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# Adapting cropping systems to climate change - a literature review

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# Abstract

As overconsumption, food waste and diet choice of increase global food demand and climate shifts to warmer and more extreme conditions, action is needed to reduce the devastating effects of climate change on global food production to ensure food security. Heatwaves, droughts, floods are few extreme examples of disturbances that cropping systems have to face, which often result in crop failures and yield reductions. Crop and soil management practices can adapt cropping systems to a range of climatic and weather conditions, allowing the farmers to reduce negative and exploit positive effects of climate change. Here I review the potential of commonly used practices in adapting cropping systems to climate change and the mechanisms underlying the resilience of such systems to climate-induced disturbances, with the intent to identify: 1) Climate adaptation practices efficient for maintaining high and stable yields in cropping systems under climate-induced disturbances; 2) Knowledge gaps relative to climate adaptation potential of crop management practices. The results indicated that crop and soil management practices can partially adapt cropping systems to local and climate-change induced conditions, especially under water-stress conditions. However, studies analysing yield stability of cropping systems under detrimental conditions are scarce. Addressing to this knowledge gap might promote the uptake of climate-adaptation practices, thus increasing global food security under the uncertainty of climate change.

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# 1. Introduction

Today, global food demand increases and impacts in food production systems can lead to severe consequences in human welfare. Dietary preferences, food waste and overconsumption are major contributors to increases in global food demand (Lusk & McCluskey, 2018). There is a strong connection between affluence and consumption, which also correlates to environmental impacts (Wiedmann et al., 2020). The world's 10% richest individuals (630 M people) are accountable for half of the global carbon emissions, as opposed to the 7% emitted by the poorest 50% (3.1 B people) (Gore, 2020). At the same time global human population is expected to grow up to 9.7 billion by 2050, further contributing to food demand. Currently, the numbers of undernourished people are slowly rising since 2015 (from 785 M to 821 M people in 2018), while 26,4% of the world population suffers from limited access to nutritious and sufficient food (FAO et al., 2019). This is likely to be exacerbated by the ongoing COVID-19 pandemic, as the resulting global economic crisis could result in reductions in food accessibility on a long-term period (OECD, 2020). Disruptions of global food production are a threat to food security especially for low-income individuals, both in terms of food availability and price volatility. On the one hand, it is difficult for the poor to adjust to increases in food costs (Regmi & Meade, 2013); on the other hand, low-income producers are less likely to invest their limited resources into productivity if the market is uncertain (World Bank & International Monetary Fund, 2012). Changes in climate and increases in frequency of anomalous weather can directly and negatively influence food production in terms of food access, consumption and price stability (Porter et al., 2014). Given the importance of agriculture in meeting food demand, adapting crop production to climate variability is an essential step in increasing global food security.

Crop production depends on climatic and weather conditions, which can boost or hinder crop productivity, or even damage the crops through physical and biochemical processes (Suzuki et al., 2014). Crops have an optimal range of abiotic conditions, under which they thrive and can achieve their potential yields. For example, plant growth rate increases with temperature because of boosts in metabolic rates and efficiency (Criddle et al., 1997), but temperatures above the optimal range can inhibit photosynthesis, increase rate of respiration and transpiration, and cause loss of fertility (Eyshi Rezaei et al., 2015), with consequent decreases in crop productivity. Combinations of abiotic, but also biotic stressors are common, and can be more damaging to the crops than the same disturbances occurring in isolation (Suzuki et al., 2014). For instance, the combination of high temperatures and prolonged drought that struck Sweden in 2018 caused a severe national reduction in grain, oilseed, field beans, and potato yields, with a yield decrease of 45%, 42%, 41%, and 15%, respectively, compared with 2017 (Statistiska Centralbyrån, 2019). Anomalous weather conditions, i.e., outside of the seasonal averages, can both enhance or hinder productivity. Nevertheless, here, I focus on extreme weather conditions that have negative effects on crop yields, i.e., to indicate distinct episodes of single or compound anomalous conditions that reduce crop yields below the range of their normal variability.

Climate change (CC) will result in warmer conditions (Battisti & Naylor, 2009) with increasing frequency of events such as anomalous warm seasons (Weisheimer & Palmer, 2005), dry spells and increasing intensity of precipitations (Seneviratne et al., 2012). While increased air $CO_2$ concentration boosts photosynthesis rate, the effect saturates at elevated concentrations (Long et al., 2006), and negative effects of warmer conditions and anomalous events generally exceed this benefit. Some positive effects of CC can be observed in temperate and boreal regions, where longer growing seasons could benefit agriculture (Altieri et al., 2015). But CC is predicted to negatively impact crop yields and yield stability globally, especially in tropical regions (Challinor et al., 2014). It should, however, be noted that yield instability can be a desired quality, if driven by positive deviations from the average yield. Further, CC can also increase occurrence of pathogens, pests and weeds (Altieri et al., 2015), adding a biotic dimension to the climatic-induced disturbances.

Farmers have no control over climatic conditions, but to a certain extent they can avoid, adapt to, or even exploit local conditions. The aim is to minimize yield losses under unfavourable conditions and maintain or increase maximum yields under favourable conditions. But CC might cause cropping systems to produce lower and unstable yields (Ray et al., 2015). It is thus necessary to address CC via both mitigation and adaptation. Mitigation directly reduces the environmental impact of cropping systems, e.g., reducing CC-inducing emissions or boosting sinks of greenhouse gasses by adopting sustainable practices such as use of organic fertilizers and natural pest control. Adaptation is instead aimed at reducing the negative impact of actual or expected climatic conditions on production, and exploiting the positive ones, through the adoption of specific management practices, e.g., shifting sowing dates and choosing crops that can tolerate specific climatic conditions. However, while most research focus on the climate mitigation aspect of management practices, much less is known about their efficiency from a climate adaptation perspective.

The efficiency of climate adaptation practices could be interpreted using the concept of resilience, defined as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks” (Walker et al., 2004, p. 2). In managed ecosystems such as cropping systems, economic and management factors can affect the level of resilience of a farm (Darnhofer, 2010). A farm can be reorganized, e.g., following losses caused by climate-induced disturbances, if the upkeep costs of the cropping system are affordable, which ultimately depend on the revenues generated by the farm. Farmers thus invest their resources in external inputs and interventions to ensure successful harvests. The capability of a cropping system to retain its state when facing external disturbances, is therefore a highly valuable quality, as it decreases its vulnerability and the risk of economic losses. This quality is also known as resistance (Walker et al., 2004) or robustness (Urruty et al., 2016), and it is a component of resilience. A climate resilient cropping system is expected to exhibit reduced yield variability compared with non-resilient ones, with less chances of crop failure, and thus to provide a reliable source of income under CC uncertainty.

Weather and climatic disturbances can affect crop systems over different time scales, from relatively short-term events such as heat waves, floods or dry periods, to long-term effects such as CC. It is thus necessary to identify the time-scale and effects of likely disturbances prior to the selection of adaptation practices. Management practices can in fact provide short- to long-term resilience to adverse conditions, by improving ecosystem properties such as biodiversity, soil health, and control of detrimental organisms (Lin, 2011).

Various management practices have been suggested as adaptive measures against CC and other extreme conditions, based on observations on how they affect yields and yield stability under climatic conditions similar to what are expected in the future. Examples are: increasing the diversity of cropping systems, through e.g. intercropping and crop rotations; the use of organic fertilizers; or tillage techniques with low impact on soils (Altieri et al., 2015). Their effects on yield variability and potential is, however, seldom analysed, while most research focus on the effects on crop yield averages, and on sustainability indicators such as water and N use efficiency, and soil organic matter dynamics. While there can be synergies between sustainability and adaptation to CC (Smith & Olesen, 2010), these indicators are unable to provide direct evidence for increased yield resilience as opposed to yield stability and potential. Addressing this knowledge gap could highlight the efficiency of management practices in reducing negative impacts of CC, thus boosting an otherwise hindered farmer uptake. Another issue that can limit the uptake is the wide perception of such practices as risky and/or cost-intensive, as they can lower yields on short-term scales and/or harder to adopt compared with more common and less complex management methods (Kleijn et al., 2019). We therefore need a clear understanding of the viability, costs and benefits of adaptation practices to promote their use in crop production. To tackle part of this knowledge gap, I aim to answer the following questions: [1] How is the negative impact of climate-induced disturbances reduced by management practices? [2] Which practices tackle climate adaptation effectively?

The focus is on adaptation practices applied directly to the single field, although management of the surrounding landscapes can also provide benefits in terms of climate adaptation (Scherr et al., 2012). After presenting the methods of this review (Section 2), I discuss potential adaptation practices and the mechanisms involved in increasing CC resilience in Section 3, as well as their synergies and conflicts, and knowledge gaps in Section 4.

# 2. Methods

To answer question [1] and [2], I selected literature from online databases, e.g., “Web of Science”, “Google Scholar”, using relevant keywords and combinations of search operators, e.g., (“yield resilience” OR “yield stability”) AND “climate change” AND (“crop rotation” OR “crop diversity”) AND (“climate adaptation” OR “adaptation”), during Spring 2020. To restrict the focus of the study on state-of-the-art management practices, articles prior to year 2000 were excluded from the literature search. The exception was articles discussing the effects of biological or climatic processes on agriculture, as these relations are qualitatively unaltered by time-varying factors, e.g., technological advancement and CC. Abstracts were scanned to determine if the article was relevant for this review. No specific geographical boundaries were imposed. Part of the literature was also obtained from experts in the field, e.g., supervisors, and fellow researchers.

Given the breadth of the arguments featured by the articles, these were subjectively grouped into categories, each reviewed in one sub-sections in Section 3. Following the selection and grouping process, I read the suitable articles with the intent of identifying: 1) effects on yield potential and stability, and/or indicators for increased resilience, e.g., increased soil organic material, and resource use efficiency; 2) efficacies and limitations of the focal management practices in tackling specific climatic conditions and extreme weather events; 3) synergies and conflicts among the practices; 4) remaining knowledge gaps. The final outcome of this research is a narrative review, featuring the afore-mentioned points and addressing question [1] and [2] (see Section 1).

# 3. Review of climate adaptation practices

The most common management practices with a potential for climate adaptation can be divided into two main groups: crop and soil management practices (Section 3.1 and Section 3.2, respectively). Although the two approaches are quite dissimilar from a practical point of view, they bear similar ecological consequences that can foster the resilience of farming systems to climate-driven disturbances. For each management strategy (Figure 1), I will discuss evidence and mechanisms for increased yield and yield stability in relation to climatic conditions and CC-induced disturbances (e.g., weather extremes, pathogen occurrence), limitations to applicability of the strategy, and knowledge gaps.

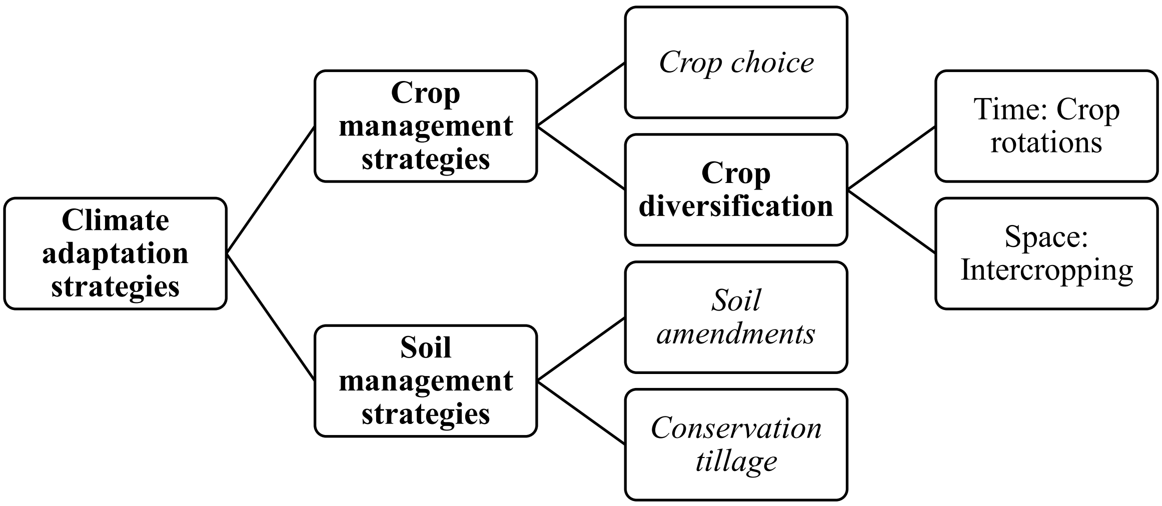


*Figure 1. Scheme representing the focal management practices discussed in this review (in italics), and their categories and sub-categories (in bold).*

## *3.1. Crop management*

Farmers can adapt their cropping system to climate by directly managing crop species. Examples of crop management include selecting specific crops to cultivate, based on their climate and weather tolerance. Crops can also contribute in shaping the surrounding environment, from biological, chemical, and physical viewpoints. The induced changes can boost the overall resilience of the cropping system to climate-induced disturbances. Farmers might also cultivate more than one crop over one growing season,  such as in intercropping, or over two or more growing seasons, such as in crop rotations.  Intercropping and crop rotations provide additional benefits to the environment and the climate resilience of the cropping system. In the following sub-sections (3.1.1 and 3.1.2), I thus describe how the choice of crops and adding complexity to crop diversity can enhance climate adaptation in crop production.

### *3.1.1. Crop diversification*

Crop diversity is an aspect of biodiversity applied to cropping systems, thus a measure of the complexity of cropping systems in terms of, e.g., taxonomic, genetic, habitat, and functional diversity. High species diversity often translates into highly complex and dynamically stable multi-trophic interactions, resulting in productive and disturbance-resilient systems (Cardinale et al., 2012; Elmqvist et al., 2003; Wan et al., 2020). While disturbances still affect single species, their average effect on the community level is reduced, a concept also known as portfolio effect (Schindler et al., 2015).

Via crop diversification, farmers can directly and indirectly influence the above and below-ground biodiversity within, across and in proximity of the crop fields, with benefits to ecosystem properties such as soil quality, nutrient cycles, pollinator activity, and biological control of pests (Kremen & Miles, 2012). Therefore, it can be useful to distinguish diversity into managed and wild, the former pertaining species actively introduced by the farmer and the latter related to non-domesticated species indirectly affected by management practices.

The managed diversity of a farm system can be altered from a time and space perspective, the former represented by the turn-over of crop species in the same field (Section 3.1.1.1), and the latter by the co-existence of several crop species from small to large spatial resolutions (Section 3.1.1.2).

#### *3.1.1.1. Crop diversification in time: crop rotations*

By allowing a succession of two or more crop species in the same field in distinct periods, i.e., using crop rotations, farmers can provide resilience to adverse climatic conditions, extreme weather events, and pest outbreaks, which could as well be facilitated by CC (Fitt et al., 2016). Compared to monocultures, spring and winter crop rotations provided higher yields in high temperatures and scant precipitations (Marini et al., 2020). Increasing crop rotation diversity could reduce risk of maize failure under harmful conditions (Bowles et al., 2020), impacts of droughts to winter wheat (Degani et al., 2019), and improve yield stability of maize and soybean (Gaudin et al., 2015). Crop rotations could also improve yields over time and during productive growing conditions (Bowles et al., 2020; Gaudin et al., 2015).

Increasing the managed diversity in cropping systems increases the diversity of plant litter input to the soil which can sustain a higher microbial diversity (Hättenschwiler et al., 2005). Microbes living in the soil decompose soil organic matter (SOM), including plant residues, releasing nutrients, e.g., N and P, and producing stable SOM (SSOM) as the final product (Cotrufo et al., 2015). SSOM improves physical properties of the soil, e.g., soil water capacity and infiltration. These properties regulate water and nutrient retention (Yang et al., 2014), which can provide resilience to drought events (Hueso et al., 2011), and increased rainfall variability (Sun et al., 2017). Additionally, water infiltration can bolster the exploitation of positive effects of CC (Song et al., 2015). Increasing the temporal diversity of cropping system, and therefore below-ground diversity, can hence improve water use efficiency and nutrient use efficiency, with less need for synthetic chemical inputs (Davis et al., 2012), especially when including cover crops in the rotation (Renwick et al., 2019). A more effective use of resources that would otherwise be lost due to e.g., leaching, allows crops to better exploit favourable environmental conditions, and to reduce yield losses under resource-limited ones.

Including specific functional type of crops in the rotation can provide additional benefits. For example, legumes can fix atmospheric N, supplying N to subsequent crops, reducing the need for fertilizers and thus reducing environmental impact (Cai et al., 2018). Rotations might also include crops with the sole scope of preserving the soil, i.e., cover crops, providing, amongst other benefits, control of soil moisture and temperature, and potential suppression of weeds by competition (Kaye & Quemada, 2017).

Crop rotations might also indirectly increase aboveground abundance of natural enemies, which can act as natural pest control, by supporting larger populations of below-ground decomposers (Birkhofer et al., 2008). Additionally, disease cycles can be interrupted if different functional groups are used in a rotation, for instance by alternating cereal and broadleaf crops, as they are less likely to be susceptible to the same pathogens (Lin, 2011).

There is a shortage of research assessing the effects of rotation diversity to yield stability, and these are mostly studied under droughts. Covering this knowledge gap by also including other extreme conditions would clarify under which conditions crop rotations perform best, in relation to specific combinations of crop types.

#### *3.1.1.2. Crop diversification in space: intercropping*

Spatial diversity can be increased by practices that promote e.g., the existence of more than one crop species per field. This section focuses on intercropping, a management practice that aims at fostering spatial diversity within the crop field, through the co-existence of two or more functionally diverse crop species for a substantial part of the growing season (Brooker et al., 2015).

Cereal-legume intercropping provided more stable yields in tropical and sub-tropical climatic zones, compared with pure cultures (Raseduzzaman & Jensen, 2017), and it could produce yields with high land use efficiency (Xu et al., 2020). Intercropping is efficient under water stress conditions (Natarajan & Willey, 1986), and is thus a valuable measure against droughts. More in general, because of portfolio effects, crop failure in intercropped systems might be limited to one or few crop species (Altieri et al., 2015). This suggests that intercropping can foster adaptation to a broad variety of extreme conditions, depending on the chosen crops.

The benefits of intercropping to yield stability are connected to resource use efficiency, soil quality, pest and disease control, and differential response to adverse conditions (Bybee-Finley & Ryan, 2018). Growing multiple crop species in the same field can boost water and resource use efficiency through differentiation of resource acquisition in time and space. Different growth rates among species can, for instance, imply peaks of resource demands at different time points of the growing season, while differential species root lengths imply diverse depths of nutrient and water acquisition (Willey, 1990). Intercropping can also augment SSOM and soil fertility by increasing soil microbial activity and diversity, similarly to diverse rotations (Section 3.1.1.1). For example, intercropping potatoes with legumes could significantly reduce SOM deterioration associated with potato monocultures, sustaining higher microbial biomass and activity (Nyawade et al., 2019). Biological control of pest can also be achieved by intercropping cash crops with plants producing repellent compounds for pests and attractors for natural enemies, providing a sustainable alternative to pesticides (Pickett et al., 2014). Additionally, intercropping can suppress disease occurrence through, e.g., microclimate, morphological, and physiological alterations, or direct inhibition through the production of allelochemicals (Boudreau, 2013).

The efficacy of intercropping on yield stability in a variable climate relies on a series of well-planned choices. For instance, relative performance of cereal-legume intercrops can be manipulated by the farmer by modifying sowing densities, relative sowing times, and fertilization rates, potentially increasing species complementarity, total productivity and economic profit (Yu et al., 2016). Choosing profitable combinations of crops requires knowledge of the life history of the selected species and that of the wild diversity, e.g., pests and diseases, in the vicinity of the fields. A combination of crops occupying similar niches, and/or intercropping with no regards to, e.g., sowing times and density, could in fact promote excessive resource competition and therefore lower yield potential (Craufurd, 2000), or even facilitate the occurrence of shared pest and disease through apparent competition (Rand, 2003).

It is unclear how intercropped systems perform under extreme precipitations and temperatures, although the portfolio effect and improved soil quality indicates that intercropping could buffer such disturbances. Covering this knowledge gap is essential to identify the most suitable combinations of crops against extreme precipitation and temperature events.

### *3.1.2. Crop choice*

Whether in monoculture, intercropping or crop rotations, the choice of crops is crucial to adapt to local conditions. Depending on the crop species and variety, response to climatic conditions vary, which is why farmers generally choose crops and cultivars that perform best according to the local climate, although consideration is given also to market conditions. The choice can be based on local average temperatures and precipitation, favouring e.g., maize in warmer climates and wheat in cooler ones, with similar patterns of crop choices observed at (sub)-continental scales (Kurukulasuriya & Mendelsohn, 2008; Seo & Mendelsohn, 2008; Wang et al., 2010). Additionally, inherent characteristics of diverse crop species influence the responses to weather-induced disturbances, potentially increasing minimum and maximum yields, hence providing an efficient weather adaptation measure in areas affected by frequent and specific perturbations. For instance, cereals tended to be more resistant to droughts than legumes and tubers (Daryanto et al., 2017), making them a preferable choice in regions often afflicted by such events. Because CC can render local climatic conditions sub-optimal or even damaging for crops, predictions on shifts in crop-climate relationships are an essential for food security (Egbebiyi et al., 2019), as they could allow farmers to switch crop accordingly and potentially avoid economic losses. Following global trends in crop shifting, rainfed wheat and rice are currently growing in colder temperatures than experienced in past years, maize is adopted in farms experiencing longer growing seasons and less frequent extreme heat, while soybean is more exposed to extreme warm temperatures (Sloat et al., 2020).

Other factors might drive the adoption of new crops by farmers. In Ethiopia, market fluctuations have a stronger influence on the adoption of new crops than CC, although climate generally drives crop abandonment (Tessema et al., 2019). This marked-oriented approach could temporarily hinder adaptation, if the newly adopted crops do not perform well in the local environment, until the crop is replaced with a more optimal choice. This can be especially problematic for low-income farmers established in developing countries for two reasons. First, crop choice is more likely to be constrained to low-cost crops because of limited incomes. Second, CC exert more severe impacts to agriculture in developing countries compared with developed ones (Mirza, 2003).

Only few other investigations have attempted at disentangling the importance of climate from socio-economic and political factors in determining the adoption of new crops (Alauddin & Sarker, 2014; Mertz et al., 2009). Further, while there is evidence for global crop shifting to more favourable climates (Sloat et al., 2020), no research has examined its effect on crop yield and yield stability to my knowledge. Covering these aspects may provide necessary knowledge to promote a more proactive approach when it comes to crop adoption, with potential benefits to food security.

## *3.2. Soil management*

Direct management of the soil is another approach to climate adaptation, achieved for instance through direct input of soil amendments (Section 3.2.1), e.g., organic litter inputs, or through reduced soil disturbance (Section 3.2.2), e.g., reduced tillage. Such methods can increase the quality of the soil, by fostering physical and biochemical properties that may increase the overall resilience of the farming systems to climatic variability and detrimental weather conditions.

### *3.2.1. Soil amendments*

Soil amendments consist in direct input of external material to the soil, aimed at increasing its quality, potentially enhancing yields and yield stability in the long-term. Soil quality can be improved from the bio-chemical and physical perspective, through the addition of inorganic material, e.g., synthetic fertilizers, and organic material, e.g., crop residues, compost, animal manure, and biochar. Inorganic material provides significant increases in soil nutrients with no direct benefits to soil structure, while the latter benefits the soil in both perspectives but requires higher application rates compared with inorganic fertilizers (Mtaita, 2003). While a direct input of mineral fertilizers is of immediate benefit to crop productivity, part of them might be lost due to physical processes such as leaching if soil structure is poor, leading to lower yield potentials and net incomes, as well as increased eutrophication of water bodies (Smolders et al., 2010). These problems can be tackled by using organic fertilizers, which can improve soil quality through a direct input of organic residuals and consequential increased soil microbial activity (Dangi et al., 2020). As previously discussed, soil micro-organisms recycle nutrients and produce SSOM, with consequential increases in resource and water use efficiency and yield outcome and stability (see Section 3.1.1.1). Inorganic and organic fertilizers combined might therefore provide higher and more stable yields at lower application rates than when used separately (H. Chen et al., 2018; Li et al., 2018; Qaswar et al., 2019; Qin et al., 2015), offering simultaneous climate mitigation and adaptation.

Carefully planned selection of soil amendments and of their application rate is required to maximize treatment efficiency (Y. Chen et al., 2018) and to prevent pollution, as excessive or incorrect use of fertilizers could result in e.g., accumulation of heavy metals and organic pollutants belowground, and excess of nutrients, with consequences to human health and the surrounding environment (Urra et al., 2019).

To my knowledge, no research specifically assessed the adaptation potential of soil amendments in specific climates and weathers. However, based on the benefits associated with SSOM and increased microbial activity, it can be speculated that such practice could provide increased resilience to water-stress and water-excess conditions.

### *3.2.2. Conservation tillage*

Soil tillage is one of the most ancient management practices used in agriculture. although its execution and intensity has changed over the years (McKyes, 1985). Tillage is used to prepare the soil for cultivation and turn over crop residues and weeds. Intense tillage can however facilitate soil erosion and therefore loss of nutrients and water (Cerdà et al., 2009), increasing demands for inputs such as fertilizers and irrigation.

A more sustainable is conservation tillage (CT), which includes management practices with reduced or absent tillage (Carter, 2005). But the efficacy of CT is highly dependent on soil composition and quality, crop type, and local climate (Pittelkow et al., 2015; Toliver et al., 2012). For instance, CT did not perform well in humid climates, where yields and yield stability were generally lower than conventional tillage systems (Knapp & van der Heijden, 2018), whereas in water-limited conditions yields were often equal to or higher than conventional tillage systems (Pittelkow et al., 2015).

CT preserves soil fertility by minimizing soil disturbance and thus reducing soil organic carbon (SOC – a component of SOM) losses caused by weathering events such as soil erosion (Almagro et al., 2016) and have a lesser negative impact on below-ground biodiversity (Lupwayi et al., 1998; Säle et al., 2015) compared with conventional tillage. As discussed in Section 3.1.1.1 below-ground diversity regulates nutrient cycles, improves soil structure, and can promote natural pest control. A major downside with crops grown under CT is more intense weed infestation compared with fields under conventional tillage (Cardina et al., 1995), increasing demand for effective weed control. This problem can be partially tackled by pairing CT with the use of crop residues as mulch, which can physically suppress weed growth (Nawaz et al., 2017), contemporarily reducing exposure of undisturbed soil to weathering. In fact, plant residues can intercept rain drops, which contribute to soil erosion and runoff, and facilitate infiltration during abundant precipitations (Jordán et al., 2010) while also regulating soil temperature and moisture during dry conditions (Chakraborty et al., 2008).

The effects of CT on yield stability is still unclear. To the best of my knowledge, there is only a single meta-analysis (Knapp 2018) analysing such relationship, where no-tillage systems had no significant effect on yield stability. Nevertheless, only relatively short-term experimental data (4-5 years) were considered, while long-term experiments are needed to gauge the effectiveness of CT in climate adaptation, because the benefits linked to higher soil quality can emerge on a long time scale (Franchini et al., 2012). More specifically, there is a lack of studies analysing the effectiveness of CT in tackling high temperatures.

# 4. Discussion

The reviewed literature indicated great potential of climate adaptation practices in promoting resilience of cropping systems to climate variability, but also contrasting results, limitations, and some unknown mechanisms that might hinder their uptake. In general, the reviewed management practices offer resilience to some but not all disturbances (Table 1). Crop management offers possibilities to tackle a wide array of disturbances by customizing the cropping system with appropriate combinations of species. The main limitation of crop diversification practices is the advanced knowledge required for their application. Conversely, soil management is easier to apply and could offer resilience mostly to scant precipitation and droughts thanks to improvements to nutrient and water use efficiency. The main short-coming of soil management is a lack of biological control, which needs to be compensated with complementary management practices or external inputs.

*Table 1. Efficacy of management practices (rows) in maintaining high and stable yields in the face of the most known negative effects of climate change (columns), where "+","-", "=", and "?" indicate, respectively, positive, negative, negligible, and not well-known relations, based on the reviewed literature. Symbols within parenthesis indicate that there was no direct evidence of the efficacy, but that it could be speculated from the literature.*

| Management practice | Higher temperatures | Less frequent precipitation | Increased rain intensity | More frequent dry spells | Increased pest occurrence | Increased disease occurrence | Increased weed infestation |
|---|---|---|---|---|---|---|---|
| Crop choice | +/- | +/- | +/- | +/- | = | = | = |
| Crop rotation | + | + | (+) | + | + | + | + |
| Intercropping | + | + | + | + | +/- | +/- | +/- |
| Soil amendments | ? | (+) | (+) | (+) | = | = | = |
| Conservation tillage | ? | (+) | - | (+) | (+) | = | - |

The evidence for improved yields compared with more common practices is sometimes contrasting due to a highly context-dependent efficacy, with positive effects that are often observable over the long- but not short-term. Further, shifting to climate adaptation practices might imply additional structural changes that require large economic investments and learning processes, such as changing types, application rates and timing of pesticides and fertilizers. As a consequence, smallholder and risk-averse farmers could be reluctant in adopting climate adaptation practices, favouring a more familiar configuration with higher short-term gains, albeit more vulnerable to climate variability. This highlights the limitations in utilizing yield averages to compare performances among crop management practices, especially in short-term studies. Incorporating yield variability and/or likelihood of low yield in such comparisons in long-term studies could help the farmers to make more informed choices between maximizing average crop yield and minimizing the risk of crop failure.

## *4.1. Interactions among adaptation practices: synergies and trade-offs*

Farmers can choose several management practices, of which adaptation effects can accumulate and interact, resulting in synergies and/or trade-offs. For example, the effects of crop diversification can vary according to crop choice, especially in intercropping, where crops directly interact with each other. Farmers can promote interspecific facilitation by coupling cash crops with complementary ones, e.g., push-pull crops and N-fixing crops (see Section 3.1.1.2). Conversely, conflicts might arise if the intercropped species overlap in functionality, where excessive interspecific competition hinders crop performance. In rotations, adding cover crops provides extra benefits to the soil, protecting it from weathering effects while controlling soil moisture and temperature (Dabney et al., 2001). Cover crops also greatly benefits farms where conservation tillage is applied, compensating the risk associated with weed infestation (see Section 3.2.2).

It can be particularly advantageous to utilize combinations of climate adaptation practices, such as in conservation agriculture. This approach combines diversification, conservation tillage, and retention of crop residue as mulch, creating a low-input, drought-resilient cropping system. Conservation agriculture provided greater resistance to maize against extreme droughts and high temperatures, especially when utilizing crop rotations (Steward et al., 2019), most likely due to increased resource use efficiency given by the rotation, and the temperature and moisture control offered by the combination of reduced soil disturbance and soil coverage.

## *4.2. Experimental and theoretical knowledge gaps*

While the practices discussed here provide indications of resilience to climate change and weather extremes, few studies assessed the effects of management practices to yield resilience under climate-induced disturbances, and most were related to droughts. Additionally, trade-offs among climate adaptation practices are seldom discussed, so that it is unclear which combinations of practices and conditions are the most fruitful.

More in general, much is known about resilience in grasslands (e.g., Isbell et al., 2015; Kowalchuk et al., 2002; Tilman & Downing, 1994), but knowledge on resilience of agricultural lands is limited (Meuwissen et al., 2019). Similarly, much attention had been given to climate mitigation (e.g., Dalal et al., 2003; Paustian et al., 1997), while research interest in climate adaptation is relatively new (Ford, 2007) and unknown. There is however great potential for synergies among mitigation and adaptation management practices, as many of the adaptation practices discussed here also reduce GHG emissions and/or carbon sinks (Smith & Olesen, 2010).

# 5. Conclusion

I reviewed literature related to the potential of management practices in adapting cropping systems to climate change. While there is no universal solution to minimize risk of crop failure, cropping systems can be at least partially adapted to the environmental conditions, including those imposed by climate change, to obtain higher and more stable yields. Crop type and cultivar, crop rotations, intercropping can enhance resilience to droughts, high temperatures, excessive precipitation and occurrence of detrimental organisms. Soil amendments and conservation tillage mainly provide resilience to water stress conditions. Adaptation practices can be combined to obtain broader resilience and reduce input requirements. Yet, there are gaps in our knowledge that should be addressed to promote uptake of climate adaptation practices in crop production, ultimately increasing food security in the face of climate change.

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