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The role of crop diversity in climate change adaptation: insights from local observations to inform decision making in agriculture

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Homogenization of crop portfolios from the field to the global scale is raising concerns about agricultural adaptation to climate change. Assessing whether such trends threaten farmers' long-term adaptive capacity requires a thorough understanding of changes in their crop portfolios, identification of the drivers of change, and the implications such changes have for local nutrition and food production. We reviewed the available literature on farmers' reports of climate-driven crop changes. Small-scale farmers tend to adopt water-demanding crops, even in areas where models predict that reduced rainfall will reduce yields. The adoption of horticultural cash-crops combined with the abandonment of subsistence cereals modifies farmers' nutritional inputs in terms of calories and nutrients, potentially undermining their food security. Farmers' knowledge contributes to understand trends in crop diversity and support the design of strategies for adaptation to climate change.

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Introduction

Diversification and modification of crop species and variety portfolios are widespread strategies used by farmers to cope with environmental and socio-economic variability and to adapt to change [1] including climate change [2]. Despite the significance of crop diversity for the ability of agroecosystems to adapt to climate change, existing public policies and development interventions provide limited support for crop diversification [3]. Rather, development policies combined with market demand over the last forty years have led to the general homogenization of crop species and varieties across regions [4•], as well as of national and global food supplies [5]. Now, in the face of climate change, crop homogenization is jeopardizing global food security [5] and weakening farmers' adaptive capacity [2]. The impacts of climate change on agriculture are expected to be particularly strong in Africa, Southeast Asia, Central America, the Pacific, and the Caribbean [6], where small-scale farmers are already facing pressure due to increasing market globalization, urbanization, and population shifts, all of which impact farmers' crop portfolios [7–9] and household nutrition [10].

Several studies report a global reduction in crop diversity [4•,5], but a thorough understanding is needed of how changes in farmers' crop portfolios are linked to global trends and of the combined effects of climatic and socio-economic factors on these changes. Understanding changes in farmers' crop portfolios, the interplay between climate and other drivers of change, and the implications for farmers' food security, nutrition, and income is crucial to inform agricultural decision making, particularly to design viable strategies for long-term adaptation in a rapidly changing world.

Local knowledge is a relatively untapped source of information on the impacts of climate change on local communities and their adaptation strategies [11•]. Here, drawing on farmers' reports of observed changes in crop abundance and/or diversity at the level of the species or variety, we describe patterns of climate-related changes in crop diversity and the potential impacts of such changes on farmer's nutrition. Finally, we discuss how studies on local farmers' knowledge contribute to crop diversity research and agricultural decision-making in the face of climate change.

Methods

We searched scientific literature databases covering the semantic fields of local knowledge and observations, crops, and climate change. We selected 95 articles published in English up to and including 2019, that documented changes in crop diversity reported by farmers and explicitly linked to medium-term to long-term climate change (see SI 1 for details). For each reported change, we (i) recorded the geographical location, the corresponding climate zone according to the Köppen–Geiger classification [12,13], and the predominant farming system (i.e. small-scale or large-scale system) in the area concerned, (ii) coded the trajectory of change at the species or variety level as 'an increase in abundance or adoption' (hereafter 'adoption') or 'a decrease in abundance or abandonment' (hereafter 'abandonment'), (iii) coded climate-related drivers of crop changes based on a classification proposed by [14], and (iv) recorded additional non-climate related drivers of crop change, classifying them in economic, ecological, institutional, and socio-cultural categories.

We then classified the documented crops in eight categories: cereals, legumes, tubers, horticultural crops, oilseed, fruit and nuts, service crops (e.g. shade trees), and others (e.g. spices, fodder, and fibers; see SI 2 for details). We calculated the most frequent trajectories of change in each crop category and species and the distribution of perceived drivers of change. Finally, to explore the potential nutritional impacts of the documented crop changes (in terms of total energy, macronutrients and micronutrients [see SI 1 for the complete list]), we performed two-way ANOVA to compare the nutritional values of adopted and abandoned crop species, using the crop-specific USDA Food and Nutrient database for raw crops [15].

Results

Geographic and climatic distribution of observations

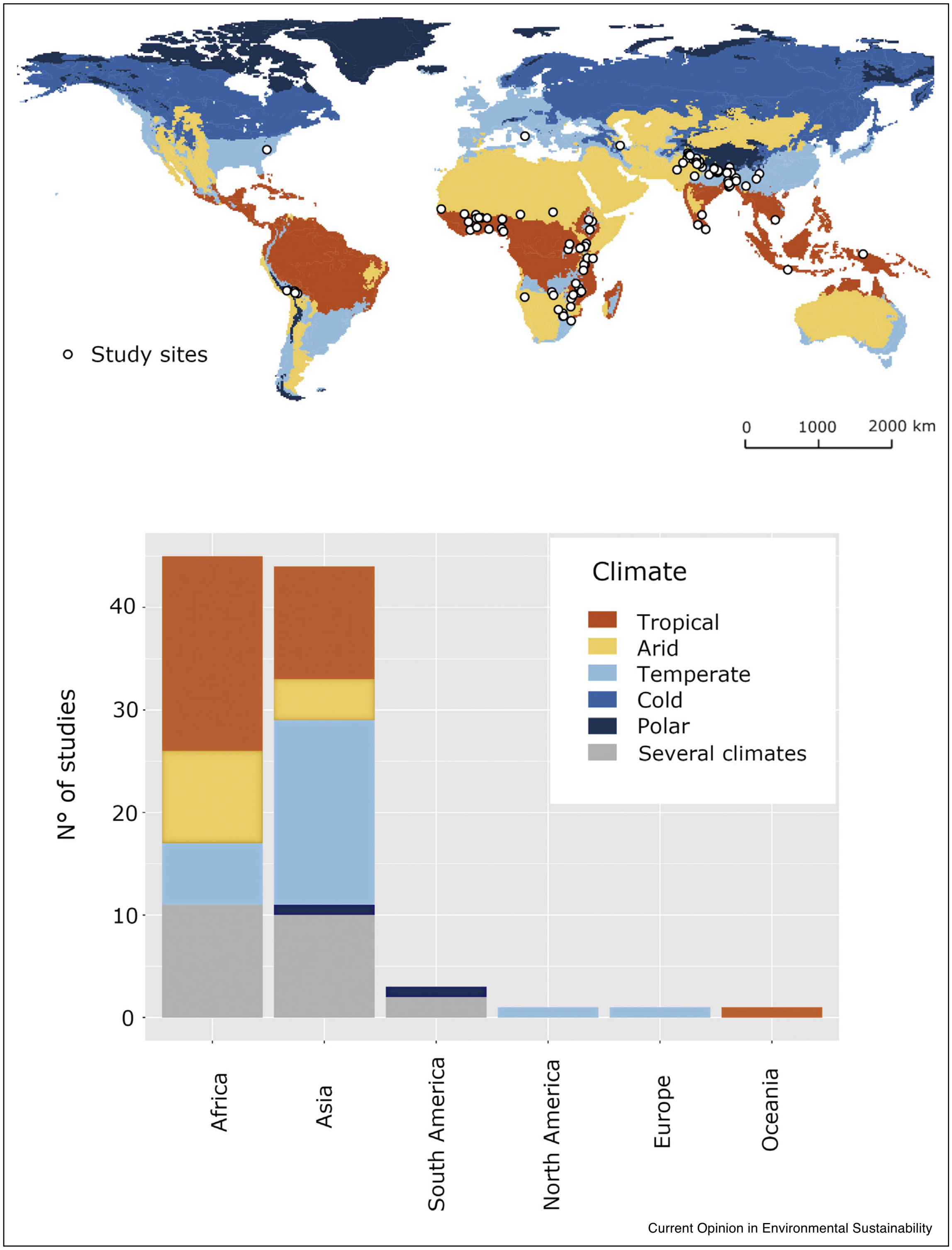
The 95 studies reporting farmers' observations of climate-related changes in crops we reviewed were conducted in 34 countries, 87% of which were in small-scale farming systems. Only 14% of the studies focused specifically on the impacts of climate change on crops, while the majority (86%) mentioned impacts on crops among other elements affected by climate change (e.g. water availability, natural ecosystems, forests). Our results reveal very uneven geographic and climatic distribution of research aimed at documenting climate-related local observations of changes in crops (Figure 1). Forty-seven percent of the studies were conducted in 20 African countries and 46 in 10 countries in Asia. Europe, North America, Oceania, and Latin America were poorly represented (7%, 4 countries). Furthermore, studies were clustered in specific areas, especially in Southern Asia, where most studies focused on India and Nepal, and in southern, eastern, and western Africa. In terms of climate zones, 33% of the studies were conducted in tropical climates, 27% in temperate climates, and 14% in arid climates, and only two studies in polar climates, where agriculture is a minor activity. Twenty-four percent (n = 23) of the studies reported data from more than one site located in different climate zones.

From local to global patterns of changes in crop diversity

Out of 428 observations of changes in crop abundance, reports of adoption of species (54%) and varieties (18%) in response to climate change were more common than reports of abandonment of species (23%) or of varieties (5%). Overall, we found reports of changes in the abundance of 113 different species, although 16 species (6 horticultural, 5 cereal, 3 tuber, 1 oilseed, and 1 fruit species) accounted for half the observations that mentioned changes in species.

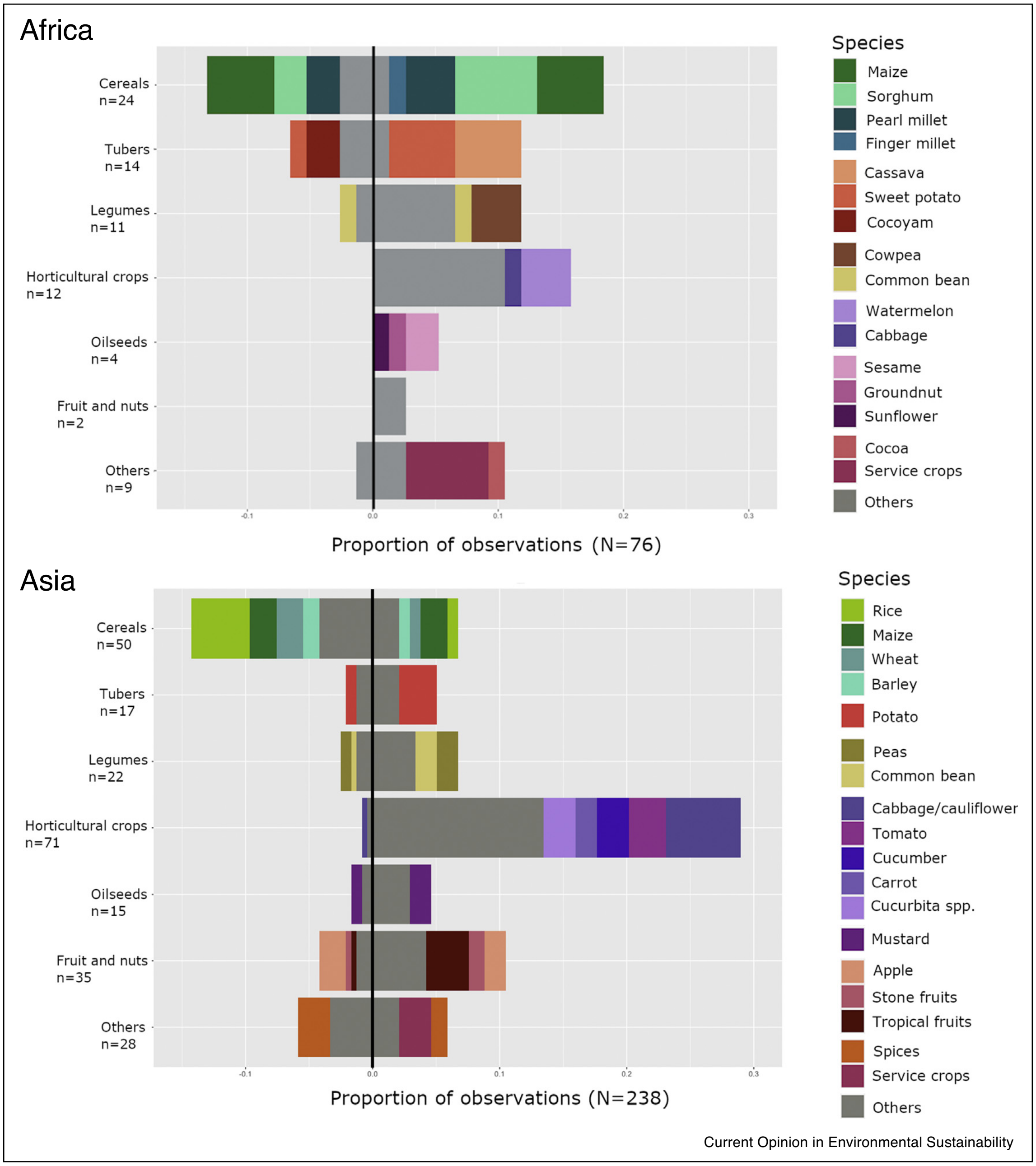
At the species level, 38% of the reports of species adoption (n = 231) referred to horticultural crops, followed by cereals (14%), legumes (12%) and fruit and nuts (12%). Most reports of species abandonment (n = 97) referred to cereals (47%). While studies in Africa reported more cereal adoption than abandonment, the opposite was observed in Asia (Figure 2). In Africa, both species abandonment (56%) and adoption (24%) mainly concerned cereals (especially sorghum, maize and pearl millet). Horticultural crops (especially watermelon) also represented a large share of species adoption in Africa (21%), followed by tubers (16%, mainly cassava and sweet

Figure 1



Top: Geographic and climatic distribution of the case studies analyzed. Bottom: Number of studies per continent and climate zone according to the Köppen–Geiger classification [12,13].

Figure 2



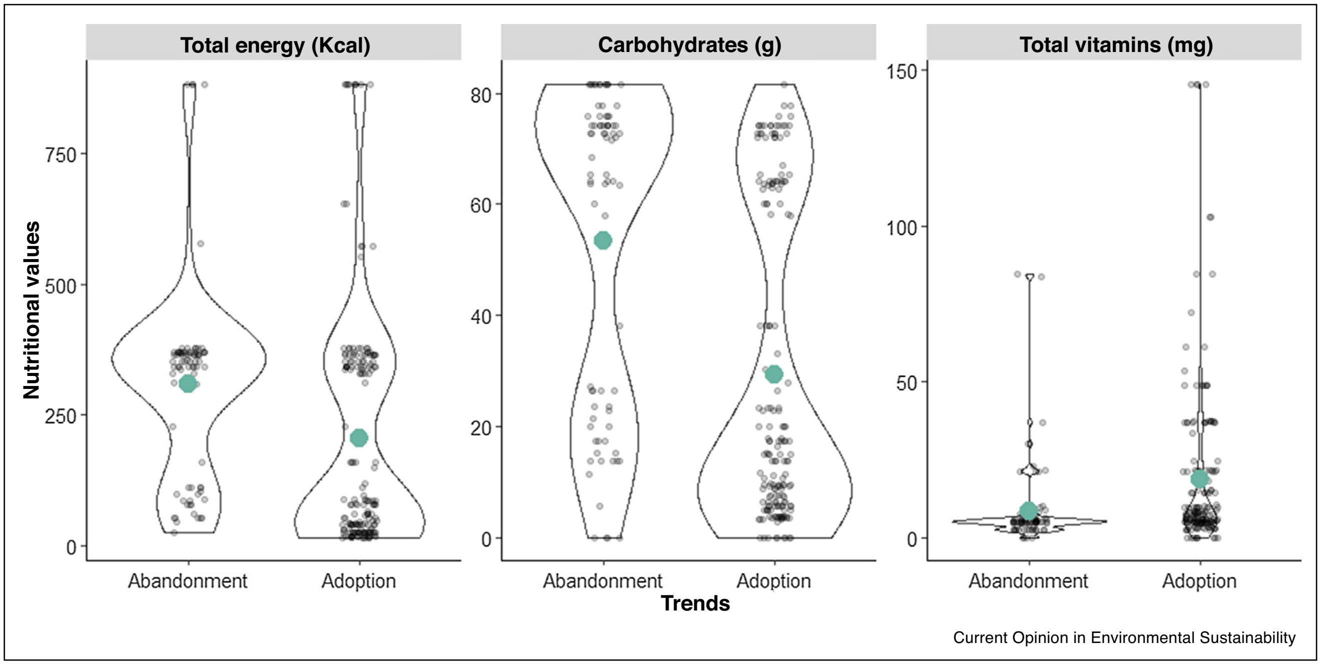
Relative proportion of crop species adopted (right) and abandoned (left) per continent. The x axis shows the number of observations of change in a given species out of the total number of observations for that continent. The main species are displayed in color (i.e. representing more than 3% of the observations at the continent level) and the remaining species are grouped as ‘others’.

potato), and legumes (16 %, especially cowpea). In Asia, abandonment mainly concerned cereals (45%, mainly rice, wheat and maize), and adoption mainly concerned horticultural crops (43%, mainly tomato, cabbage and cauliflower).

The crops that have been adopted have, on average, fewer calories ($F = 12.1$; $P = 0.001$) and carbohydrates ($F = 39.4$; $P < 0.001$) and higher total vitamin ($F = 9.8$; $P = 0.02$) contents than crops that have been abandoned (Figure 3, see SI 3 for details).

At the infraspecific level, 150 observations reporting changes in the abundance of varieties were found in 66 studies. More adoptions (79%) than abandonment (21%) of varieties were reported. Cereals were the most

Figure 3



Caloric and nutritional content of abandoned crop species (left) and adopted species (right). The violin plot and the dots show the distribution of the crop-specific caloric values, macronutrients, total vitamin and mineral contents, while the green dots represent the average value per trend of crop change.

frequently reported category (65% of adoptions and 58% of abandonments). The adoption of varieties mainly concerned rice in Asia and maize in Africa. Most of the varieties that were adopted were modern varieties (74% of the observations), whereas most of the varieties that were abandoned were landraces, that is, local 'heirloom' varieties (74%).

The relative role of climate change as a driver of changes in farmers' crop portfolios

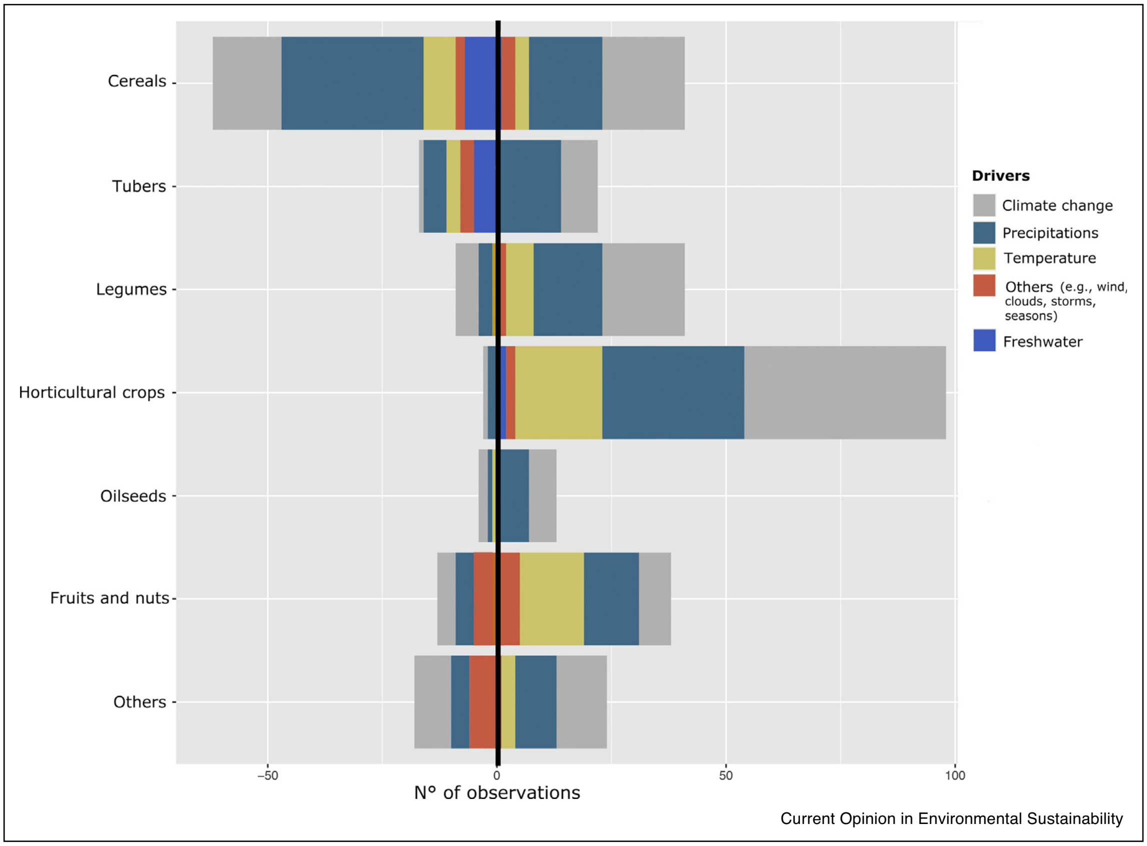
The literature refers to climate change as a driver of changes in crop portfolios both in broad and specific terms. In 43% (n = 185) of all the observations, researchers broadly reported that farmers attribute changes in their crop portfolio to 'climate change' (Figure 4). Among the observations in which climate was mentioned as a specific driver (n = 251), changes in precipitation, particularly increased variability, was the most frequently cited climate driver, and appeared in 86% of the reports. Changes in precipitation itself (mean and variability) were reported to drive 36% of the cases in which horticultural crops were adopted, 67% of the cases in which cereals were abandoned, and 50% of the adoption of cereals. Changing temperatures were also reported to drive the adoption of horticultural crops (22%). Cascading effects of climate changes affecting freshwater availability were only reported as a driver in 5% of the observations of changes in crop portfolios reported.

While our search focused on the role of climate as a driver of changes in crop portfolios, we noted that climate change was often interlinked with other important drivers of change, sometimes acting in synergetic and sometimes in antagonistic ways. Thus, 32% (n = 139) of the reports of changes in crop portfolios were also associated with non-climatic drivers. Economic drivers (55%), and particularly increased access to market opportunities, were the most frequently cited co-drivers of changes in crop portfolios. For example, farmers reported that adopting cash crops (e.g. vegetables) helped offset the lower yields of food crops (e.g. cereals), with the pressure of the two drivers acting to change cropping systems (see SI 4 for further details). Some studies also reported that farmers mentioned other environmental changes, such as declining soil fertility and increasing cases of disease, increasing damage caused by pests or predators as co-drivers of changes in crop portfolios (32%). In a few cases (8%) development programs or NGO projects were also mentioned as drivers of changes in crop portfolios.

Discussion

Our findings suggest that farmers' observations are a valuable source of information on climate-related

Figure 4



Share of observations of changes in crop portfolios at the species level per crop category and climate-related indicators of change. The x axis represents the number of observations of change in crop species associated with each category of climate-related drivers. Positive and negative values along the x axis indicate crop adoption and abandonment, respectively.

changes in local crop diversity. However, to understand global trends, research should aim to fill two important gaps, namely the strong geographical clustering of studies and the strong focus on small-scale farming systems. Our review showed that available literature is focused on a small number of regions in Asia and Africa where climate change is particularly obvious (e.g. in the Himalayas), and that research on farmers' knowledge is circumstantial in regions where large-scale farming predominates (e.g. Europe, USA, Australia). Further, our results suggest that in some regions (e.g. Latin America or North Africa), studies focused on local knowledge are probably published in other languages than English. The body of knowledge on climate-related changes in crop diversity would benefit from including areas that are particularly threatened by climate change and where a drastic decrease in crop yield is expected [16] (including arid regions: the Sahel, North Africa and the Middle East), and those where climate change may open up new farming opportunities (Northern Europe) [17,18].

Our results also suggest that an approach based on farmers' knowledge could provide a complementary perspective to current agricultural research on adaptation to climate change in two important ways. First, current research largely neglects the Southern Hemisphere [19,20]. Second, our review reports on changes to a wide range of crop species, including neglected ones, that is, species that have been the subject of less research despite their potential for adaptation to climate change [21]. Further study of farmers' knowledge would complement the limited scope of current agricultural research on the impacts of climate change that is focused on a small number of crops, maize, wheat, rice and soy [19].

The patterns of changes in crop portfolios reviewed here raise concerns for small-scale farmers' capacity for adaptation to climate change in the long term. We documented the adoption of water-demanding crops (e.g. maize, tomato, watermelon), even in areas where models based on IPCC scenarios predict a decrease in their yield, driven by reduced rainfall [22]. This is particularly the case in

Africa [6,23]. The high proportion of reports on non-climate drivers of crop change (i.e. market incentives, development programs) in our search (that itself focused on climate change) suggests that other factors also drive shifts in crop portfolios. In particular, several articles reported that farmers consider the adoption of high-value cash crops, mainly irrigated horticultural crops, as an opportunity to cope with the impacts of climate change on rainfed food crops (e.g. Refs. [24,25]). Strategies to cope with the impacts of climate change are supported by technological improvements in local agricultural systems (e.g. access to irrigation) and better access to markets. However, they may also threaten farmers' adaptive capacity in the long term, as opportunities to cultivate more water-demanding and high-market value crops are likely to shrink under future climatic conditions [26,27•].

Our review revealed that species' adoption concerns a wide range of crop species and categories (i.e. horticultural crops, tubers, legumes). However, these results call for further investigation to assess if changes to local crop portfolios would lead to homogenization at the regional or global scale that would also pose a threat to the resilience of food systems [4•,5]. Furthermore, despite this apparent gain in diversity at the species level, we also noted that most of the crops that are adopted are modern varieties and that abandoned crops are local landraces. This trend could reduce intraspecific diversity and shrink the diversity reservoir that is critical for adaptation to climate change [28].

The cropping trends we identified also raise concerns for food security. The crop species that have been adopted (i.e. fruit and vegetables) have lower energy and carbohydrate contents than abandoned crop species (i.e. cereals), but are richer in vitamins that are essential for human health. On the other hand, the fruit and vegetables that are being adopted are often geared towards markets, and these new sources of vitamins may not necessarily benefit smallholders' nutrition [29•]. Conversely, the decline in the cultivation of staple cereals, widely reported for major African cereals like millet or sorghum, could increase farmers' food and nutrition insecurity by increasing their dependence on imported crops (e.g. rice) of low nutritional quality [30] and that are also subject to market fluctuations [31]. The benefits of commercial horticulture and associated global food trade for smallholder remains highly controversial, and is strongly scale-dependent and context-based [32–34].

Our review identified important issues for agricultural decision making, especially for development initiatives aimed at strengthening the capacity of small-scale farmers to adapt to climate change. Rural development actors including national and international development agencies and NGOs promote the development of horticulture in small-scale agriculture (e.g. Ref. [35]), but we argue that such recommendations should not be made without prior evaluation of their medium to long term consequences for small-scale farmers food security and adaptive capacity. The dramatic expansion of horticulture is already causing groundwater depletion in some places (e.g. Ref. [36]). Rural development actors should consider supporting agricultural water uses that are suited to predicted climate change, and need to be sure that expanding commercial horticulture will benefit smallholders' livelihoods without jeopardizing their capacity to adapt in the long term.

Conclusion

Farmers across the world are reacting to the combined effects of climate and non-climate drivers of change by adjusting their crop portfolios. While such adjustments involve both the adoption and the abandonment of certain crops or landraces, we identified a general trend involving the adoption of water-demanding horticultural crops with little energy content. We argue that this trend may threatens the resilience of local cultivation systems and livelihoods. Our review calls for coordinated interdisciplinary research to fill methodological and geographical gaps that currently limit a thorough understanding of farmers' responses to climate change [37]. Such collective efforts are urgent, and could represent a unique opportunity to monitor the dynamics of underresearched crops and trends in regions where long-term research is a challenge. Information concerning climate-related changes in crop diversity at the local scale and their co-drivers could help reorient agricultural policies and development programs toward long-term adaptation to climate change.

Conflict of interest statement

Nothing declared.

CRediT authorship contribution statement

Vanesse Labeyrie: Conceptualization, Funding acquisition, Data curation, Methodology, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Delphine Renard:** Conceptualization, Funding acquisition, Data curation, Methodology, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Yildiz Aumeeruddy-Thomas:** Methodology, Writing - review & editing. **Petra Benyei:** Data curation, Methodology, Writing - review & editing. **Sophie Caillon:** Methodology, Writing - review & editing. **Laura Calvet-Mir:** Data curation, Methodology, Writing - review & editing. **Stéphanie M. Carrière:** Methodology, Writing - review & editing. **Marilou Demongeot:** Data curation, Methodology, Formal analysis, Writing - review & editing. **Elsa Descamps:** Data curation, Methodology, Formal analysis, Writing - review & editing. **André Braga Junqueira:** Data curation, Methodology, Writing - review & editing. **Xiaoyue Li:** Data curation, Methodology, Writing - review & editing. **Jonathan Locqueville:** Data curation, Methodology, Writing - review & editing. **Giulia Mattalia:** Data curation, Methodology, Writing - review & editing. **Sara Miñarro:** Data curation, Methodology, Writing - review & editing. **Antoine Morel:** Data curation, Methodology, Formal analysis, Writing - review & editing. **Anna Porcuna-Ferrer:** Data curation, Methodology, Writing - review & editing. **Anna Schlingmann:** Data curation, Methodology, Writing - review & editing. **Julia Vieira da Cunha Avila:** Data curation, Methodology, Writing - review & editing. **Victoria Reyes-García:** Conceptualization, Funding acquisition, Methodology, Writing - original draft, Writing - review & editing.

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.cosust.2021.01.006.

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This meta-analysis revealed that only 20% of studies reviewed showed a consistent positive association between farm-level production diversity and household and individual level dietary diversity. This study interestingly questions the assumption that farm diversification is an effective strategy to improve diets and nutrition for smallholder farmers.

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