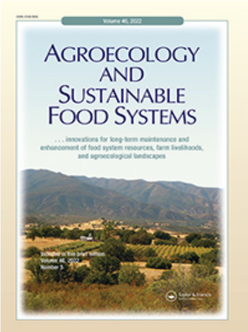

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REVIEW

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Does crop diversification lead to climate-related resilience? Improving the theory through insights on practice

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ABSTRACT

In recent years, CGIAR researchers have investigated the effectiveness of using agrobiodiversity, and more particularly crop and crop varietal diversity, as an adaptive practice to mitigate climate-change impacts on agriculture and to contribute to rural household and community resilience. The hypothesis informing this research is that the sustained practice of crop diversification leads to ecological redundancy, which allows farmer households and their communities to produce multiple positive livelihood benefits. The validity of this hypothesis is investigated by means of an extensive literature review (covering 2015–2020). Findings reveal ample evidence of positive outcomes, including increased yields and household incomes, improved nutrition and food security, new marketing opportunities, reduced poverty, and strengthened adaptive and innovative capacity. However, the evidence is far less convincing about the last part of the hypothetical impact pathway, i.e. the link between positive livelihood benefits and (increased) resilience. This shortcoming is addressed through the elaboration of a more clearly articulated theory of change for crop diversification and a refined methodology to support farmers in making appropriate diversification decisions. At the same time, the critical review opens a window on an important, novel perspective, which is to look at the role that crop diversification could play in a wider societal transition toward a more sustainable future.

KEYWORDS
Adaptation; crop diversification; impact pathway; resilience; transition

Introduction

In recent years, Bioversity International (now the Alliance of Bioversity International and CIAT) and partners have researched the effectiveness of using agrobiodiversity, in particular in the form of crop and crop variety diversity, as an adaptive practice to mitigate/attenuate the impacts of climate change on agriculture and to contribute to rural household and community resilience. The hypothesis underpinning this research is that crop diversification can result in positive livelihood outcomes, such as food and nutritional security, income generation and better health. These outcomes, in turn, could

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lead to the (increased) resilience of rural households and communities with regard to environmental, socio-economic and climatic shocks. In this article, we test the validity of this hypothesis. Does crop diversification deliver resilience? The key questions are whether practical experience and evidence support it or not; and what effective impact pathways for crop diversification look like. This article looks for answers to these questions by means of a systematic review of the most recent literature on crop diversification.

The literature review was conducted in 2020 using the Web of Science database, with *crop diversif* as the key search term. The search covered the period 2015–2020 in order to document and analyze the more recent developments and new insights on the subject, with the assumption that some of the newer research likely would synthesize previous research dating farther back in time (this proved to be the case). Articles used focused and clearly reported on the outcomes of crop diversification strategies and practices. We discarded articles that focused on the determinants of (non)adoption of crop diversification without paying detailed attention to the actual outcomes.

Following this brief introduction, Section 2 first presents a synopsis of the theory (conceptual framework) that informs the crop diversification hypothesis, largely based on insights from agroecology. In conducting action-oriented research, the Alliance of Bioversity International and CIAT teams experiment with this framework. This is followed by both positive and negative practical evidence, drawing attention to conceptual and methodological challenges. Section 3 discusses the findings and implications by suggesting a way forward, using the evidence presented in Section 2 to propose key elements for a more clearly-articulated theory of change for increased use of crop diversity and a related stepwise methodology to support farmers in making appropriate diversification decisions. At the same time, the review opens our eyes to another important perspective, which is to look at the role of crop diversification in a wider societal transition toward a more sustainable future. Section 4 concludes.

Materials and methods

The theory of diversification

Based on insights from agroecology (e.g. Altieri et al., 2015; Attwood et al. 2017; Folke et al. 2010; Frison, Cherfas, and Hodgkin 2011; IPBES 2019), diversity among and within species provides insurance or a buffer against environmental fluctuations, because different species and varieties occupy different niches and respond differently to change. If one species fails, another or others can nonetheless play its/their role, leading to more predictable aggregate community responses or ecosystem properties. When species outnumber functions, redundancy emerges in an agroecosystem, which facilitates ecosystem functioning and the provisioning of ecosystem services (Hajjar, Jarvis, and Gemmill-Herren 2008; Lin 2011). Species diversity therefore acts as a buffer against crop failure and agrobiodiversity fosters ecological resilience (Schroff and Ramos Cortés 2020).

From these theoretical insights, the hypothesis is that crop diversification – the cultivation of different crop species and/or varieties spatially (mixed land use, intercropping) or temporally (rotations in different seasons) – can maintain stability in food production (thus contributing to food security), contribute to dietary diversity and income generation, and reduce risks from climate variability, diseases, pests, and market changes. Farmers can practice crop diversification at the household level. However, some authors have hypothesized that farmers can strengthen their capacity to access and use "new" species and varieties, e.g. obtained from communities that have successfully adapted local varieties to new climate stresses through (participatory) variety selection, more effectively through community-based approaches. These include community-based biodiversity management by farmer groups (such as Farmer Field Schools, seed savers, women self-help groups), cooperatives, and community seed banks, local seed businesses. This will build on and strengthen the many forms of traditional agricultural diversity management practices that farmers have used around the world for centuries (De Boef et al. 2013). Applying these insights at the farming system level, diversifying adaptation strategies through combining activities of different types could be effective in dealing with the increasing number of unpredictable extreme weather conditions in many parts of the world (Chen et al. 2018). Households can use such strategies to manage risk and reduce their vulnerability (Ortiz 2011).

While the practice of on-farm crop diversity is most often associated with risk-coping strategies, Bellon et al. (2019) sustain that it also offers other potential benefits, particularly in regions where markets function poorly. These benefits could include: optimal crop production under difficult growing conditions; a larger portfolio of goods for different uses; new marketing avenues; increased consumption of self-produced crops with higher nutritional content, quality, and cultural significance; and poverty reduction. Crop diversification could also improve the management of other natural resources, such as (irrigation) water (Watson 2019), through the smart use of crop combinations that, together, are less water demanding. Other researchers identified another, more indirect benefit: agrobiodiversity can also provide the basic material for experimentation and innovation in the face of climate change (UNU-IAS et al., 2014), e.g. for crop improvement experiments. Learning how to experiment with this basic material can be a key element in the process toward strengthening adaptive capacity.

Having summarized the key theoretical principles, the following section provides an overview of the main evidence found to answer the key review questions.

Results (part 1): positive evidence

A number of recent meta-analyses, such as Mijatović et al. (2012), provides positive evidence, on the multiple roles of agrobiodiversity managed by traditional communities, and Tamburini et al. (2020) on the impact of agrobiodiversity on ecosystem services. Beillouin, Ben-Ari, and Makowski (2019) mapped the impact of various crop/tree diversification strategies around the world by means of a meta-analysis of 99 meta-analyses (covering more than 3700 field experiments). Despite observed shortcomings in many of the meta-analyses, the authors report largely positive outcomes of the seven diversification strategies analyzed, for: agroforestry, associated plant species, cultivar mixture, intercropping, landscape heterogeneity, and crop rotation. The study revealed that crop diversification has, to a large extent, produced good results in terms of production (increased yields) and environment (increased associated biodiversity), particularly in rice, maize and wheat cropping systems, which represent 34% of the species mentioned in the 3700 experimental studies. Combining several strategies, e.g. crop rotation with associated plants, appears to further improve performance (echoing Mijatovic et al. 2012). However, outcomes are site-specific and depend on the original level of diversity and on local climate and soil conditions (ibid: 7–8).

Another meta-analysis(Raseduzzaman and Jensen, 2017), of the effects of intercropping (one of the most common crop diversification practices) on yield stability, also found strong evidence of the multiple benefits of this diversification strategy – beyond yield stability. This study confirmed that intercropping reduces the risk of complete crop failure, can improve the diversity of small-scale farmers' diets and contribute to their food security, as well as support the adaptation of crop production to climate change. The study also concludes that another common practice, crop rotation, a form of temporal intercropping, has the ability to enhance soil fertility and water-use efficiency. A third practice, mixing different varieties of the same crop in a field, can help decrease pest and disease pressure on crops and result in better yield in space and over time. Research led by the Alliance of Bioversity International and CIAT has demonstrated this, for example, for common bean in Uganda (Nankya et al. 2017).

The benefits of these practices can build up and extend over a long time horizon. Based on 31 years of research in Ontario, Canada, Gaudin et al. (2015) report good results and less risk of crop failure. In hot and dry years, the combined practices of maize-soybean rotation and reduced tillage increased yield by 7% and 22% for maize and soybean, respectively, increasing farm income and, according to the authors, most likely contributing to more farm-level resilience.

Several other studies provide ample evidence about the effective use of agricultural biodiversity contributing to positive livelihood outcomes, through a number of strategies that could be implemented in any combination. These include the protection and restoration of ecosystems, sustainable use of soil and water resources, agroforestry, diversification of farming systems, various adjustments in cultivation practices, and the use of stress-tolerant crops/varieties and (participatory) crop improvement (Dwivedi et al. 2017; Gaudin et al. 2015; Hansen et al. 2019; Tanner et al. 2015; Waha et al. 2018).

Diversity of traditional crop varieties in a production system can play a key role, enabling a farmer's crop population to better evolve and adapt to changing environmental and economic conditions. Widening the genetic base of the crop population is a very effective strategy for this (Jarvis et al. 2011). This kind of diversity can also provide ecosystem services, e.g. regulation and control of pests and diseases, maintenance of soil health, sustenance of pollinator diversity, and support of below-ground biodiversity. These benefits could reduce the financial, environmental and personal health risks that usually result from a high level of (externally-sourced) agricultural inputs. The authors contend that this kind of diversity is crucial for achieving global food security. This strategy can be successful for many crops, including major food crops. Some examples of the latter are given in the next paragraph.

In Burkina Faso, Nelimor et al. (2019) carried out research on maize landraces over several cycles to evaluate their adaptation to local conditions. The recurring selection process of the best performing ones led to a portfolio of varieties with rich genetic diversity and the capacity to cope with pests and diseases, and tolerate abiotic stresses (drought and/or high temperatures). The authors argue that the availability of such genetic diversity is critical for multiple genetic improvements, including nutritional quality and genetic base broadening. Another example of the potential effective use of land races and related wild relatives comes from the Mediterranean basin where breeders successfully identified a series of promising local durum and bread wheat cultivars capable of increasing variety adaptation to climate-change induced stresses (Abu-Zaitoun et al. 2018).

Traditional varieties can include so-called orphan crops, nearly abandoned, or neglected varieties, e.g. vegetables. Mabhaudhi et al. (2019) found that, as a result of generations of landrace cultivation, several orphan crops are nutritious, resilient and adapted to very specific marginal agricultural environments. They argued for increased integration of orphan crops in monocultural cropping systems, among other reasons, to reduce greenhouse gas (GHG) emissions along the value chain. In their study about wheat varieties and organic agriculture in Europe, Béné (2020) found that both registered varieties of ancient wheat species and their landraces can provide sustainable alternatives for organic farmers and for the diversification of agriculture. Research conducted in Mali on the conservation, sustainable use and value chain development of a number of neglected and underutilized crops (Bambara groundnut, fonio, jute mallow, leaf amaranth), based on a climate-change-focused community biodiversity management approach, reported significant productivity and income generation gains, while restoring and strengthening the contributions of agrobiodiversity in rural livelihoods (Meldrum, Sidibe, and Padulosì 2020).

Country studies

Many country studies have reported positive crop diversification outcomes. Some examples from Africa are the following. A study based on data gathered on 500 rural households from Zimbabwe found positive impact of crop diversification on legume and cereal crop productivity and enhanced resilience measured by household income, food security, and nutrition (Makate et al. 2016). Results from Malawi indicate that farmers who practice crop diversification are more likely to have a diverse diet and better capable of pursuing food security. Producing more than one crop produces benefits, such as more stable food supplies and income (Mango et al. 2018). FAO (2016) reported similar results from Zambia. Research conducted in Kenya found that diversification increases the number of potential crops that can be sold and improves agroecosystem functioning through more system redundancy. It also stimulates farmer innovation in the face of climate variability (McCord et al. 2015).

In Uganda, Tesfaye and Tirivayi (2020) showed that crop diversification improves household welfare by means of diet diversity and reduced consumption expenditures. This benefits in particular households that have a low level of consumption. According to the authors, this finding suggests that crop diversification could be a pro-poor (policy) strategy. Another study conducted in Uganda on banana-based production systems (Kozicka et al., 2020), found that banana-based systems can be enriched by intercropping other crops, which can increase adaptive capacity in the face of climate change or banana disease outbreaks. The ultimate result, according to the authors, is increased farm resilience. In Ethiopia, Michler and Josephson (2017) found that households that produce a basket of diverse crops are less likely to be poor than those that practice crop specialization; that crop diversity reduces the probabilities that a non-poor household will become poor and a poor household will remain in poverty. This led the authors to recommend that the country's policies be directed toward encouraging and increasing household-level crop diversity, instead of promoting crop specialization (e.g. in cash crops such as coffee, sesame or Chat).

A practice known as the "doubled-up" legumes system is based on intercropping of grain legumes with pigeon pea (*Cajanus cajan*) to increase the total legume yield per unit area. Chikowo, Snapp, and Vanlauwe (2020) argue that this diversification practice is particularly useful for marginal smallholders, who have limited access to land and usually practice cereal monocropping (most often, maize). Doubling-up legumes allows to overcome this constraint, rehabilitate fields with poor soil fertility and reduce soil erosion (usually, pigeon pea remains in the field for 6–8 months depending on the variety used). This technology has been piloted with Malawian smallholders on 0.5–2 ha of land. Another study involving 425 smallholder households in Malawi, showed that farmers who employed agroecological practices, including intercropping, legume diversification, composting, and application of manure and crop residues, improved their food security. Moreover, the use of organic soil amendments was associated with gains in dietary diversity. Results also indicated that spousal discussion about how to practice agroecological farming was strongly associated with increased household food security and dietary diversity. This research demonstrates how agroecological approaches can rapidly improve food security and dietary diversity, even under conditions of acute forms of stress (Bezner Kerr et al. 2019).

There are also examples from Asia. Vernooy and Vongkhamsao (2015) reviewed evidence from South-east Asia and found positive outcomes in Cambodia, Lao PDR and Vietnam. In Cambodia, farmers who gained knowledge and skills about crop production techniques, integrated farming systems (including crop rotation and intercropping), and climate-resilient production techniques, succeeded in improving agricultural production (notably of vegetables) and household income, leading to enhanced food security. Farmer household income also increased from selling agricultural products. In Lao PDR, the diversification of home gardens contributed to improved food security and income generation and more resilient rural livelihoods. In Vietnam, crop diversification was part of a broader development strategy that also included securing long-term and stable land-use rights, and encouraging investments to increase production and ensure food security.

Lal et al. (2017) demonstrated that, in India, crop and varietal diversification of the rice-based cropping systems, when applied in the right cropping season and under favorable conditions, can significantly improve the productivity and profitability of the systems. Aggarwal et al. (2018) identified seed/breed-smart options (adapted varieties and breeds, seed banks, including community-based activities) as one of the components of the climate-smart village approach developed by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Other components are weather-, water-, carbon/nutrient-, and institutional/market-smart options. In all regions of CCAFS interventions, examples of crop, tree, and animal diversification (including the introduction of improved species/varieties, e.g. more drought-, cold-, and saline-tolerant crops) were introduced and tested, at varying scales ranging from a few farmers in some sites (e.g. Vietnam and Guatemala) to larger numbers in others (e.g. Nepal, Senegal, and Uganda). In their review, the authors conclude that the different options packaged in the CCAFS portfolio approach contribute to both mitigation and resilience, but they also observe that there is still a need for greater evidence for the approach in different agroecological environments.

Between 2016 and 2018, a team of Nepali and international researchers replicated on-farm and on-station trials of different mixtures of landraces and improved varieties (compared to sole cultivars) of rice, buckwheat, bean, naked barley, and finger millet in the high Himalayan mountain districts of Dolakha, Humla, and Jumla. For the majority of traits in all these crops, the performance of mixture plots was significantly better than the monoculture treatments. Buckwheat mixtures performed well in all sites (with low levels of disease infection). The researchers concluded that mixing landraces and improved varieties can help conserve crop diversity without compromising grain yield (Joshi et al. 2020).

In another study in Nepal (Chapagain et al. 2018), researchers found that legume intercropping produced good results across seasons and locations, suggesting it is an effective practice for smallholder farming on terraces and a good alternative to mono-cropping. It improves land productivity, soil fertility management, and income generation.

Table 1 presents the main findings of this section about positive evidence.

Enabling and disabling factors

All the above examples are illustrative of the argument that crop diversification can result in multiple benefits, including increased adaptation to climate change. However while it appears that these results are usually dependent on

Table 1. Overview of the benefits of crop diversification identified in the literature review.

Benefit	Author
Enhanced soil fertility and health	Jarvis et al. 2011
Reduced pest and disease pressure	Jarvis et al. 2011; Kozicka et al., 2020
Increased associated biodiversity	Beillouin et al., 2020; Jarvis et al. 2011; Joshi et al. 2020
Increased ecological redundancy	McCord et al. 2015
Increased yield	Nankya et al. 2017; Vernooy and Vongkhamsao 2015
More marketing opportunities	McCord et al. 2015
Increased income	Beillouin, Ben-Ari, and Makowski 2019; Chapagain et al. 2018; Meldrum, Sidibe, and Padulosì 2020; Vernooy and Vongkhamsao 2015; Tesfaye and Tirivayi 2020
Increased food supply/security	Aggarwal et al. 2018; FAO, 2016; Bezner Kerr et al. 2019; Mango et al. 2018
Improved nutrition	Mabhaudhi et al. 2019; Nelimor et al. 2019
Reduced poverty	Michler and Josephson 2017
Strengthened innovation capacity	McCord et al. 2015
Increased adaptive capacity to climate change	Abu-Zaitoun et al. 2018; Aggarwal et al. 2018; Kozicka et al., 2020; Nelimor et al. 2019; Md and Jensen 2017
Reduced GHG emissions	Mabhaudhi et al. 2019; Meldrum et al. 2018
Increased resilience	Kozicka et al., 2020; Makate et al. 2016; Vernooy and Vongkhamsao 2015
Multiple and simultaneous benefits	Chikowo, Snapp, and Vanlauwe 2020; Dwivedi et al. 2017; Gaudin et al. 2015; Hansen et al. 2019; Joshi et al. 2020; Bezner Kerr et al. 2019; Lal et al. 2017; Makate et al. 2016; Meldrum, Sidibe, and Padulosì 2020; Mijatovic et al., 2012; Md and Jensen 2017; Tamburini et al. 2020; Tanner et al. 2015;Tesfaye and Tirivayi 2020; Waha et al. 2018

several or a combination of factors, including the base-line conditions in terms of crop diversity, climate, environmental conditions, and socio-economic variables (class, sex, and ethnicity). A number of studies (Asfaw et al. 2019; Ochieng et al. 2020; Tesfaye and Tirivayi 2020; Waha et al. 2018), briefly reviewed in the following paragraphs, elaborate on these factors.

Waha et al. (2018) used a multi-scale approach to explore the relationship between farming diversity and food security and the diversification potential of African agriculture. They also analyzed to what extent it could benefit households and the continent. Based on 28,000 households located in 18 African countries, the authors determined the available diversification options for farmers by analyzing the relationship between rainfall, rainfall variability, and farming diversity. On the household scale, it was found that households with greater farming diversity are better able to meet their consumption needs, but only up to a certain level of diversity per hectare of cropland, and more often if food can be purchased with off-farm income or income from farm sales. The authors concluded that more diverse farming systems can contribute to household food security. However, they observed that the relationship is influenced by other factors, e.g. household market orientation, livestock ownership, non-agricultural employment opportunities, and available land resources. The authors observed that, on the continental scale, the greatest opportunities for diversification of food crops, cash crops, and livestock are located in areas with 500-1000 mm annual rainfall and 17-22% rainfall variability. Forty-three percent of the African cropland currently lacks these opportunities – a major bottleneck.

A recent study covering Malawi, Niger, and Zambia (Asfaw et al. 2019) indicated that the impact of both crop and income diversification on rural household welfare is generally higher for the poorest, while it decreases, and in some cases becomes negative, for the higher income households in the three countries. The authors conclude that diversification strategies can positively address poverty, but that tailored diversification interventions are required to achieve this. Based on a modeling study, Tesfaye and Tirivayi (2020) report similar results for Uganda.

Roesch-McNally, Arbuckle, and Tyndall (2018) contend that cropping system diversity can help build greater agroecosystem resilience by suppressing insect, weed, and disease pressures, while also mitigating effects of extreme and more variable weather. Despite these potential benefits, the authors found that few farmers in the USA Corn Belt use diverse rotations. They postulate that this is because farmers are locked into the intensive corn-based cropping system in the region, which gives little scope to change their practices. However, they did find farmers in more diversified watersheds, those farming marginal land and those with livestock, who were more likely to use extended rotations. Their findings also indicated that farmers who currently use more diverse rotations are also more likely to plan to use crop rotations as a climate-change adaptation strategy. To encourage more farmers to opt for diversity, the authors argue that policy and economic incentives that presently discourage cropping system diversity in the region must be modified.

Findings from Kenya point to the importance of site-specific climatic conditions: in areas with increased temperatures, farmers practice more crop diversification in lowlands, while increased rainfall was negatively associated with increased diversification in the lowlands and midlands. In the rainfed lowlands, with warmer climates and frequent prolonged dry spells, crop diversification makes good sense as a livelihood strategy given the increasing uncertainties caused by climate change (Ochieng et al. 2020). The authors conclude that there are good prospects for crop diversification to reduce household vulnerability in semi-arid agricultural systems, although it is challenging given the greater variability in annual precipitation they experience.

Results (part 2): challenges

The empirical evidence presented in the previous section is strong on the causal relationship between crop diversification and positive livelihood outcomes, but what is often missing is a concise elaboration on the relationship between livelihood outcomes and resilience. Several authors have made a similar point. Feliciano (2019) argued that, in theory, crop diversification is one of the most cost-effective ways of reducing uncertainties in farmers' income, in particular in support of those smallholder farmers most affected by poverty. Poverty, she argues, is a complex concept, which includes more dimensions than only income, namely gender equality, food security and nutrition, and vulnerability to climate change. Feliciano found that the contribution of crop diversification to poverty alleviation in all the above mentioned dimensions has not been properly researched or documented. She concludes that new research and policy impact evaluation methods are needed that follow a sustainability approach to poverty. This viewpoint is echoed by Hansen et al. (2019), who conclude that there is a lack of evidence demonstrating how the risk reduction benefits of the strategies used (such as crop diversification) contribute to lifting large numbers of poor farmers out of poverty, although they may have a positive impact on household welfare.

In their review of the impact of adaptation measures on resilience in Nigerian agriculture, Onyeneke et al. (2019) come to a similar conclusion and argue that additional studies are required to obtain a better understanding of how implemented measures affect the indicators that make up the three major components of resilience: buffer capacity, self-organization, and capacity for learning and adaptation.

As previously mentioned, the 2019 study by Beillouin et al. observed that, despite reporting largely positive outcomes of crop diversification strategies, the high number of strategies analyzed and the heterogeneity in the quality of the meta-analysis articles hamper a concise synthesis of the results. Thus, the authors conclude that a significant knowledge gap remains, in particular regarding the impact of the strategies on water use (and, as a result, on agricultural sustainability), farmers' income and profitability, product quality and production stability – the latter three being key components of livelihood resilience.

Others have drawn attention to the need to (more) carefully analyze farmers' conditions at baseline when designing a diversification strategy. Results from a study in Sri Lanka (Burchfield, de la Poterie, and Tozier 2018) indicate that many farmers cannot diversify because of the characteristics of their fields (elevation, soil quality, irrigation infrastructure and relative position within the irrigation system). At the same time, of the farmers identified whose fields potentially could support diversification, many were still unable to obtain positive results, due to lack of access to water, poor market access, market instability, limited government support and relatively high input costs.

Meldrum et al. (2018) found that that farmer households across study communities in the highlands of Bolivia developed a variety of diversification pathways. Some introduced and expanded the area under commercial "sweet"-tasting potatoes, while others started more commercial-oriented production of quinoa, vegetables, and dairy. The shift to commercialization is the strategy that some farmers use to adapt to warmer temperatures and new economic opportunities. However, the authors caution that this strategy based on commercial crops and varieties is more risky than the use of some traditional crops (e.g. "bitter"-tasting potatoes). The displacement of local crops and varieties leads to overall diversity loss, and, likely, less resilience.

Other conceptual and analytical shortcomings have been noted. In another major review article of 193 primary field-level agronomic studies, Hufnagel, Reckling, and Ewert (2020), observed that, although they found thousands of scientific papers on crop diversification in the field of agronomy, there seems to be no coherent theoretical concept or framework of crop diversification (what it is and how it works). Accordingly, these authors sustain that this has led to non-systematic implementation of diversification experiments worldwide and difficulty in comparing them with regard to: the problems to be solved, the baseline for comparison, the kind and number of crop diversification measures applied, and the targets (outcome or performance variables) analyzed. Concerning target variables, the study reports (ibid: 13) that about 10% of the 193 experiments reviewed focused on agronomic and or economic target variables with half of them focusing on both; 45% analyzed mainly biotic and abiotic variables with no attention paid to agronomic or economic ones. The other 45% focused on agronomic and/or economic variables and on/or biotic variables (e.g. impact on soil, water, and food webs). In brief, the review did not mention or look into variables beyond the immediate production domain. To address these shortcomings, the authors propose some first steps toward a conceptual framework on crop diversification, by means of a clear and concise definition of: (i) the problem to be solved; (ii) the baseline, particularly in terms of (crop) diversity; (iii) the scale (plot, field, or landscape); (iv) the experimental design, including a minimum set of outcome/performance variables; and (v) the actual outcomes/performance.

Earlier, Altieri et al. (2015) pointed to another conceptual shortcoming in the study of diversification. They argued that most of the research focuses on the ecological resiliency of agroecosystems, but little has been written about the social resilience of the rural communities that manage such agroecosystems; this is echoed by Beillouin, Ben-Ari, and Makowski (2019) and Hufnagel, Reckling, and Ewert (2020). They make the point that the ability of groups or communities to adapt in the face of external social, political, or environmental stresses must go hand in hand with ecological resiliency. According to the authors, to be resilient, rural societies should be able to buffer disturbance with agroecological methods adopted and disseminated through self-organization and collective action, e.g. through strong local institutions (see Ng'ang'a et al. 2016, for Ethiopia) and social networks (see Dapilah, Østergaard Nielsen, and Friis 2019, for Ghana), both locally and at regional scales. Córdoba Vargas, Hortúa Romero, and León Sicard (2019) build on this argument by highlighting the political dimension of resilience. Thus, resilience requires simultaneous and mutually reinforcing solid natural and social (political) capital.

Recent research by Reynolds et al. (2020) on the dynamics of household crop selection strategies draws attention to another analytical shortcoming of many crop diversification studies, i.e. the lack of understanding the role played by gender dynamics. Based on research in East Africa, the authors observe that there are significant gendered differences in crop choices and resource access across multiple contexts in sub-Saharan Africa (see also FAO 2016, for a study on Zambia reporting marked differentiated benefits of crop diversification accrued by female-headed households when compared to male-headed ones). They found that male-headed households have greater access to land for crop cultivation and opt more for income-oriented crops more than female-headed households. While increased market opportunities could be seen as a key element of resilience, the authors argue that that the gender dynamics, which occur as rural agrarian communities shift their focus from crops for home consumption to more market sales, must be carefully monitored.

Another recent study about gender and agricultural development in Bangladesh (De Pinto et al. 2020), explored whether women's empowerment, measured by using the Women's Empowerment in Agriculture Index (WEAI), can lead to increased diversification in the use of farmland. The results show that some aspects of women's empowerment in agriculture, but not all, are conducive to more diversification and a shift from cereal production to other crops, such as vegetables and fruits. The authors conclude that a well-designed gender-sensitive crop diversity strategy can mitigate risks and improve nutrition.

Studies do pay some attention to the roles of policy (change) and crop diversification and agrobiodiversity (e.g. Bedmar Villanueva, Halewood, and López-Noriega 2015), but perhaps not to the degree hoped for. In a global review of farmers' perceptions of agricultural risks and risk management strategies, Duong et al. (2019) found, that there is a serious lack of institutional support by governments to rural communities and households in managing agricultural risks in both developing and developed countries. Asfaw, Pallante, and Palma (2018) observed this in Niger, where rural Nigerien communities have developed autonomous adaptation responses through self-organization, which could benefit from government support, e.g. to strengthen network infrastructures and promote local crop varieties, which in turn could trigger livelihood diversification. Di Falco, Bezabih, and Yesuf (2010) drew attention to the importance of revising crop-related policies, which may help to foster in-situ conservation of resources, the basis for crop diversification. Often, policies that appear well formulated lack appropriate instruments/ mechanisms to support their implementation and enforcement, e.g. national subsidies are offered for major food crops – such as maize – yet are overlooked for other crops that would support diversification, in addition to livelihood and nutrition outcomes. In a detailed policy study of the food economy of Nakuru, Kenya, researchers found that current policy implementation contributes to an overall food system bias against the production, distribution, and consumption of indigenous vegetables (Rampa and Knaepen 2019). So far, very few countries have developed agrobiodiversity policies in which crop diversification is mentioned. Nepal is one of them. Its *Agrobiodiversity Policy* links conservation, characterization, and sustainable use of biological diversity with climate change adaptation, acknowledging that it will be necessary to strengthen ties between farming communities, the national agricultural research system, the national genebank, and community seed banks in order to boost adaptation.

Table 2 presents the main articles about specific challenges from which findings informing this section were drawn.

Discussion

Plusses and minuses

This review of the strengths and weaknesses of crop diversification (and the body of research on it) suggest that there is evidence that crop diversification can contribute to positive livelihood outcomes. However, the findings indicate

Table 2. Challenges of crop diversification identified in the literature.

Challenge – specific	Authors
Maladaptation due to unbalanced crop portfolios	Meldrum et al. 2018
Insufficient insight about the multiple dimensions of poverty	Feliciano 2019; Hansen et al. 2019
Insufficient insight about crop quality, income and profitability	Beillouin, Ben-Ari, and Makowski 2019
Insufficient insights about the different dimensions of resilience	Onyeneke et al. 2019
Lack of analysis of gendered nature of outcomes	Food and Agricultural Organization of the United Nations [FAO] 2016; De Pinto et al. 2020; Reynolds et al. 2020
Lack of analysis of the role of social resilience	Altieri et al., 2015; Beillouin, Ben-Ari, and Makowski 2019; Hufnagel, Reckling, and Ewert 2020
Lack of analysis of the political dimension of resilience	Córdoba Vargas, Hortúa Romero, and León Sicard 2019
Lack of analysis of policy influence	Bedmar Villanueva, Halewood, and López-Noriega 2015; Di Falco, Bezabih, and Yesuf 2010; Duong et al. 2019; Rampa and Knaepen 2019
Incoherent conceptual framework of crop diversification (what it is and how it works)	Hufnagel, Reckling, and Ewert 2020

that evidence concerning the last part of the hypothesized impact pathway – increased adaptive capacity and resilience – is far less positive. This means that it is a challenge to realize the full potential of crop diversification (Njeru 2013). The results of the review also point to the many and diverse benefits of broader livelihood diversification strategies beyond the diversification of crops.

The literature review identified several conceptual and methodological bottlenecks that require urgent attention. Conceptually, there appears to be a need for a more nuanced and elaborated theory of change that links particular crops to a particular diversification strategy (or multiple strategies), to livelihood outcomes (for a good example of four different impact pathways from seeds to improved nutrition, see Nabuuma et al. 2020), and then to strengthened adaptive capacity and resilience. In such a more sophisticated theory of change, attention needs to be paid to possible trade-offs between livelihood outcomes (Kozicka et al. 2020), as it may not be feasible to substantially improve all envisioned outcomes (e.g. more diverse food and increased income) simultaneously. Other adaptation-focused impact pathway studies have come to a similar conclusion. Examples include Ansah, Gardebroek, and Ihle (2019) about the causal relationship between food security and resilience; Gil et al. (2017) about integrated agricultural systems and resilience; Donatti et al. (2020) about ecosystem-based adaptation and climate-change adaptation; and Béné (2020) about the impact of Covid-19 on resilience and food security.

Methodologically, there is scope for several improvements, from a more precise analysis of the baseline situation to a more systematic exploration of adaptation options and their strengths and weaknesses. A more refined conceptual framework and methodology are elaborated in the following paragraphs.

A more refined theory of change

A more refined theory of change could look like this. Better access to crop/tree and varietal diversity (from diverse sources) provides farmers with an opportunity to more effectively diversify and/or sustainably intensify crops/livestock/tree systems production, management, harvesting, and marketing of derived products in space and over time. Making use of more and better quality agrobiodiversity ultimately benefits natural resource management, household consumption, nutrition, and health.

Improved, more ingenious agroecological resource management practices can contribute to making the farm more productive and/or efficient. An example is the use of leguminous crops and forages (including trees and shrubs) as organic fertilizer in fields with mixed rotation and strip cropping and crop/livestock integration and rotations. This could serve as a mitigation measure and result in higher yield(s), higher quality of produce and cost savings on inputs.

Access to broader crop, tree and animal varietal diversity also offers added income generation opportunities through the development of product value chains and the sale of principal and by-products, including animal-sourced foods, seeds and vegetative planting material, timber and firewood, draught power, and manure. Payments for ecosystem services resulting from an increased biodiversity can also support income diversification and create additional welfare for the producer, the community, and the environment.

Crop diversification can be more effective when combined with the strengthening of social and political relationships, which in turn, can open avenues for other types of diversification, e.g. off-farm income generation. Supportive policies can further make agrobiodiversity work for adaptation through incentives and rewards, opportunities to build skills through training, new information services, and promotion of production and marketing alternatives (Fraval et al. 2019). Overall, improved livelihood outcomes can lead to an increased capacity to foresee and deal with shocks, e.g. by distributing farming uncertainties and risks over space and time.

In this theory of change, resilience is constructed or emerges through the aggregation of two or more mutually-reinforcing livelihood outcomes. Owen (2020) offers a useful grouping of five outcome areas that, together, can lead to increased resilience: improving the environment, developing resilient social systems, increasing economic resources, enhancing governance and institutions, and reducing risk and vulnerability. Building on this grouping, the

theory of change can be strengthened through the identification of useful indicators. Expanding on Vernooy and Vongkhamsao (2015), proposed indicators are:
Improved environment

- Generation of new (agroecological) knowledge and innovative practices, including new approaches, methods, tools and technologies, e.g. evolutionary plant breeding, soil and water conservation measures, pest and disease control techniques, and circular agricultural processes
- Improved (e.g. more nutritious, with higher adaptive capacity) plant, tree and animal varieties/species/breeds developed
- More sustainable, available sources of energy used
- Conservation and exchange of plant genetic resources improved
- Labor productivity Increased

Social resilience

- Farmer groups formed or strengthened to do research (e.g. on agroecology, seed management), improve seed and food security, and defend their rights
- Local knowledge systems and cultural practices recognized, strengthened and supported
- Women and youth empowerment, inclusiveness, and gender equity increased
- Demonstration farms and plots for experimentation and learning set up
- Autonomy

Income generation

- Income generation opportunities created, based on on-farm production and complemented by off-farm work
- Linkages established among actors in the value chains and new (niche) market opportunities developed
- Increased investment of the government and private sector in value-adding activities

Governance and institutions enhanced

- Increased public awareness of the importance of biodiversity and the benefits of diversification
- Increased and meaningful farmer participation in policy processed
- Policies formulated and effectively implemented to support (crop) diversification

- Better institutional coordination and cooperation at and across all levels

Less risks and vulnerability

- Overall, improved and more diversified farming systems
- Overall, improved and more diverse nutrition
- Overall, improved and more stable income streams
- Overall, recognition, respect and support for smallholder farmers' knowledge, preferences, skills and practices
- Some form of insurance in place (e.g. household savings or crop insurance)

These indicators can be integrated in the design of diversification strategies and then be used as part of the monitoring and evaluation framework. This brings us to the methodological improvements that we are proposing.

A more refined methodology

Building on van Zonneveld, Turmel, and Hellin (2020), who developed a participatory, stepwise methodology to support farmers in making wise diversification decisions, we propose the following sequence:

Step 1. Identifying farmers' goals, including a gap analysis of functional diversity in the current farming system. The baseline analysis should begin with an understanding of the livelihood goals of the different farm household members (and the challenges they face in achieving these goals) and explore how different on-farm diversification strategies could contribute to these goals and to overcoming challenges. As Hufnagel, Reckling, and Ewert (2020) argued, it is critical to define how to diversify and for what reason(s), e.g. to introduce cereals with C4 photosynthesis capacity or the establishment of shade trees to make farm systems more resilient against climate changes (van Zonneveld, Turmel, and Hellin 2020).

Step 2. Assessing current and future climate-related production risks. The potential of crop diversification strategies to produce positive outcomes will be influenced by current and future climate conditions. An ex-ante assessment of the possible influence should be part of the baseline study.

Related to steps 1 and 2, with progressing climate change, spatially-explicit vulnerability assessments can be of great help for governments and other institutions (Wichern et al. 2019). They offer a conceptual and methodological framework for such analysis, identifying areas of vulnerable households, determining the crops contributing most to household vulnerability, and testing which intervention efforts could be effective and where, considering the heterogeneity of household livelihood activities. Wichern et al. suggest that their framework could be further advanced by including non-crop livelihood activities, such as livestock production and off-farm income. Such a "whole-farm" assessment can be strengthened by inclusion of indicators of underlying food insecurity and poverty that influence adaptive capacity and vulnerability. A similar, but more gender-focused methodology has been developed by Chanana-Nag and Aggarwal (2020), to identify hotspots where climate change adaptation and gender-based interventions could be prioritized, based on the identification of sites where large number of women farmers are impacted by high levels of climate risks in socio-economic terms (e.g. access to labor, credit and markets, wage rates for female laborers).

Step 3. Assessing enabling and disabling factors. Enabling/disabling factors, such as access to and availability of knowledge, capital and markets, determine the feasibility and potential of crop diversification strategies. These factors are context-specific and may vary over time.

Step 4. Designing the crop diversification strategy to include impact pathway and expected outcomes: The design should include a sketch of the impact pathway and expected outcomes and include one or more indicators of success, to allow for a more precise evaluation of the strategy or strategies selected. Any selected strategy could have multiple expected outcomes in terms of improved productivity, nutrition and health, and income generation, and how these outcomes in turn contribute to agroecological and social resilience.

For this step, it is useful to borrow from McGuire and Sperling (2013), who argued that much can be learned from the work on resilient seed systems, which is guided by: (i) developing options that anticipate varied fluctuation scenarios; (ii) options made available in time and across geographic and temporal scales; (iii) a diversity of supply or delivery channels to ensure wider access to technologies and strategies; (iv) a balanced contribution by the formal and farmer innovation systems; and (v) the provision of timely and useful information, so that users can make informed decisions about qualities of performance, possible risks and emerging opportunities.

Step 5. A Theory of Change-based evaluation: The Theory of Change evaluation verifies each of the presumed causal linkages in the chain of events through a mixed methods approach.

Conclusion: a broader perspective

The critical examination of evidence presented in this article has led to a rethinking of the theory and methodology of crop diversification, as elaborated in the previous section. At the same time, the review opens our eyes to another important perspective, which is to look at the role of crop diversification in a wider societal transition toward a more sustainable future. In the case of agriculture, this could mean the exploration of a transition to a circular agriculture. Dealing with production risks remains important for such a transition, but diversification could also be a means to redirect material flows in agroecosystems at large scales, backed up by a comprehensive agroecologically-based agricultural policy. For example, monocrops could be replaced by growing (mixtures of) legumes to increase/restore soil nitrogen availability or by forage crops for livestock to give nutrients "legs" across landscapes at scales that reach far beyond the farm scale. Such changes could be promoted through market reform and policy incentives, but the most important interventions are those that support and strengthen smallholder farmers' (and their communities' and organizations') ability to provide for local needs and ecosystem services, as well as promote diverse cultural lifestyles and community-based ways of living.

Some authors have elaborated such a broader perspective by using a landscape management lens, which assesses how best to combine productive activities at scale (e.g. Tittonell et al. 2016) or through a livelihood management lens, which assesses how to most effectively combine farm and non-farm activities related to food production, nutrition, and income generation (e.g. Fraval et al. 2019). Such a broader perspective is also advocated in a recent major review of diversification in Sub-Saharan Africa edited by Heumesser and Kray (2019), which argues that crop diversification can be a component of a larger diversification strategy that includes both on-farm and off-farm activities. This kind of broader diversification "approach" can be an effective risk management strategy to deal with production, market and environmental risks. However, the authors warn that there is no one-size-fits-all solution across Sub-Saharan countries or agroecological zones. Policies need to factor-in the diversity of conditions in which farmers operate and offer a menu of options for diversification (on-farm, off-farm) based on smallholders' own needs, interests and perspectives, or, where diversification does not seem promising, recommend farm specialization. To conclude in a few words, achieving diversity needs to harness diversity.

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