to ameliorate extremes of weather and provide natural enemies of pest species, but might also increase understory humidity which favours fungal pathogens.

2.1. Tree and shade systems

In shade systems, trees can support climate change adaptation by reducing daytime air temperature in the understory, thus reducing physiological stresses. Temperature regulation depends on the density and type of shade trees, the combination of which determines the percentage shade cover in agroforestry systems (Nesper et al., 2019). Air temperature reduction of up to 5 °C during daytime in coffee agroforestry has been reported (Siles et al., 2010; Souza et al., 2012), though other studies report lower buffering effects (Campanha et al., 2005; Lin, 2009). Yet the benefits of shade for climate adaptation depend on interactions between solar radiation, temperature, water availability, soil characteristics, and shade tree species (Rahn et al., 2018b). Locations with persistent cloud cover, for example, need little if any shade cover (DaMatta, 2004). The minimum tree density necessary to reduce ambient temperatures also depends on shade tree species, due to differences in tree architecture and management interventions such as pruning. Figures in the literature vary widely: to achieve 60% shade cover, Lin (2009) reported ca. 36 shade trees per hectare, while Siles et al. (2010) mentioned between 280 and 380 shade trees per hectare for equivalent shade cover.

Shade trees draw water from deeper soil layers and thus support root water uptake by the crop via hydraulic lift (Padovan et al., 2015), reduce crop transpiration by shading (Verchot et al., 2007), and minimize water losses by runoff (Lal et al., 1991). Trees can, however, increase system-level transpiration, rainfall interception, and reduce throughfall, all of which reduces soil moisture (van Kanten and Vaast, 2006). Others have reported higher soil moisture content under shaded conditions, as well as less water runoff, but also reduced infiltration during the wet season (Cannavo et al., 2011). The choice of shade tree species and the selection of appropriate stem densities are important criteria to manage stand water use (Lin, 2010). Nesper et al. (2017) reported that a diverse mix of native shade trees was more effective in limiting water losses than shade canopies dominated by exotic monoculture shade trees, due to a combination of factors that included throughfall rates.

In sun systems, planting boundary trees can protect crops from hails and windstorms (Läderach et al., 2017; Lin, 2011; Rahn et al., 2014). In Central America where hurricanes are becoming more frequent, windbreaks will be a very important adaptation measure (Philpott et al., 2008).

2.2. Integrated pest management

A limited number of studies have considered the potential impact of climate change on pests and diseases of tropical crops (Andrew and Hill, 2017). Only a few empirical studies show an increase in the prevalence of pests and diseases in coffee systems (see Ghini et al., 2011 and references therein). Shaded systems have variable impacts on the prevalence of pests and diseases (Boreux et al., 2013; Lin, 2011; Nesper et al., 2017). Higher humidity and reduced diurnal thermal amplitude under shade can increase susceptibility to fungal pathogens, which spread more easily in higher humidity environments of the shaded understorey (Avelino et al., 2015; López-Bravo et al., 2012). Conversely, pests, such as the coffee berry borer, have lower incidence in

Table 1
Frequently mentioned adaptation measures to climate change for coffee systems.

Frequently mentioned adaptation measures	Scale of operation	References
Tree windbreaks	Farm	Lin (2011), Rahn et al. (2014), Läderach et al. (2017)
Shade systems	Farm	Campanha et al. (2005), Lin (2009, 2011), Siles et al. (2010), Souza et al. (2012), Nesper et al. (2019), Rahn et al. (2018b)
Integrated pest management	Farm	Bedimo et al. (2008), Jaramillo et al. (2009), Lin (2011), Boreux et al. (2013), Mariño et al. (2016), Nesper et al. (2017)
New crop varieties	Farm	van der Vossen et al. (2015)
Diversifying income	Farm	Mijatović et al. (2013), Vaast et al. (2015), Jezeer et al. (2017)
Water and soil conservation	Farm	Lin (2010), Nesper et al. (2017)
Landscape forest cover (soil water conservation and temperature buffering)	Landscape	Seneviratne et al. (2010), Minang et al. (2014)
Landscape forest cover (pollination and pest control)	Landscape	Kellerman et al. (2008), Avelino et al. (2012), Boreux et al. (2013), Pavageau et al. (2018)

shaded coffee plantations (Mariño et al., 2016). Shade trees have been suggested to reduce the amount of rain falling directly on the coffee berries, which limits the spread of the fungal spores (Bedimo et al., 2008). By reducing ambient temperatures, shade slows the development rate of coffee berry borer larvae which exposes them to greater mortality risk (Jaramillo et al., 2009). Furthermore, shade trees can contribute to pest control by favouring pest control species such as birds and ants (De la Mora et al., 2008; Karp et al., 2013). Shade trees also provide a litter layer which affects nutrient cycling and thus soil fertility, soil water content and soil temperature. Other measures could include crop rotation or intercropping, adequate cultivation techniques including weed control, balanced fertilization and irrigation, reduced or no pesticide use (using biological control instead), and where appropriate the use of resistant cultivars (see 2.3). Examples of effective integrated pest management are available from European agricultural systems (Barzman et al., 2015), but less is known about coffee production systems.

Disease management strategies are influenced by climate conditions. Since limited knowledge is available on how pest population dynamics, biological control agents dynamics, and pest interactions will change due to climate change, it is difficult to predict the effectiveness of integrated pest management. More knowledge on the effects of climate change is needed (Barzman et al., 2015) in order to develop effective pest and disease management (Ghini et al., 2011).

2.3. New crop varieties

It is likely that many coffee farming systems are currently not using the best adapted varieties for their specific context (i.e., climate, soil, shade level conditions) and there seems to be ample opportunity for using existing varieties to adapt to a changing climate. Improved crop varieties can better withstand higher temperatures, are more resistant to pests and diseases and can be better adapted to increased shade in agroforestry systems (van der Vossen et al., 2015). Recent efforts are targeting coffee breeding specifically to adapt varieties to agroforestry systems (CIRAD, 2017). Arabica grafted on Robusta root stocks can provide improved drought tolerance (van der Vossen et al., 2015). Knowledge on which variety is best suited for a specific context is still limited and international multilocational variety trials conducted by World Coffee Research and partners are currently underway to provide more insights. To benefit from improved varieties, good agricultural management practices regarding nutrients and pruning need to be met, which requires more than simple access to seeds. Furthermore, despite the existing variability in genotypes, drastic impacts of climate change will require breeding efforts to produce new climate resilient varieties. Despite the potential, it is still unclear to what extent adequate selection of varieties and breeding efforts might adapt coffee to climate change.

2.4. Diversifying systems

Additional sources of income beyond the principle crop can be provided by shade trees (Jezeer et al., 2017) and crop diversification (Mijatović et al., 2013). In Costa Rican coffee agroforests, timber revenues contribute up to 15% and 34% of additional household income (Vaast et al., 2015). Additional sources of income may also include fuel wood, fruit or spice trees (Vaast et al., 2015). In Indian coffee agroforests, pepper vines growing up the stems of exotic *Grevillea robusta* shade trees can account for as much farm income as coffee does, although this encourages the replacement of native shade trees by *Grevillea*-dominated systems (Garcia et al., 2010). Additional sources of income from more diverse systems contribute to resilience to climate change (including fluctuating coffee production and market prices) and can therefore be an effective adaptation strategy.

2.5. Soil and water conservation at plantation level

A diversity of native shade cover trees can also favour the maintenance of soil quality. Such trees provide a richer leaf litter and year-round soil surface protection from heavy rainfall (Nesper et al., 2017). Appropriate selection of shade tree species is crucial. In India, shading with exotic trees, such as *Grevillea robusta*, is less effective at maintaining soil quality on account of seasonal leaf shedding and reduced litter decomposition rates (Nesper et al., 2017).

2.6. Forest conservation at landscape scales

Forested areas close to coffee plantations can improve the local climate and potentially lessen climate extremes by conserving soil moisture and through albedo effects (Seneviratne et al., 2010), and contribute to pest control, pollination, water and soil erosion regulation, wind protection, and carbon sequestration (Minang et al., 2014). High species diversity supported by forest cover across the landscape can maintain these services and enhance community resilience to climate change (Chaplin-Kramer et al., 2011; but see Karp et al., 2018). Deforestation and forest degradation could therefore substantially exacerbate climatic vulnerabilities.

Relations between ecosystem processes and ecosystem services are, however, complex and may have counter effects (Boreux et al., 2013). In Southern India, native forest patches in the landscape matrix provided some pollination benefit, but this varied with landscape pattern across scales, and among pollinating bee species (Pavageau et al., 2018). Some co-flowering native shade trees might even have a negative effect on coffee pollination as they compete with coffee when pollinators are locally limited (Boreux et al., 2013).

Forest cover can provide pest control by predators, such as birds (Kellerman et al., 2008), and the spatial configuration of forest relative to coffee plantations is crucial (Avelino et al., 2012). Pest control services by birds appear most effective in forest landscapes with scattered coffee plots (Avelino et al., 2012). Limited wind flow in forested areas can inhibit dispersal of coffee leaf rust, while in large blocks of open non-shaded plantations pathogen epidemics can increase substantially (Avelino et al., 2012).

3. Adaptation measures in certification systems

Numerous voluntary certification standards exist, currently certifying about 53% of total coffee production (Panhuysen and Pierrot, 2018), and ranging from business-to-business programs to business-to-consumer programs. But only a few rely on external audits (Lambin et al., 2017). Business-led programs such as Nespresso AAA, Starbucks or 4C (Global Coffee Platform) have developed guidelines but are not certified by external organizations. Hence, their effectiveness is difficult to assess (e.g., Lambin et al., 2017). The standards of Rainforest Alliance,[2] UTZ, Fair Trade and Organic[3] are accredited by external organizations (Soto and Le Coq, 2011), and are currently covering 24.8% of total coffee production (Panhuysen and Pierrot, 2018).

The four standards mention comparable criteria to farm management in terms of broad potential adaptation measures (Table 2), such as integrated pest management (Soto and Le Coq, 2011), creation of buffer zones (trees), and water and soil conservation practices. Yet few tangible climate adaptation measures are specified. In relation to shade trees, criteria differ among the standards while criteria may also change

[2] In January 2018, Rainforest Alliance and UTZ merged but a new joint standard has yet not been developed. We have therefore analysed their codes of conduct separately.

[3] Fair Trade and Organic mainly focusses on respectively the social or environmental aspects of sustainability. Therefore, some farmer co-operations use and comply to both standards for their commodities.

Table 2
Criteria to farm management which are related to climate change adaptation derived from the codes of conduct of the Rainforest Alliance, Fair Trade, UTZ and Organic standards. See supplementary material for information sources. SAN = Sustainable Agriculture Network, FLO-CERT = Fair Trade Labelling Organisations - Certificate, IFOAM = International Federation of Organic Agriculture Movements, OCIA= Organic Crop Improvement Association International.

Aspect	Rainforest Alliance	Fair Trade	UTZ	Organic
Organisation level	Individual/Cooperation	Cooperation	Individual/Cooperation	Individual
Accreditation	SAN	FLO-CERT	UTZ (SAN since 2018)	IFOAM, OCIA
Climate change references in codes of conduct	Assess risks associated with climate change	Reducing emissions by energy consumption, increasing carbon sinks	Diversification of production and/or other sources of income. Reduce energy consumption	Energy consumption from renewable sources
Tangible climate change actions in guidance documents	Prevent land degradation by planting native species. Increase of-farm carbon stocks	Carbon accounting (CDM or Gold Standard)	Apply risk assessment. Use of more pest resistant species. Include more shade providing trees	No specific guidance documents
Deforestation	No conversion of high conservation value ecosystems, from November 1, 2005 onwards	No deforestation or degradation of primary forest occurred since 2008	No deforestation of primary forest	No clearing of high conservation value areas in the preceding 5 years before compliance with this standard
Restoration activities	Yes	Yes	Yes	Yes
Establishment of buffer zones	Yes	Yes	Yes	Yes
Agroforestry systems	Yes	No criteria	Yes	Yes
Number of shade trees	A minimum of 12 trees per hectare	No criteria	An “adequate number” per hectare, depending on local conditions	A minimum of 10 species per production area
Canopy density, shade level and strata	At least 15% total native vegetation coverage across the farm or groups of farms, minimum regional canopy cover of 40%	No criteria	No criteria	Minimum canopy cover of 40%
Type of shade trees	Native tree species	No criteria	Non-invasive, nitrogen fixing trees	Non-native species no more than 20% of shade trees. Inga spp., no more than 50% of the trees
Fertilizer use	Organic and non-organic fertilizers, with organic priority	Providing training on fertilizer use	Organic and non-organic fertilizers, with organic priority	Only organic fertilizers
Chemicals use	May be used if legally registered	May be used if legally registered	May be used if legally registered	Pesticides are prohibited
Integrated Pest Management	Must be applied	Can be applied with additional training and monitoring	Must be applied	Integral part of the organic system
Water use and conservation	Water conservation program, maintaining natural vegetative cover	Water conservation program and training	Water conservation program	Water conservation program
Prevention soil erosion	Soil erosion program and maintain vegetative ground cover	Identify land at risk of soil erosion and provide training	Soil erosion program and soil conservation techniques	Program to prevent erosion and minimize loss of topsoil
Energy and climate change	Diminish emissions of greenhouse gases and increase sequestration	Monitoring energy consumption, increase energy efficiency and use of renewable sources	Risk assessment of climate change impacts. Increase energy efficiency	Energy consumption from renewable sources and energy efficiency

over time. For example, in Rainforest Alliance the code of conduct in 2010 had set a shade criterion of “tree canopy comprises at least two strata or stories and an overall canopy density of at least 40% of shade cover”, while in 2017 this was reduced to “at least 15% total native vegetation coverage across the farm or groups of farms or a minimum regional canopy cover of 40% shade cover” (Table 2). Rahn et al. (2018b) showed that at the plot level and depending on environmental context, these lower shade cover criteria might not suffice as adaptation to climate change.

Most climate change guidance documents provided by the standards only address mitigation aspects (e.g., energy consumption, carbon stocks) such as Fair Trade’s carbon accounting system. Adaptation is rarely mentioned, although UTZ addresses product diversification to improve smallholder resilience to climate change, and SAN (Sustainable Agriculture Network; Rainforest Alliance) reports preparedness to engage in payments for ecosystem services in the SAN climate module. All these options are non-binding. The role and function of landscapes and forest ecosystems in enhancing farmers’ adaptation capacities are not elaborated, with certification being evaluated and applied only at the farm level.

Appropriate plot and farm level adaptation practices need to be tailored to local socio-economic conditions. This can vary among coffee farmers, even within a single landscape. This variation is related to access to resources, education, farm and plot size, and also other household activities (Rahn et al., 2018a). Mostly, certification programmes emphasise relatively short-term environmental benefits, though some of these also provide some protection from climate change, such as nitrogen fixation, soil improvement, and nutrient recycling. Organic fertilizers, improved waste management and carbon storage through maintaining shade trees (van Rikxoort et al., 2014) can add mitigation potential that has synergies with adaptation (Harvey et al., 2014).

4. Implementation complexity

The identified adaptation measures (Section 2) range between incremental – defined as extensions of actions that can be readily applied - to fundamental transformative options (Kates et al., 2012). Although differences between incremental and transformative adaptations can be ambiguous (Kates et al., 2012), incremental options can be seen as measures that can be implemented in incumbent systems, while transformative options require more radical socioecological changes in production systems and the institutions supporting them (Rickards and Howden, 2012).

The need for either incremental or radical changes depends on the degree of climate change impacts (Fig. 1; Rickards and Howden (2012). Incremental options, such as water and soil management improvement, planting tree windbreaks, and introducing new crop varieties may suffice to respond to modest climate change, and can be implemented in high productive sun systems (Table 3). With increasing climate change impacts, more substantial system adaptations are required (Table 3). System adaptations include adding a shade tree layer to coffee monoculture (sun systems), product diversification and integrated pest management (Läderach et al., 2017). Although smallholder farmers (traditionally) may apply shade management, the general trend has been the conversion of shade systems to sun systems, also by smallholders. In a number of coffee producing countries, the areas under (traditional) shade systems have decreased from 33.4% of total coffee area in 1996 to 24% in 2012 (Jha et al., 2014). This reduction is most pronounced in Latin America (up to 68% reduction in agroforestry area), while in upcoming coffee producing countries, such as Vietnam, mostly sun plantations have been established (Jha et al., 2014).

Most radical transformations are expected at the highest degree of climate change impacts, and may include switching to other crops, increasing off-farm labour, or abandoning agriculture (Läderach et al., 2017). Other ways to cope with climate change is to make better use of landscape processes, such as improved watershed management or landscape level pollination or pest management (see Section 2.6). Such management requires various landscape interventions, for which farmers will become increasingly dependent on the actions and decisions made by other (landscape) actors.

As Kates et al. (2012) and Rickards and Howden (2012) pointed out, the difficulties to implement options, and transformative adaptations in particular, depend on the uncertainties of climate change and the associated risks and benefits, the perceived costs of actions and the suite of institutional and behavioral barriers. Kates et al. (2012) and Rickards and Howden (2012) however, do not discuss the barriers that may also be related to the sociotechnical transitions that are needed to change ‘business as usual’ to new sustainable practices including climate change adaptation.

Innovation theories increasingly emphasize innovation as a key process in such sustainable societal challenges (Hekkert and Negro, 2009) and a suite of frameworks have emerged to analyze this process. The Technical Innovation System (TIS) framework (Hekkert and Negro, 2009), which has also been reframed as Agricultural Innovation Systems in the case of agriculture (Klerkx et al., 2010), addresses uptake of innovations, such as adaptation measures. This uptake requires sound entrepreneurship, knowledge networks and diffusion, and the creation of common rules and design. The TIS framework identifies seven functions in innovation that can be applied to implementation of potential adaptation measures (Table 4).

In certification systems the functions described in Table 4 are largely met. For example, certification gives competitive advantage through niche market promotion and access (Market Formation), mobilizes financial resources such as green premiums or higher prices for better quality products, invests in training by providing material (Knowledge Development and Diffusion), and creates legitimacy to address social and environmental sustainability issues. Certification

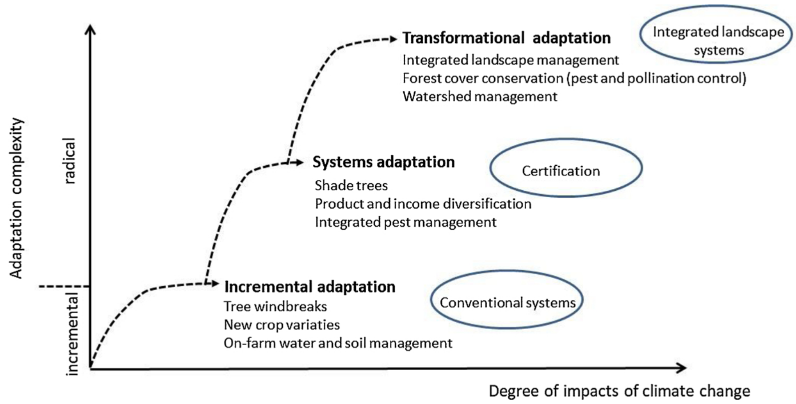

Fig. 1. Three levels of climate adaptation in coffee cultivation in relation to the degree of impacts of climate change. Adapted from Rickards and Howden (2012).

Table 3
Type of adaptation, the aim of adaptation, associated adaptation measures and level of implementation complexity.

Type of adaptation	Aim	Possible associated adaptation measures	Implementation complexity
Incremental adaptation	Maintain current production system (sun systems) with some adaptation measures	Farm-level water and soil management, planting tree windbreaks, introduce new crop varieties	Low
Systems adaptation	Enhance resilience of production system, partly by changing sun systems into shaded systems	Add shade trees, diversify production and income, integrated pest management	Medium
Transformational adaptation	Landscape integration of shade systems	Integrated landscape management, forest conservation and watershed management	High

falls short, however, on landscape transformational adaptations. Although some landscape aspects are addressed in certification, such as the deforestation commitments, landscape integration is beyond the capabilities and remits of current certification schemes.

Moreover, it is also clear that the large majority of independent smallholders will have difficulties in implementing a suite of adaptation options, largely due to a lack of resources and capabilities, limited access to technical and market knowledge, and insufficient institutional support (Borsky and Spata, 2018). This raises the questions on how independent smallholders can be supported to adapt to climate change, and how certification systems might enable transformative adaptations in smallholder systems at landscape scales.

5. Scaling up adaptation measures beyond certification

Apart from strengthening smallholder capabilities, implementing system and transformative adaptation measures requires long term visions, the involvement of other landscape and value chain actors, adaptation of public policies, and the creation of new incentives and markets.

5.1. Development of long-term visions

Implementing adaptation options requires large and long-term investments of smallholders, value chain actors and governments for both on-farm measures and interventions at landscape scale. The returns might not be immediately apparent or tangible. Uncertainties about the value of such long-term investments, particularly in view of unclear policy goals of governments and potentially changing value chains, will make actors reluctant to implementing adaptation measures. Hence, a certain degree of legitimacy of adaptation implementations needs to be created in the context of climate change (e.g., Hekkert and Negro, 2009). Large research programs, such as the CGIAR (Consortium of International Agricultural Research Centers) Climate Change Agriculture and Food Security (CCAFS) program are addressing this issue by developing joint scenarios and visioning of plausible futures (Vervoort et al., 2014). Also the Global Coffee Platform is explicitly designed to facilitate such visioning (Panhuysen and Pierrot, 2018).

To further shape visioning, landscape approaches purport to engage with diverse stakeholders across multiple spatial scales and sectoral interests to develop shared futures (Sayer et al., 2013; Scherr et al., 2012). The roles and commitments of value chain actors are, however, often ignored (Marshall, 2015; Milder et al., 2014). Coffee production and processing are ‘vertically’ organised in international value chains (Lambin et al., 2017). There are few links between actors who produce different commodities in the same landscape, and ‘horizontal integration’ across different production systems is lacking, which might promote more effective landscape wide-management for environmental benefits and social wellbeing (Deans et al., 2017). This would require governments to provide incentives and legislation, while the roles and commitments of value chain actors need to be further stipulated (Mithöfer et al., 2017). Landscape scale coordination of adaptation options thus requires multi-stakeholder negotiations, continuous learning, and long-term funding (Cundill and Fabricius, 2010; Sayer et al., 2013) for which the Global Coffee Platform and the Sustainable Trade Initiative have both set up a landscape program (IDH, 2017).

5.2. Creation of incentives and supporting institutions for adaptation uptake

Although the outcome of visioning processes may point at stimulating shade systems, in many coffee producing countries smallholders are increasingly supported by governmental incentives, research institutes and extension services to increase yields and to transform (traditional) shade systems to sun systems (Jha et al., 2014). Moreover, certification programs are not well-designed to provide solutions for the adaptation options that require transformational changes at landscape scales. Adaptive landscape transformation requires new policy frameworks, institutional arrangements, and appropriate financial investments (e.g., Harvey et al., 2014). However, lack of funding, distrust among private and public partners, and weak institutions currently complicate such interventions (Cundill and Fabricius, 2010; Scherr et al., 2012).

One mechanism for financing climate adaptation measures is payments for ecosystem services (PES). In Peru, for example, carbon credits

Table 4
Functions of innovation processes, as described by the Technical Innovation System (TIS) framework and applied to climate adaptation measures in coffee production. Adapted from Hekkert and Negro (2009).

Function	Description
Guidance of the Search	The adaptation measures need to have a positive effect, visibility and clarity that need to be shared among government, landscape actors and value chain actors. Policy goals to adaptation implementation may provide legitimacy to systems and transformative adaptation. Expectations need to be included to generate a momentum for change.
Creation of Legitimacy	Adaptation measures need to become part of an incumbent regime or replace the regime. Parties with vested interests, like value chain actors will often oppose this since it will put pressure on their current economic interests.
Market Formation	Adaptation measures may come at higher costs (opportunity costs) relative to the incumbent production system. Value chain actors may therefore need to create temporary niche markets for experimentation. Tax regimes or payments (incentives, subsidies) may also support farmers.
Farmer Activities	The farmer has to incorporate adaptation measures and generate (new) opportunities in coffee production while coping with increasing climate change.
Knowledge Development	Research and knowledge development should support farmers in taking relevant adaptation measures.
Knowledge Diffusion	Networks are essential to exchange information. Farmers depend on both public networks (governmental extension services), farmer cooperation’s and private value chain actors.
Resource Mobilisation	Both financial and human resources need to be supported by value chain actors and/or farmer cooperatives since it is unlikely farmers alone can bear the costs.

generated by reforestation in upper watersheds are sold to coffee businesses in the value chain, a mechanism called 'insetting' (Amrein et al., 2015). While PES has been well publicised, its implementation and uptake has also been limited, mainly due to high transaction costs that disproportionately exclude poor smallholders (Wunder, 2008). Moreover, PES programs do not yet address climate change, but positive results have been found for water services that are clearly linked with climate change (Porras et al., 2008). To be effective, implementation of PES requires a balanced mix of private, institutional and government instruments such as sound (participatory) land-use governance and planning that should include zoning of particular land-uses in watersheds (Ferraz et al., 2013).

5.3. Market formation

Group certification, in which farmer cooperatives are certified rather than individual farmers, is applied by some standards. This allows sharing the burden of high transaction costs. Even so, the net added value of certification can still be questionable, as certification costs remain high relative to price premiums secured (Latynskiy and Berger, 2017). Group certification does, however, offer the possibility for more efficient participation in PES schemes, where the ecosystem benefits of land management can be realized and verified at aggregated landscape scales (Ghazoul et al., 2009). Recognizing this, the alternative landscape labelling approach has been suggested (Ghazoul et al., 2009). This jurisdictional approach to certification is gaining considerable traction in international discussions (Hart et al., 2014) as it enhances inclusiveness, and integrates PES with bundled-commodity certification systems.

5.4. Smallholder knowledge development, networks and capabilities

Strengthening local capacities and improving access to insurance, technical support and markets for sustainable products are key ingredients for smallholders. Agricultural and forestry extension services need to be strengthened to provide local support for adaptation measures to farmers (Schroth et al., 2009). For example, multi-stakeholder initiatives, such as the SAFE (Sustainable Agriculture Food Environment) platform, Sustainable Coffee Challenge and Coffee & Climate (Panhuysen and Pierrot, 2018) develop knowledge infrastructures for smallholder coffee farmers. Adaptation options are further elaborated in the context of smallholder climate change resilience. Yet, knowledge production and diffusion are still rather scattered which makes it difficult to prepare independent smallholders for climate change.

5.5. Mobilizing resources for smallholders

Implementation of adaptation options by smallholders requires a different finance model because a production lag will occur between implementation and obtaining positive returns (Basak, 2017). Medium to long-term financing must allow smallholders to make the necessary investments. New climate-smart agriculture programs of the World Bank and FAO are currently developing financial instruments that especially target climate adaptation measures (FAO, 2013).

Furthermore, access to crop insurance can support farmers in coping with the impacts of climate change and insurance can be coupled to other adaptation measures. For example, Giné and Yang (2009) analysed the take-up of a weather insurance product by groundnut and maize farmers in Malawi and found that the rate of take-up was higher when insurance was combined with finance for hybrid seeds.

Donor interventions might aid farmers in their systems and transformative adaptations. The effectiveness of financial aid can, however, be undermined by low willingness to implement supportive policies, unfavourable commodity prices, or limited knowledge network formation (Hansen and Nygaard, 2013). As Hansen and Nygaard (2013) argue, donor interventions could also lead to the creation of new arenas in which conflicts over resources, interests, interpretations, and rationalities can inhibit necessary transformations. Governmental interventions are therefore needed to efficiently steer (private) financial support to smallholder farmers.

5.6. Concluding remarks

Although tangible climate change adaptation measures are incipient, many organisational issues are currently hampering the implementation at farm and landscape scale. Using the functions from innovation management, we show many obstacles have to be overcome for effective implementation. Independent farmers need access to knowledge networks, finance and appropriate training. Moreover, there are currently large hurdles to be overcome to cover increased costs. Certification systems can aid implementation since knowledge structures, resources, and market formation are largely in place, while sustainability goals are acknowledged and addressed. Yet certification only address market niches, and scaling up certification of coffee farmers globally remains challenging. Nonetheless, certification processes and the standards that they represent can be used to leverage good practice for climate change adaptation as well as broader sustainability goals. This would require a refinement of certification systems, including considering their role in catalysing transformational adaptations at landscape scales.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2019.03.017.

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