Received: 29 January 2025 | Revised: 19 June 2025 | Accepted: 19 June 2025

DOI: 10.1002/ppp3.70072

OPINION

Plants People Planet PPP Open Access

Embracing new practices in plant breeding for agroecological transition: A diversity-driven research agenda

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Societal Impact Statement

Plant breeding for agroecological transition (AET) holds the potential to transform agriculture by fostering crop diversification and empowering farmers through collaborative, inter- and transdisciplinary research. By adopting a systemic, co-learning approach, we can deepen our understanding of the complex interactions between plant diversity, management practices and socio-ecological contexts. Achieving this transition requires responsible governance to co-design cropping systems and ensure sustainable, safe and resilient agricultural systems with healthy nutrition. Embracing these integrative practices will not only advance plant breeding science for the transformation of sustainable food systems but also strengthen food security, safety and resilience in the face of pressing environmental and societal challenges.

Summary

This opinion paper advocates for a transformative approach to plant breeding to support the agroecological transition (AET), essential for addressing global challenges such as biodiversity loss and climate change. It emphasizes the need for inter- and transdisciplinary, collaborative and inclusive research to enhance plant and crop diversity while empowering farmers. Key strategies include co-designing agroecological systems with stakeholders, leveraging crop inter- and intraspecies diversity and establishing responsible governance. The participatory approach encourages collaboration between farmers and researchers to co-develop solutions that enhance crop inter- and intra-species diversity within cropping systems. Through responsible governance, we aim to ensure inclusivity, participation and equitable access to knowledge at individual and institutional levels. In addition, researchers and institutions must collaborate with farmers to co-design systems that prioritize context-specific solutions, sustainability and diversity.

Enhancing plant diversity for AET requires plant breeding tailored to diverse agroecological contexts and farming needs, supported by collaborative networks, participatory methods and appropriate experimental and modelling tools. We conclude with a call for inter- and transdisciplinary training to better prepare future researchers in plant breeding for AET.

KEYWORDS

co-learning, global changes, intersectionality, participatory research, smallholder farmers, social inclusion

1 | INTRODUCTION

Global changes, including land use changes, climate changes and biodiversity loss, deeply impact ecological systems and human societies. The agroecological transition (AET) is advocated as a way to mitigate the impacts of global changes, adapt to their consequences and simultaneously preserve social and cultural values and environmental health (Dittmer et al., 2023). Agroecology (AE) is a dynamic concept, with evolving definitions since the early 20th century. In this paper, we refer to AE as defined by the Food and Agriculture Organization of the United Nations (FAO) (De Schutter, 2010) and the High-Level Panel of Expert on food security and nutrition (Wezel et al., 2020). AE is considered as a set of 13 principles aimed at enhancing the resilience and sustainability of healthy food systems, while ensuring equity and social justice (Anderson et al., 2021). While AE encompasses a broad set of principles and practices, this paper focuses on two key dimensions, which we consider central for guiding plant breeding within the context of AE: participatory approaches (including systems, governance, breeding), and plant genetic diversity. Over the course of the twentieth century, research in plant breeding has significantly contributed to the transformation of food systems. It is therefore important that future plant breeding efforts align with the goals of AET. Research in plant breeding plays an important role in supporting AET. Indeed, researchers must contribute to the inclusive and sustainable development of cropping systems by addressing the needs of diverse stakeholders and promoting responsible governance among them. This raises the important question: how the challenges of the AET are reshaping research questions and practices, and to what extent? As researchers from various disciplines who contribute to plant breeding and management of crop diversity in Mediterranean and tropical agro-systems, we argue that leveraging the diversity of plants, practices and stakeholders offers a pathway for transformative changes towards sustainable agriculture and healthy food systems. Integrating these different forms of diversity requires the co-development of knowledge through responsible governance, while supporting farmers in the transformation of their systems.

Cultivation and management of crop inter- and intra-species diversity in space and time are promising levers towards an AET, ensuring the resilience and sustainability of cropping systems in an increasingly fluctuating environment (Bedoussac et al., 2015; Tamburini et al., 2020). Crop diversity in agroecological systems can be declined at various genetic levels, ranging from population varieties to varietal and species mixtures—through diverse spatial and temporal arrangements. Spatial diversity includes intercropping, varietal mixtures and population varieties, while temporal diversity involves crop rotations and relay cropping.

In this paper, we explore how plant breeding practices can align with and operationalize agroecological principles to promote resilient and healthy food systems. More specifically, we highlight new research practices for plant breeding based on the three recognized dimensions of AE (Wezel et al., 2020, 2009): practices, social movements and scientific disciplines (Figure 1). While participatory breeding is a valuable initial step in this direction, our proposed approach is broader, ranging from system co-design to responsible governance, and considers participatory breeding as one component of a comprehensive framework. We first discuss the importance of co-designing methods to explore a diversity of practices that rely on plant diversity within cropping systems. We then argue that including a diversity of stakeholders in the research process requires a responsible governance approach. Finally, we emphasize key disciplinary challenges in biology for producing scientific knowledge in plant breeding that is relevant to AET. While the three dimensions of AE are well established, the novelty of our approach lies in how these dimensions are integrated within the context of enhancing diversity at all its levels. Specifically, what distinguishes this approach is the continuous interactions among disciplines (interdisciplinary) and actors (trans-disciplinary), aimed at deepening our understanding of the role of plant diversity and its interactions — both among plants and with diverse environments including pedoclimatic, ecological and socio-cultural contexts. Such an integrated framework encourages to revisit the roles of research for plant breeding adapted to the challenges of AE.

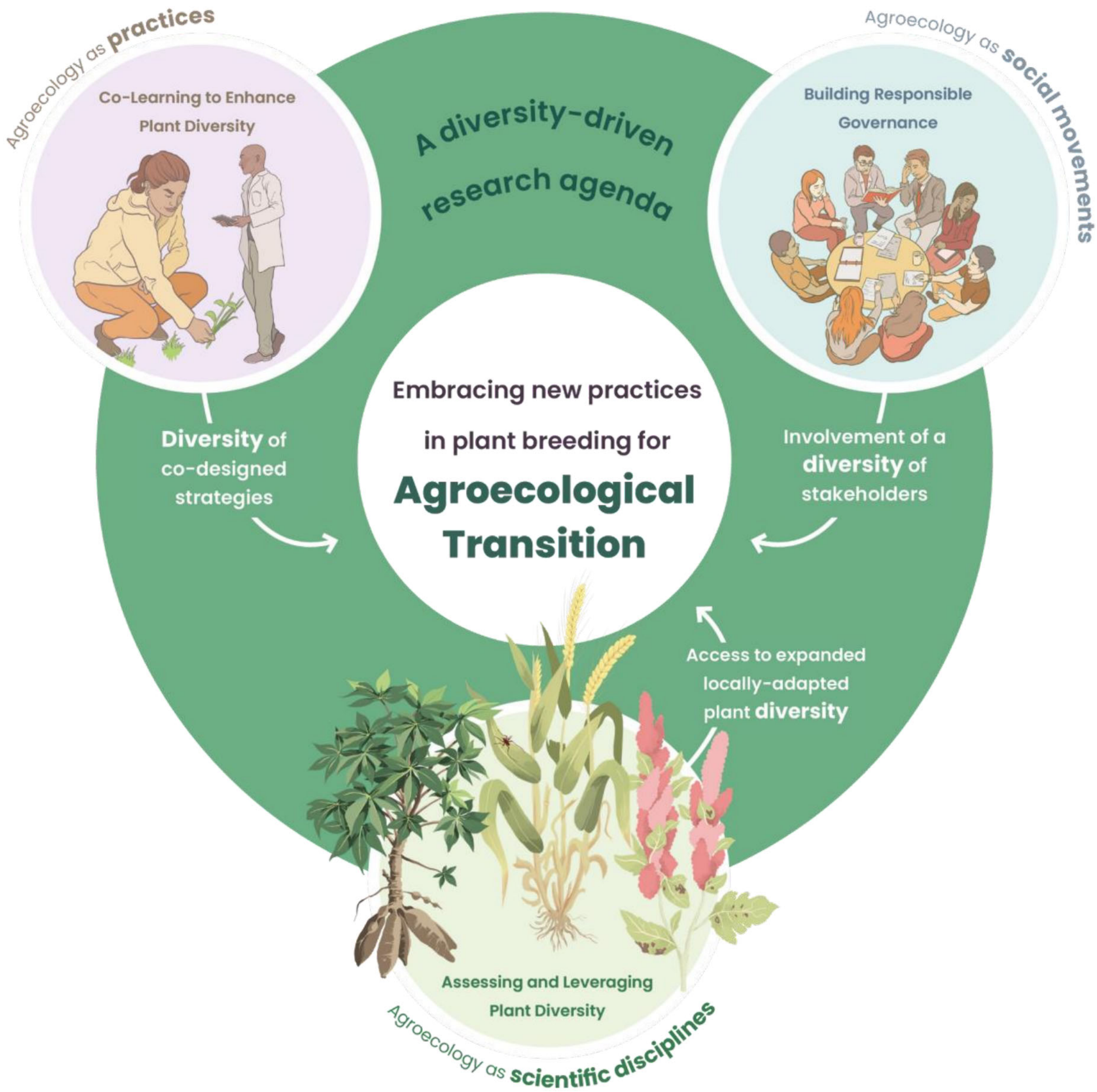

FIGURE 1 A diversity-driven research agenda for plant breeding for agroecological transition. The framework integrates co-learning to enhance plant diversity (practices), responsible governance through diverse stakeholder involvement (social movements) and the assessment and leveraging of locally adapted diversity (scientific disciplines). These interconnected strategies support new practices in plant breeding to promote resilient, sustainable and inclusive agricultural systems.

2 | PART 1. ADVANCING TOWARDS AGROECOLOGICAL SYSTEMS: CO-LEARNING TO ENHANCE PLANT DIVERSITY

When AE is considered as a set of practices, researchers' practices are often overlooked. Nevertheless, by mobilizing participatory approaches, researchers can work with farmers to co-define research questions and co-develop solutions (Figure 1). Through this process, we show in the following that we can develop and share knowledge on the crop inter- and intra-species diversity used by farmers in their cropping systems. We expect this process to favour the mobilization of plant diversity to co-design AE cropping systems, and to facilitate the integration of plant diversity available in farmers' networks and beyond into cropping systems. This should also favour the development of a diversity of locally adapted solutions.

2.1 | Mobilizing plant diversity through co-design

The multiplicity and complexity of cropping systems to be considered call for new experimental designs and new methods of analysis. Co-designing agro-ecological systems by integrating plant diversity will enable addressing stakeholders' requests and facilitate their adaptations to the local context (Descheemaeker et al., 2019). This requires the mobilization of local knowledge associated to this diversity. The co-development of new knowledge based on integrating local and academic knowledge is one of the key principles of AE (Wezel et al., 2020). It forms the basis of farmer-led participatory research processes and co-innovation within multi-stakeholder cooperative platforms.

Researchers in plant breeding can foster the co-design of agroecological systems relying on genetic diversity and hybridization of knowledge by taking part to participatory breeding programs (Camacho-Henriquez et al., 2015; Katwal et al., 2024; vom Brocke et al., 2020). This represents a paradigm shift moving from developing varieties adapted to a large range of environmental conditions (targeted by private breeding programs), to varieties with specific adaptations to their local contexts, including biophysical and social components (Atlin et al., 2001; Tufan et al., 2018). In participatory breeding programs where farmers participate in several cycles of selection and recombination, in one hand, farmers contribute to define the breeding objectives (Soleri et al., 2000), facilitate access to local genetic diversity (Baum et al., 2003), make resources available in terms of time and land area and drive plant selection to meet the breeding objectives. This process is itself a co-learning process during which farmers can get used to many concepts associated with plant breeding, such as trait inheritance, genotype-by-year interaction and correlation between traits. On the other hand, researchers provide technical knowledge and facilitate access to a broader range of genetic diversity when locally available varieties are insufficient to achieve the co-defined objectives (Hamidou et al., 2023). Furthermore, following the "DEED" cycle of Describe, Explain, Explore and Design (Ronner et al., 2019) for co-designing diversified cropping systems, researchers collaborate more closely on issues related to access to seeds and use of varieties adapted to specific soil and climate conditions, as well as to farmers' objectives (Raboin et al., 2023; Soleri & Cleveland, 2001). In this line, promoting evolutionary breeding, a more dynamic and adaptive strategy than participatory breeding, enables genetically diverse populations to adapt to local conditions. Hence, promoting in-situ adaptation — crops evolving in response to local environmental conditions and practices — is very relevant to address the challenges of AE (Ceccarelli & Grando, 2024). In this process, participatory modelling (Sachet et al., 2021) can be used to support the co-designing of diverse collective seed management systems, and the use of genetic diversity in farmers' cropping systems. Researchers provide modelling methods (conceptual models, role-playing games, numerical models), and knowledge on available genetic diversity, while farmers are engaged in the co-design through role-playing games (Abrami et al., 2008). Collective adaptation strategies that integrate phenotypic and genetic diversity into cropping systems emerge as outputs of such approach.

2.2 | Assessing cultivated plant diversity

As stated above, researchers can provide valuable insights into the phenotypic and genetic diversity of cultivated plants. Farmers manage this diversity across different spatial and temporal scales. They can choose which crop species and varieties to grow, as well as whether to rely on genetically heterogeneous populations.

Crops continuously adapt to environmental conditions and farming practices, as long as there is genetic diversity both within and between fields (Bretting & Duvick, 1997). Therefore, once collective adaptation strategies have been co-defined and are established, documenting both phenotypic and genetic diversities of crops in situ will assist farmers to harness the benefits of agrobiodiversity. Moreover, given the dynamic nature of these AE cropping systems, understanding the evolutionary forces that shape both phenotypic and genetic structures - including selection, genetic drift and migration (pollen flow according to species biology and spatial arrangement of varieties and seed/seedling exchange within farmer networks) – will support the development of management strategies to sustain diversity over the long term (Ceccarelli & Grando, 2024; Thomas et al., 2012). Studying genetic structure helps to understand how on-farm seed production and selection practices affect phenotypic changes within fields (Thomas et al., 2012) among the various mechanisms shaping the phenotypic and the genotypic structure of plant diversity, cultural factors play a key role (Yogom et al., 2020). Therefore, combining knowledge on both biological and cultural factors allows for adjustments in management strategies: for instance, (re)introduction of genetic and functional diversity can ensure that cropping systems remain diverse over time. Studying the functional diversity present in the system can help to understand plant communities use resources, respond to stress and contribute to the overall performance and resilience of agroecosystems (Lavorel & Garnier, 2002). Beyond understanding plant diversity dynamics and use in the targeted area, we could also facilitate the mobilization of diversity from outside farmers' networks (see also section 5.3).

To decipher such complexity, researchers can provide phenotypic and genetic tools to characterize plant diversity at different scales, and according to different criteria (quality, nutrition, productivity and cultural value). They can also co-design with farmers phenotyping tools that can subsequently be used in agroecological cropping systems. Advances in high-throughput phenotyping including the use of sensors on unmanned vehicle (drones) have significantly improved our capacity to acquire non-destructive data on large numbers of genotypes in agroecological cropping systems (Audebert et al., 2022). However, technical and theoretical bottlenecks still remain. For example, obtaining genotype related-metrics in intercropped species or mixture of varieties is still a technical challenge (Bourke et al., 2021). Researchers can also define new proxies to help characterize complex cropping systems that meet multiple objectives, such as crop production (e.g. number of panicles per area or leaf area index defined by imagery), farmers' practices (e.g. number of variety used by farmers) and cultural values (e.g. diversity of culinary uses).

Further, co-designed approaches allow multiple farmers to evaluate plant diversity in their own context (i.e. diversity of cropping systems, seed systems, demands), leading to large numbers of trials (large N approach, Nelson et al., 2019, TRICOT approach, De Sousa et al., 2024). This will help test the adaptability and suitability of genotypes in specific environments. However, on-farm experiments also bring technical challenges that researchers can help to overcome by developing new statistical methods specifically designed for the unbalanced nature of farmers' trials (David et al., 2020; Turbet Delof et al., 2025). Two approaches have been explored so far: assessing a limited set of genotypescandidates to selection (up to 30) by a large number of farmers (Ceccarelli & Grando, 2009; Steinke et al., 2017) and evaluating a large number of candidates to selection (more than 100 s) by a smaller set of farmers at a limited number of locations (Gesesse et al., 2023). New methods are needed to bridge the gap between these two strategies (Oberson et al., 2024).

Enhancing and maintaining diversity on farms will undoubtedly benefit from our collective ability to aggregate heterogeneous information, including genetic and environmental data, cultural values and agronomic practices. In this context, genotypic information will play a key role, as estimating the genetic relationships between tested varieties improves the assessment of their genetic values. Optimizing the assessment of genetic value will also depend on our ability to collect and better integrate environmental data, such as weather, soil conditions and agronomic practices. Such approach could benefit from dedicated statistical methods (Costa-Neto et al., 2021; Garin et al., 2024) or for applying current physiological knowledge in crop growth models and functional structural plant models (Gaudio et al., 2019). Some of these models already account for spatial diversification within stands (Blanc et al., 2021; Rubiales, 2023). Altogether, the aggregation of large and diversified datasets will require the development of more integrative modelling approaches to link the various existing models, including genetic, physiological and agronomic ones.

3 | PART 2: PARTICIPATING IN THE MOVEMENT: BUILDING RESPONSIBLE GOVERNANCE FOR AGROECOLOGICAL TRANSITION

To co-design agroecological cropping systems, we need to develop a responsible governance for ensuring inclusion, participation and democratic access to knowledge (Figure 1). This section outlines the rationale for implementing such governance in research activities that support farmers towards agroecological transition. Responsible governance is crucial in this context, as the visions of the different stakeholders - including researchers from various disciplines - may differ. This transformative process requires researchers to assume responsibility on two levels: 1) individually, within on-going research activities and 2) institutionally.

3.1 | Contribution to a responsible governance at the individual level

Relying on responsible governance offers an alternative space (e.g. Living labs, Cascone et al., 2024; Gardezi et al., 2024) for coordination and negotiation among stakeholders. This allows social and cultural values, as well as sustainability issues, to be integrated into the process of a large plant diversity mobilization within cropping systems. Responsible governance can be achieved through different ways.

First, recent transdisciplinary projects focussed on seed systems diversity and management practices for cultivated diversity have shown the value of setting up Communities of Practice (CoPs) at the project level. CoP is composed of groups of people that share a common objective and learn together while interacting regularly. These CoPs ensure the possibility for different stakeholders to work together both to enhance the sustainability of agroecosystems, and the diversification of food and nutrition (Louafi et al., 2023). When it comes to promoting access to plant diversity, questions arise regarding the legal status of co-produced varieties and the relevance of the Distinctness, Uniformity and Stability criteria (DUS, Aurélia et al., 2021) for registering varieties in agreement with agroecology principles. We argue that the production of seeds/seedlings adapted to the AE principles and to local contexts could be carried out by collective farmers' dynamics, producing diversified seeds/seedlings according to local specificities, needs of farmers, food processors and consumers with the support of researchers. Hence, Communities of practices (CoP) could also contribute to boost co-produced knowledge meaningful for each stakeholder involved. Some farmer networks in Europe already implement CoPs (Chable et al., 2020), and this model is also widespread, especially in Africa, where local seed systems are deeply embedded within social networks (Labeyrie et al., 2016; Porcuna-Ferrer et al., 2023). Setting up a responsible governance approach through CoP, where farmers' organisations are involved in decision-making bodies at every stage, allows for diverse perspectives and recognizes equal rights over data, both for the collection and the analysis (Nelson et al., 2019).

Second, responsible governance can also be set up using a protocol of Collective Intelligence facilitation. While CoP operates at the level of each project, facilitation through Collective Intelligence goes beyond the limiting scope of project development and implementation. It was successfully tested to support co-design, co-innovation and sharing across various projects aimed at supporting agroecological systems in West Africa. This approach has been key in maintaining long-term stakeholder's involvement in a network of agroecology-related projects. It relies on distributed leadership and tools that support varying levels of engagement according to stakeholders' contributions. It supports synergies and mutual aid to co-design and monitor integrative experiments across projects, building on previous independent initiatives (Alami & Cornu, 2022). By upscaling this responsible governance at different levels, we believe that the management of plant diversity could be achieved at landscape level, as the different stakeholders will come from different villages and communities.

3.2 | Contributing to a responsible governance at the institutional level

At the institutional level, we argue for the need to adapt the research academic system to better align with the agroecological agenda. Indeed, when researchers adopt a collaborative stance and work with actors outside the academic world, they often face challenges within their research institutions. Knowledge production within the academic world is a social process with its rules, for instance for recruiting staff and evaluating scientific production (at the individual and collective levels). To foster co-design of research and production of hybridized knowledge, we advocate that some evaluation criteria need to evolve.

First, evaluation criteria of researchers should consider the time needed to build trust among stakeholders (Kholová et al., 2024), which is crucial for co-learning and co-designing research, particularly in participatory plant breeding for agroecological transition (AET). Second, the way research funding is allocated through calls, which define the scope of "fundable" projects, is inadequate for participatory research. The preparation time for proposal is often too short to allow for proper co-design, and the project duration is also often insufficient. We therefore propose that funding calls allow more time for proposal preparation and that a portion of the budget be allocated to an inception phase using participatory approaches. A relevant example is the McKnight Foundation, which includes a dedicated inception phase and supports projects through multiple phases (up to five), fostering continuity and deeper collaboration between all stakeholders (Nicklin et al., 2021). Additionally, evolving benchmarks should be established to account for the progression of the collaborative process and the co-design of actions to be undertaken.

Research institutions play a key role in shaping national and international policies, participating in forum such as the Convention on Biodiversity (CDB), the Nagoya Protocol, the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and the United Nations Framework Convention on Climate Change (UNFCCC, COP on climate). They provide scientific evidences for advocacy and public policies, and help bridge regulatory gaps to support agroecological systems. However, frameworks like the International Union for the Protection of New Varieties (UPOV, which protect plant varieties, often conflict with local seed systems due to the rigid Distinctness Uniformity and Stability (DUS) criteria, and restrictions on seeds/seedlings among farmers.

Moreover, the CBD designates states as owners of biodiversity within their borders, challenging the traditional seed commons. In contrast, the ITGRFA, supports farmers' rights by facilitating the exchange of seeds/seedlings among them, but focuses mainly on major crops, overlooking the diversity of species cultivated in agroecological systems. This complex regulatory environment calls for research institutions to foster synergies among conventions. For instance, in the case of UNFCCC, research institutions should advocate for environmental regulations that enhance farmers' production flexibility, and support farmer-led seeds/seedlings exchange to maintain in-situ dynamics of diversity.

4 | PART 3. KEY DISCIPLINARY CHALLENGES IN PLANT BREEDING: ASSESSING AND LEVERAGING GENETIC DIVERSITY FOR AGROECOLOGICAL SYSTEMS

Our framework relies on the principle that researchers are part of the stakeholders involved in crop production. They engage in a co-learning process with farmers to build sustainable cropping systems by mobilizing agrobiodiversity. Here, we emphasize the important role researchers may play in broadening crop diversity, refining the selection of genotypes for diversified cropping systems and anticipating future environmental changes (Figure 1).

4.1 | Enriching on-farm plant diversity with alleles and combinations of alleles from ex-situ collections and breeding programs

As previously mentioned, on-farm diversity can be enhanced by integrating genetic diversity from external sources to farmers' networks. Researchers play a critical role in facilitating access to ex-situ collections and diversity from pre-breeding and breeding programs.

Firstly, farmers need access to ex-situ collections from national and international genebanks. However, these collections are often inaccessible to farmers due to several factors, including a lack of information associated with conserved resources, the absence of user-friendly tools for consulting and ordering these resources and a complex regulatory framework governing the possible uses of these resources (Anglin et al., 2018; Teixidor-Toneu et al., 2023). In addition, regeneration backlogs and storage methods used by genebank managers can impact genetic characteristics of conserved resources (Fu, 2017). To address these challenges, research institutions need to reassess how they provide access to and multiply the resources they conserve. They should also foster complementarities between genebank conservation practices and those of farmers to better address farmers' needs. This is particularly crucial given that genetic diversity underlying beneficial interactions in diversified cropping systems has been depleted over the course of crop evolutionary history (Fréville et al., 2022).

Secondly, researchers in plant breeding need to facilitate farmer's access to a broader genetic diversity derived from pre-breeding and breeding programs, supported by bioinformatics-friendly systems leveraging pangenomics and other omics resources. With the aim to maximize local adaptation to environmental conditions and agronomic practices, this facilitated access to genetically variable populations and panel of genotypes derived from public institutes should allow farmers to readily assess the relevance of new alleles or combinations of alleles in a genetic background that resembles the ones they work with on a daily basis vom Brocke et al., 2020). To be efficient, this approach needs to be combined with an improvement of the capacity of farmers and networks of farmers to evaluate large sets of heterogeneous materials (see section 1.2).

4.2 | Exploring the choice of variety as a component of agronomic practices in intercropping and rotation systems

Cultivating species diversity across space and time has always been a prevalent agricultural practice for a majority of farmers. Furthermore, over the past decades, there has been a growing emphasis on increasing cropping system diversity to design more sustainable systems in regions characterized by intensive agriculture (Malézieux et al., 2009). However, the exploration of varietal diversity within species to fine-tune intercropping and rotation systems remains largely overlooked in agronomy (Litrico & Violle, 2015). First, different combinations of varieties grown in intercropping and rotation systems can behave differently and provide different ecosystem services. Such variations arise from the interactions between genotypes from different species, and their responses to environmental and cropping conditions. Such patterns have been documented by numerous modelling studies (Gaudio et al., 2019; Louarn et al., 2020) and deserve more experimental investigation (Baxevanos et al., 2017;). Second, the benefits of intercropping and rotation systems can be enhanced by mobilizing genetic diversity within each species (Meilhac et al., 2019; Zuppinger-Dingley et al., 2014).

While choosing better-adapted varieties is often perceived as fine-tuning by researchers in agronomy, opting for another species is viewed as a transformative approach. In fact, changing for more adapted varieties or replacing species can be viewed as two alternative options. The inclination toward shifting to different species rather than exploring varietal diversity within each species is constrained by researchers' vision of promoting soil and plant health. Additionally, this rationale is further exacerbated by the lack of knowledge of intraspecific versus interspecific variation in relevant traits. Overall, this calls for stronger collaboration between agronomists and geneticists: geneticists must design breeding programs focused on plant diversification, while agronomists should leverage variety selection to improve cropping system productivity and resilience.

4.3 | Contribution of deductive experimentation and modelling

Beyond on-farm generated knowledge, the co-learning process can be enriched by incorporating knowledge derived from modelling approaches and deductive experimentation, which involve designing experiments to test hypotheses (Ansell & Bartenberger, 2016). In this context, we highlight two major research challenges aimed at enhancing the integration of genetic diversity on-farm.

Firstly, harnessing both inter- and intraspecific diversity in space and time for agroecological cropping systems requires identifying plant traits and their genetic determinants that drive beneficial biotic interactions among plants as well as with other cropping system organisms (Becker et al., 2023; Fréville et al., 2022; Litrico & Violle, 2015). While our understanding of the above- and below-ground plant traits involved in beneficial intra- and interspecific interactions remains limited (Becker et al., 2023; Fréville et al., 2022; Litrico & Violle, 2015), the traits targeted in breeding for AE are expected to be far more numerous. Indeed, interactions will have to promote multiple co-designed objectives, e.g. resistance to bio-agressors, resource acquisition and use, crop production and stability and nutritional quality and diversity. For instance, increased resource acquisition in low-input agro-systems would benefit from breeding for improved beneficial crop interactions with microorganisms, by targeting traits such as carbon delivery to fungi and root exudates (Preece & Penuelas, 2020). In addition, favourable trait combinations are expected to vary depending both on the targeted objectives and local environmental conditions (Fréville et al., 2022). Modelling approaches can be very fruitful to address such challenges. Significant efforts have been made to account for plant diversity and spatial heterogeneity in mechanistic models linking plant traits and resources (Weih et al., 2022). However, such models are still limited by the requirement for ideotype-specific parameters and rarely consider within-species diversity. To that respect, the framework of functional ecology linking trait to function and trait community composition to community properties such as productivity and stability (Calow, 1987; Lavorel & Garnier, 2002), can be very helpful (Litrico & Violle, 2015; Malézieux et al., 2009; Reiss & Drinkwater, 2018). Yet, we still need further quantitative assessment of ecosystem services, elucidation of trait-service relationships and their dependency to environmental factors. Once interaction traits are identified, their genetic basis can be elucidated using the classical formalism of quantitative genetics that link the phenotype with the genotype, enabling the selection of species and genotypes that are relevant to assemble (Litrico & Violle, 2015). Alternatively, interaction traits can be identified using quantitative genetics methods dedicated to the study of social interactions (Becker et al., 2023; Griffing, 1967). Trait-blind approaches are also very relevant to complement trait-based methods in designing and managing diversified cropping systems (Barot et al., 2017; Forst et al., 2019). More recently, studies linking productivity and disease severity to allelic richness in genotype mixtures revealed mixed effects of diversity, including negative ones (Montazeaud et al., 2022; Turner et al., 2020; Wuest & Niklaus, 2018), underscoring the need for further research to uncover mechanisms and establish guiding principles (Wuest et al., 2021).

Secondly, leveraging diversity for agroecological systems will benefit from controlled experiments and modelling to test responses to novel environments and multiple stress scenarios (Cooper & Messina, 2023; Langstroff et al., 2022; Yu et al., 2023). While farmer networks offer valuable diversity of environmental conditions for predicting local adaptation (see section 1.2), researchers must expose genotype and species associations to rare but likely future conditions driven by global change and reduced inputs. Linking farmer's assessment, breeding networks and crop modelling will help predict crop performance in the face of environmental and social uncertainty, by allowing the exploration of a wide range of environmental conditions and agronomic practices (Kusmec et al., 2021). In this context, significant investments are needed not only to develop phenotyping platforms for evaluating multi-stress scenarios but also to accurately characterize how genotypes and combinations of genotypes can respond to these constraints. Moreover, we need to not only predict the performance of specific combinations at a given time but also predict targeted services over time for diversified stands whose genetic composition will change in response to evolutionary forces (e.g. Gao et al., 2023) (see section 1.2).

5 | CONCLUSIONS AND PERSPECTIVES

We argue that plant breeding for agroecology transition (AET) will be most effective when guided by interdisciplinary and transdisciplinary, collaborative and inclusive research. Such an approach is essential for understanding the complex interactions between plant diversity, management practices and social contexts and to enhance crop diversification. While this may not seem novel to researchers in plant breeding already engaged in participatory approaches, they remain far from mainstream. Promoting them is therefore essential to meet the challenges of the coming decades.

To achieve this, we propose to adopt a systemic approach coupled with a co-learning process that empower farmers to access, cultivate and anticipate strategically the use of crop diversity within their farming systems (Figure 1). Through collaborative learning, we aim to enhance plant diversity, resulting in a variety of co-designed strategies that involve farmers, researchers and other stakeholders working together to identify and implement best practices for cultivating a diverse range of crops. This approach requires a responsible governance to facilitate continuous interactions among stakeholders and ensure synergistic enrichment. This is essential to ensure that the voices of farmers, community members, policymakers and scientists are heard and considered in the decision-making process. The goal is to gain a deeper understanding of how plant function and interact with each other, as well as with their environment, whether that be pedoclimatic (soil and climate conditions), ecological or socio-cultural factors. This not only enhances the resilience of farming systems but also contributes to the conservation of genetic resources, ensuring that future generations have access to a diverse range of crops. Implementing such research approaches and practices also requires addressing the issue of data access, with a strong commitment to open data systems and the preservation of the public nature of environmental knowledge. Furthermore, to support this shift, it is important to encourage the training of researchers and students in interdisciplinary and transdisciplinary research. This will enable future generation of researchers to embrace the collaborative and integrative vision required for successful plant breeding in the context of agroecological transition. Overall, this calls for researchers to shift their research posture, moving beyond traditional boundaries to new practices that align with the goals of agroecological transition.

AUTHOR CONTRIBUTIONS

This paper is the result of a collective reflection of all co-authors present in workshops dedicated to plant breeding for the agroecological transition, held in May 2022. These workshops—organized by Myriam Adam, Hélène Fréville, Alexandre Guichardaz and Hélène Joly—provided an inclusive space for dialogue, co-learning and fostering innovative thoughts. The diversity of perspectives and active engagement of all co-authors were essential in shaping this manuscript. Myriam Adam (system agronomist), Hélène Fréville (population genetics and evolutionary biologist) and Hélène Joly (population geneticist) wrote the first draft. Sophia Alami (socio-economist), Hélène Marrou (system agronomist), David Pot (plant geneticist), Sébastien Ricci (researcher in plant breeding), Mathieu Thomas (population geneticist) provided extensive feedback and Claire Billot, Nathalie Chantret, Brigitte Gouesnard, Sélim Louafi, Emmanuelle Muller, Joël Romaric Nguepjop, Christophe Pradal, Bénédicte Rohné, Stéphanie Sidibé-Bosc, Muriel Tavaud, Kirsten Vom Brocke then contributed additional feedback before the manuscript was finalized by Myriam Adam, Hélène Fréville and Hélène Joly for final approval.

ACKNOWLEDGEMENT

We would like to thank the management of AGAP Institute for their ongoing support in this process, as well as for their financial support in organizing the reflection and writing workshops. We would like to acknowledge Mathilde Cathelain for significantly enhancing the visual representation of figure 1 of this paper.

CONFLICT OF INTEREST SATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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How to cite this article: Adam, M., Fréville, H., Alami, S., Marrou, H., Pot, D., Ricci, S., Thomas, M., Guichardaz, A., Billot, C., Chantret, N., Gouesnard, B., Louafi, S., Muller, E., Nguepjop, J. R., Pradal, C., Rohné, B., Bosc, S. S., Tavaud, M., Brocke, K. V., & Joly, H. I (2025). Embracing new practices in plant breeding for agroecological transition: A diversity-driven research agenda. *Plants, People, Planet*, 1–11. https://doi.org/10.1002/ppp3.70072