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Operationalizing an innovative systems approach for breeding agroforestry trees

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Key messages

- 'Systems approach' plant breeding is about considering multiple global challenges together within the breeding process, to make sustainable progress in addressing those challenges.
- For a systems approach to tree breeding to be successful, the starting point is a broad set of measures that define breeding success. The values applied should extend beyond the traditional ones of productivity and profitability, and embrace resilience, sustainability, nutritional security, local cultures and conservation.
- Policy interventions that encourage a systems approach to tree breeding should provide incentives for tree researchers and breeders to embrace these broader values during tree characterization and genetic improvement. There should also be specific incentives for tree breeders to bring together existing breeding methods in novel ways to ensure that multiple values are addressed.

Summary

The adoption of a systems approach to plant breeding, considering multiple global challenges together, is needed to make sustainable progress towards addressing these challenges. Trees have roles in countering many key planetary health concerns and this means they provide an excellent example of where a systems approach to plant breeding is needed, underpinned by their diversity in features, uses, users and production contexts, and by their multiple domestication pathways. Here, we provide evidence as to why adopting a systems approach to tree breeding is important in addressing global challenges and explain the features of the approach. We particularly consider the application of the approach, which in the case of trees we refer to as 'tree diversity breeding', at the forest–agriculture interface, using CIFOR-ICRAF's research for development work as a case study. We suggest measures that can be taken to support the adoption of the approach for tree genetic improvement.

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Introduction

In an open-access opinion piece we published earlier in 2022 in the journal *Trends in Plant Science* (TIPS), we outlined a vision of a systems approach to plant breeding as a strategy to address multiple pressing global challenges more effectively than presently; and we illustrated the approach with the case of tree diversity breeding (Graudal et al. 2022). In this brief, we explore this concept further and assess its implications for CIFOR-ICRAF's ongoing research for development work as a real-life case study. The intention is to guide the future direction of breeding for trees planted at the forest–agriculture interface, especially for trees grown in agroforestry land-use systems. As well as a focus on the practical application of tree diversity breeding, we outline policy interventions that would support the approach.

Evidence of the need for tree diversity breeding

The crucial roles of trees in mitigating climate change, restoring soils and serving as ecological matrices to conserve biodiversity are well documented. So too are trees' roles in providing resilience and choice for human consumption, being sources of many different products that are used directly by growers and/or sold for wider use.

Many different tree species, with a broad range of biologies, are involved in supporting these multiple functions, within a wide range of production settings and serving different user groups. Genetically, the trees involved are domesticated to different extents and their improvement pathways so far have varied from simple selection by local communities to advanced breeding by scientists.

This broad contextual variation is mirrored by evidence that both species and genetic variation are crucial in optimizing the delivery of both products and services from trees. In terms of species diversity, for example, stands of mixed tree species often provide more stable total productivity, sequester more carbon, overyield, and give greater resilience to environmental and biotic stresses, relative to single-species stands. Within a species, the use of broad genetic diversity is able to prevent inbreeding depression, provide a better habitat matrix for other organisms, and lend stability to agricultural ecosystems, among other benefits. For examples referenced in our original opinion piece, see Graudal et al. (2022).

To retain and enhance these multiple benefits, careful thought is needed regarding tree breeding and selection. It is evident that if different global challenges, aligned with specific trends and their associated values, are to be considered and addressed together – as it is increasingly recognized that they must be – then new approaches to breeding and selection are required. In our TIPS opinion piece, we chose to illustrate this by focusing on responses to combinations of four key trends that will allow broad progress in meeting the multiple challenges. We described the four trends to which combined responses are required as follows:

1. The call for broader *participation* of stakeholders in the breeding process. This is primarily based on the increased recent recognition of the need for local people who have long stewarded tree genetic resources to be appropriately rewarded for doing so, in support of their cultural values and to promote equity.
2. An increased emphasis on the *environment*. This refers to the greater recent recognition of the need to develop and deliver – through breeding and genotype–environment matching – the right tree for the right place in support of global commitments to tree-based climate change mitigation, ecosystem restoration and biodiversity conservation.
3. The advances in *biotechnology* that condition improvement approaches. This relates to the importance of being responsive to those recent developments in biotechnology that affect the decisions of the investors in tree breeding and the methods that are used; for example, investors may possibly emphasize new over conventional approaches simply because they are new.
4. The evolution of *markets*. In particular, this refers to the greater recent awareness of market actors as to the need to diversify tree production with a broader range of market-competitive, context-specific cultivation options that, while supporting the economy, also promote human nutrition, biodiversity, resilience and sustainability.

Features of the tree diversity breeding approach

In our TIPS article, we presented tree diversity breeding as taking account of combinations of social, environmental, technological and economic trends, perspectives, concerns and values. Its key feature, as we described it in the article, is the application of new linking (or bridging) approaches between existing trend-responsive tree breeding methods. This enables a broadening of the values considered in tree genetic improvement and thus the support of progress on multiple fronts. In our TIPS article, we illustrated what tree diversity breeding might look like in practice by considering the six pairwise combinations of the four key global trends that we had identified related to participation, environment, biotechnology and markets (arrows show the links in Figure 1). In each case, in this section and in Table 1, we provide a summary of each new linking approach and explore the implications for CIFOR-ICRAF's work. In Box 1, we particularly consider how the tree diversity breeding approach could affect field genebank activities implemented by CIFOR-ICRAF's Genetic Resources Unit.

The use of citizen science breeding approaches to bridge *participation* and *environment* trends

The difficulties in communicating with broad and dispersed networks of grower-testers have meant that participatory tree selection and breeding trials have generally only been implemented on a modest scale, sampling only a small subset of growth environments. By making communication easier, new citizen science breeding and selection methods that use mobile phones for the recruitment of trial participants, the recording of trial findings and the sharing of results have the potential to overcome limited sampling.

Implications and opportunities for CIFOR-ICRAF: CIFOR-ICRAF has been an innovator in participatory tree domestication methods, working closely with smallholder farmers and forest-bordering communities to select, clone and cultivate superior individuals of indigenous food trees. This domestication work could be enhanced by the development and deployment of digital smartphone apps for on-farm tree evaluation, focusing initially on indigenous fruit trees that have already been subject to some genetic improvement, and that are priorities for communities. These apps could build on digital tools that CIFOR-ICRAF has already developed for monitoring tree-based restoration and carbon sequestration. The apps could also support biodiversity conservation for the selected and evaluated trees, if trees' proof of presence, confirmed through an app, could be linked to the digital payment of credits for their maintenance (conservation credits).

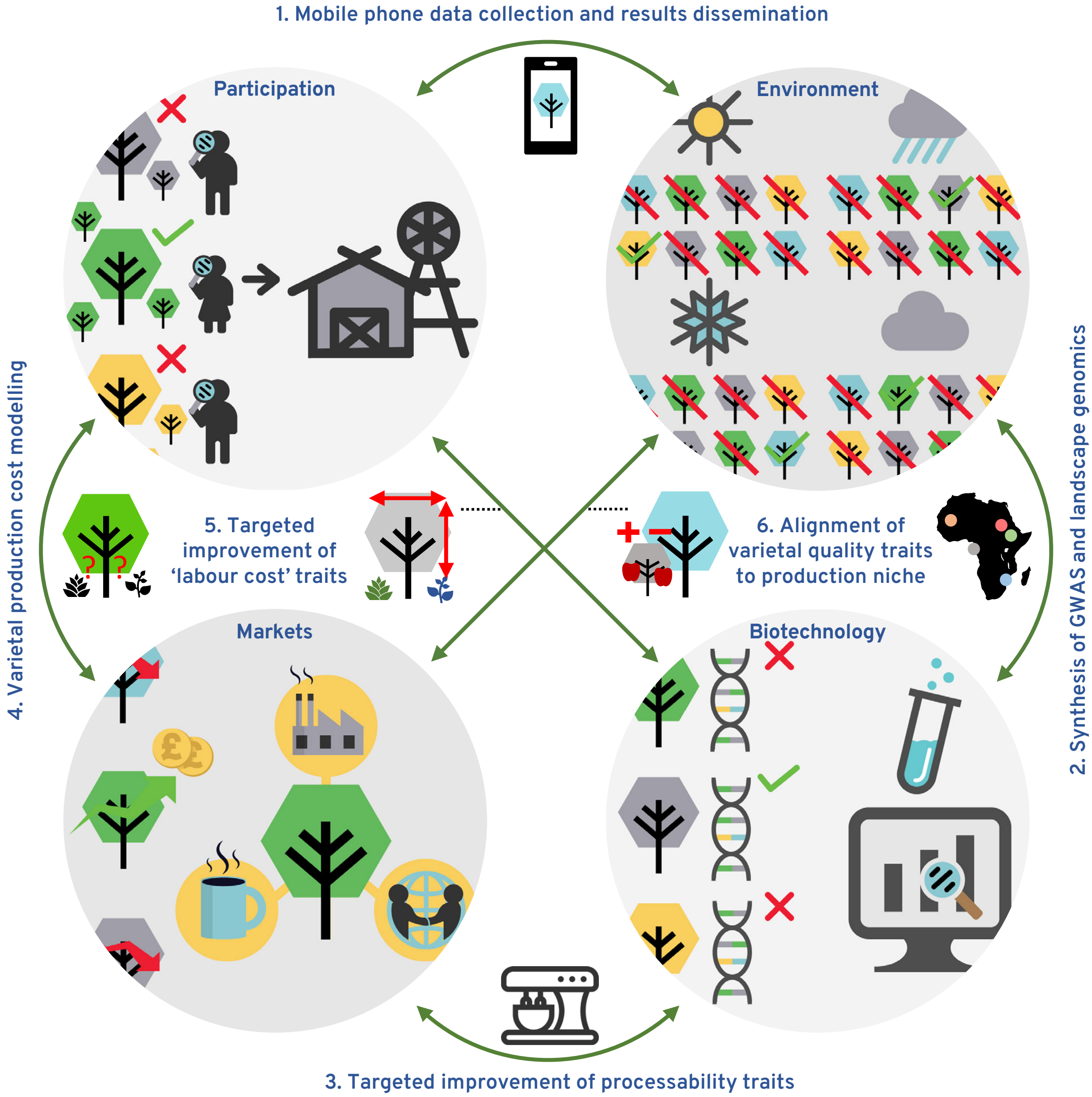

Figure 1. Schematic of the tree diversity breeding framework. Examples of novel linkages that constitute a systems approach to tree breeding – tree diversity breeding – are indicated with arrows and summary headings. Shown are linkages between existing breeding methods responsive to four important global trends of *participation, environment, biotechnology* and *markets*. "1. Mobile phone data collection and results dissemination" refers to the use of citizen science breeding approaches to bridge *participation* and *environment* trends; "2. Synthesis of GWAS [= genome-wide association studies] and landscape genomics" refers to the use of new statistical approaches to support progress in the understanding of genetic adaptation to bridge *environment* and *biotechnology* trends; "3. Targeted improvement of processability traits" refers to the manipulation of quality/processability-related genes to bridge *biotechnology* and *markets* trends; "4. Varietal production cost modelling" refers to advances in production system modelling for tree varieties to bridge *markets* and *participation* trends; "5. Targeted improvement of 'labour cost' traits" refers to the manipulation of, e.g., architecture-related genes to bridge *participation* and *biotechnology* trends; and "6. Alignment of varietal quality traits to production niche" refers to the use of novel methods to explore genetic, product quality and production system design relationships to bridge *environment* and *markets* trends. Numbers that precede the text within the schematic indicate the order that linkages are discussed in the main body of the text of this brief. The figure is taken from the *Trends in Plant Science* article of Graudal et al. (2022), on which this brief is based.

Table 1. A summary of novel linkages that constitute tree diversity breeding. Pairwise linkages are shown for four global trends (*participation, environment, biotechnology* and *markets*, as described in the text). Implications and opportunities for CIFOR-ICRAF's work are included.

Linkage between trends	Bottleneck to be addressed	Example innovation involved	How biodiversity is deployed	Desired outcome	Implications and opportunities for CIFOR-ICRAF's work
Participation + *Environment*	The small number of locations sampled currently in participatory domestication trials mean there is only limited knowledge on tree matching to planting conditions, resulting in mismatching	Citizen science-based tree breeding and selection trials using new mobile phone/smartphone approaches to recruit participants, collect data and disseminate location-specific findings allow testing across many more sites/systems	Tree genetic diversity in the landscape is better matched to growers' variable environments, cultivation practices and uses	More sustainable, context-tailored planting solutions	Develop and deploy digital apps to support participatory tree domestication with rural communities. Begin with work on priority indigenous fruit tree domesticates
Environment + *Biotechnology*	Current research provides only a limited understanding of the underlying processes of tree adaptation, restricting applicability for new environments	New statistical approaches – that synthesize genomic associations and whole genome data with phenotypes and home environments – provide a greater mechanistic understanding of adaptation	Tree genetic diversity in the landscape is better adapted to novel future environmental conditions	More efficient climate adaption and mitigation responses, including to completely new environments	Carry out genotyping and predictive modelling of breeding seedling orchards. Undertake new multi-locational, multi-provenance field trials in concert with genomic evaluation for existing leguminous tree collections with good passport data
Biotechnology + *Markets*	Current research on tree product quality/ processability traits is limited, restricting improvement progress and market uptake	Biotechnology provides new opportunities to manipulate product quality/ processability-related genes, supporting rapid genetic improvement	Tree genetic diversity in the landscape is better targeted to market-determined needs	Production system diversification and greater resilience, via a broader range of options for quality tree products	Study orthologs of known quality/ processability-related genes for relevant trees already in field trials, while newly phenotyping the quality/processability traits. Focus on edible oil/fat-producing trees
Markets + *Participation*	Limited progress in supporting the profitability of growers' engagement in market-based production is noted, leading to marginal returns	New cooperative modes of participation in production system modelling support the identification of 'what tree varieties to grow where' within production systems, in designs that maximize the value of labour investments as a major contribution to growers' profitability	Tree genetic diversity in the landscape fits more profitably in specific production system niches	Production system diversification especially for time-constrained (women) growers	Model the consequences of variation in tree phenology, maturity and architecture for growers' labour costs in agroforestry systems. Focus on tree foods that are especially important to women. Quantify variation in labour-related traits in existing field trials

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Table 1. Continued

Linkage between trends	Bottleneck to be addressed	Example innovation involved	How biodiversity is deployed	Desired outcome	Implications and opportunities for CIFOR-ICRAF's work
Participation + *Biotechnology*	Growers' labour constraints regarding profitability identified via cooperative engagement in production system modelling (as immediately above) present challenges to tree breeding, restricting improvement progress	Biotechnology provides new opportunities to manipulate labour cost-related genes, supporting rapid genetic improvement	Tree genetic diversity in the landscape fits more profitably in specific production system niches (as immediately above)	Production system diversification especially for time-constrained (women) growers (as immediately above)	Study orthologs of known genes involved in determining tree phenology, maturity and architecture that affect growers' labour costs. Study relevant trees already in field trials, ensuring at the same time to quantify variation in labour-related traits in the trials. Focus on tree foods that are particularly important for women (as immediately above)
Environment + *Markets*	Genetic/variety-level research to minimize trade-offs and maximize synergies between the environment and markets is limited, leading to lower sustainability and reduced profitability of tree planting	New systematic research methods allow the extent of the relationships between genetics, tree product quality and production system design to be determined, supporting more sustainable and profitable production	Tree genetic diversity in multi-species contexts is better matched to environments and markets	Production system diversification and greater sustainability, via a broader range of options for environmentally friendly and profitable production	Compare the product qualities of different tree varieties/breeding lines in production system configurations of varying environmental value. Focus on tree food crops currently grown in varied production system designs

Box 1. Implications of implementing the tree diversity breeding approach for CIFOR-ICRAF's field genebank activities

CIFOR-ICRAF's Genetic Resources Unit already holds, with its partners, more than 60 tree species in field genebanks. These are located in 18 countries in Africa, Asia and Latin America. The field genebanks conserve the trees and are a direct source of seeds and cuttings for growers to plant. The genebanks also serve as trials to understand more about genetic diversity in productivity-related traits, such as the amount of fruit or wood produced by the trees.

The adoption of a systems approach to tree breeding has important implications for CIFOR-ICRAF field genebanks, with a shift from business as usual to new emphases being required. In particular:

1. *The types of traits* characterized in genebank evaluations will require new thought, with increased importance being given to traits that support environmental service provision and environmental fitness, and that determine product quality and the labour costs of tree production. Specific traits that may require more attention include tree architecture and phenology, both of which determine how good a tree is in providing environmental services and both of which may affect the labour costs (or the timing of labour inputs) of production. Focusing on an expanded set of traits from business as usual may require different trial evaluators, possibly including local communities to evaluate quality, labour costs, etc.

2. *The design of stands* will need to change to support more holistic, systems-based evaluation. Instead of only planting single-species genebanks, multi-species stands may sometimes be required. This will enable an exploration of the interactions between tree species, or even between trees and important annual crops. This new approach to genebank design would allow the role of genetics in defining new, integrated production systems to be better defined. In addition, if designs for mixed-species breeding seedling orchards and the like are drawn up and implemented correctly, it should not (or at least not markedly) detract from the conservation and propagule supply functions of the stands. A particular focus could be on bringing together tree foods with other tree types, and with annual crops. Understanding how best to manage these mixed stands to maximize benefits over time would need to be a feature of such work.

The use of new statistical approaches to support progress in the understanding of genetic adaptation to bridge *environment* and *biotechnology* trends

The complexities involved mean that current field trials provide only a limited understanding of the underlying processes involved in trees' adaption to different environments, even when the trials are combined with genome-wide genetic markers to try to dissect out relevant traits. This restricts the ability to predict the performance of trees in new environments, such as those created by anthropogenic climate change. This topic is especially important when factoring in the longevity of trees, as a tree planted now may experience a range of different environments in its lifetime. New statistical approaches that synthesize genomic data with data on both trial phenotypes and home environments (information on the sites where the trees originally came from, collected in the form of passport data and extracted from high-resolution location-linked global datasets on temperature, rainfall, soil type, etc.) provide a way forward to reach a better understanding of the underlying mechanisms of adaptation. This will provide more predictive power for matching planting materials to new conditions.

Implications and opportunities for CIFOR-ICRAF: CIFOR-ICRAF has recently worked with partners in East Africa to establish breeding seedling orchards of native timber trees that are crucial for forest landscape restoration. The value of this work for evaluating adaptive variation in the trees, and supplying tree seed properly matched to different planting environments, could be enhanced by the genotyping of the trees and the combining of phenotype and genotype information with the home environments of the original seed collection sites, using predictive modelling. Good tree species candidates for additional work that combines field trials with genomic and home environment analysis are those for which the CIFOR-ICRAF Genetic Resources Unit holds range-wide, well-documented seed collections. Such collections include a range of leguminous species from Africa and Latin America. CIFOR-ICRAF also develops new soil maps that are an important feature of defining home environments and these could be integrated into the modelling.

The manipulation of quality/processability-related genes to bridge *biotechnology* and *markets* trends

Quality-related traits, including tree processability traits (the characteristics of a tree product that influence the ability to make use of the tree through processing), have been relatively understudied for trees compared with annual crops. This has limited genetic improvement progress and therefore the market uptake of tree products. Biotechnology provides new opportunities to improve these traits through the manipulation of known orthologs (genes in different species that evolved from a common ancestral gene) of the relevant genes, initially identified in model plants. Examples are ethylene biosynthesis pathway genes that regulate the ripening and shelf life of fruit, and lipase genes that control fruits' fatty acid release. Manipulation can address the preferences of retailers, manufacturers and consumers, and reduce post-production costs.

Implications and opportunities for CIFOR-ICRAF: CIFOR-ICRAF researchers work on a number of tree species providing commercial edible oils and fats for which tree-to-tree variation in fat profiles have been observed. By studying variation in orthologs of known fat-related genes in these trees, in conjunction with the new phenotypic evaluation of the lipid profiles of the same trees in existing field trials, progress in developing cultivars with improved lipid quality could be accelerated. This would be especially true if analyses were carried out in collaboration with the players in the market value chain, to support the development and mainstreaming of higher quality genetic materials.

Advances in production system modelling for tree varieties to bridge *markets* and *participation* trends

Maximizing profit for small-scale tree growers engaged in market-oriented production has not often been a priority in tree improvement, with high labour costs being a key factor in limiting growers' current returns. New cooperative modes of production system modelling can look at how the different components of a production system fit together. Their application can reduce and appropriately spread labour costs by better matching specific tree varieties or genotypes to particular production niches. This modelling involves commercial companies and tree breeders working with growers to find low-labour solutions for tree-based production. This may be especially useful for ensuring the participation of women growers in tree product markets, as women are often particularly time-constrained.

Implications and opportunities for CIFOR-ICRAF: CIFOR-ICRAF works intensively with farmers and other partners to optimize agroforestry production system designs that incorporate trees, annual crops and other production components. By considering genetic variation in key labour-related traits for trees in these designs, opportunities to develop more labour-efficient systems will be revealed. The relevant traits to consider include phenology (when in the year the tree leafs, flowers and/or fruits, which determines labour clashes or complementarities with other farm activities, and overall farm-level cash flows), time to maturity (in the sense of how many years after planting it is before the tree first produces the product it is grown for, which determines the return on the labour investment in tree cultivation over the years) and architecture (tree height, branching, etc., which determine ease and speed of harvesting over and above potential direct effects on productivity). One focus should be on tree foods that are regularly harvested and therefore more labour demanding, and are important to women growers for both family use and sale. A starting point is to ensure that traits of phenology, maturity and architecture are characterized in existing CIFOR-ICRAF field trials of the relevant food trees.

The manipulation of architecture- and phenology-related genes to bridge *participation* and *biotechnology* trends

The production system modelling described above will identify labour-related traits for genetic improvement that previously have been intractable to rapid progress by traditional tree breeding methods, restricting improvement advances. As with quality-related traits (see above), biotechnology provides new opportunities to improve labour-related traits through the manipulation of orthologs of the relevant genes, initially identified in model plants. Panels of genes that help determine phenology, time to maturity and architecture have all been well characterized in model organisms and their orthologs identified in trees.

Implications and opportunities for CIFOR-ICRAF: In conjunction with production system modelling that identifies key targets for genetic improvement in the labour-related traits of tree phenology, maturity and architecture, variation in the orthologs of the known genes involved with these traits should be analysed. This molecular genetic diversity should be explored in tree species that are already in CIFOR-ICRAF field trials that are also being measured for phenotypic variation in the relevant traits. The work should focus on food trees where labour costs are a significant constraint to production (see above). The work should be undertaken in collaboration with commercial companies and growers, to support the development and mainstreaming of higher value genetic materials.

The use of novel methods to explore genetic, product quality and production system design relationships to bridge *environment* and *markets* trends

Work to minimize the trade-offs – and maximize any synergies – between the environmental and market functions of trees during planting has been limited. This has restricted the development of a broad range of context-specific, sustainable and profitable tree production options. New systematic research approaches applied to coffee and other perennial commodity crops compare the product quality (and thus market value) of different varieties or breeding lines in different production systems of varying environmental value. In the case of coffee, for example, the work shows that certain varieties only produce high-quality, high-value beans when they grow in shade production systems that are biodiversity friendly.

Implications and opportunities for CIFOR-ICRAF: CIFOR-ICRAF should undertake research to compare the product qualities of different tree varieties/breeding lines in various production system configurations of varying environmental value, especially in those cases where a market premium for quality may incentivize more environmentally motivated practices. The focus should be on tree food crops that CIFOR-ICRAF has already studied in single species trials, but that are actually grown by farmers in various production systems (e.g., in both shade and sun systems). As already noted, CIFOR-ICRAF works intensively with farmers to optimize agroforestry production system designs, so an additional focus on tree product quality in this work, closely coupled with an assessment of the environmental benefits of designs, is recommended. This work can further build on CIFOR-ICRAF's existing efforts to develop biodiversity indicators as market differentiators.

Conclusion

In this brief, we have explained the theoretical concept of tree diversity breeding as it was first set out in our recent TIPS opinion piece (Graudal et al. 2022). We have in addition explored the application of the approach in practice, to direct the future genetic improvement of agroforestry trees in particular, taking the case of CIFOR-ICRAF's work as a case study. But the implications and opportunities in adopting the tree diversity breeding approach extend well beyond CIFOR-ICRAF, and are salient for other institutions and researchers that work at the forest–agriculture interface. On this basis, we provide some recommendations for the direction of such work more broadly (Box 2).

Box 2. Recommendations for implementing the tree diversity breeding approach for institutions and researchers concerned with tree genetic improvement at the forest–agriculture interface

- Institutions should invest in platforms, including digital apps, that support citizen science in tree breeding and selection, and deploy these across multiple situations. This will help bridge *participation* and *environment* trends and values.
- Researchers should adopt statistical approaches that synthesize genomic, phenotypic and home environment data in tree trial analysis, especially for priority tree species for forest landscape restoration, in conjunction with breeding seedling orchard development. This will help bridge *environment* and *biotechnology* trends and values.
- Researchers should give more attention to exploring quality/processability-related traits for tree products, making use of advances in biotechnology and focusing on traits that will support farmers' revenues and engagement in markets. This will help bridge *biotechnology* and *markets* trends and values.
- Institutions should adopt new cooperative modes of participation in production system modelling that better match specific tree varieties or genotypes to particular production niches, especially considering growers' labour costs for production. This will help bridge *markets* and *participation* trends and values.
- Connected to the previous bullet point, researchers should give more attention to exploring labour cost-related traits for tree products, making use of advances in biotechnology. This will help bridge *participation* and *biotechnology* trends and values.
- Researchers should undertake systematic study of the relationships between different tree varieties or breeding lines, product quality and production system designs that provide varying environmental services. This will help bridge *environment* and *markets* trends and values.

See Box 1 for the implications of the tree diversity breeding approach specifically for the evaluation and design of field genebanks, including breeding seedling orchards that serve conservation, evaluation and propagule supply functions.

The essence of tree diversity breeding involves consideration of multiple global challenges together. This is so that sustainable progress can be achieved in addressing these challenges. From the perspective of policy, the starting point for the wider adoption of the approach is to ensure that tree breeding does not only focus on the traditional metrics of productivity and (companies') profitability as measures of breeding advancement. Rather, for a systems approach to tree breeding to be successful, a broad set of measures that define breeding success is required. These should include aspects of resilience, sustainability, nutritional security, local culture and conservation. In each case, appropriate values and measures of success need to be defined and adopted by the relevant stakeholders.

Policy interventions to encourage a systems approach to tree breeding should provide incentives for tree researchers and breeders to embrace these broader values, as these values become better defined. This will include measuring the success of tree planting at the grower level in different ways and relating this back to the breeding process. We also suggest that there should be specific incentives for tree breeders to bring together existing breeding methods in novel ways – as we have described in this brief – so that multiple values are addressed together in the improvement process. This could be through a preference toward such combinatory projects when allocating public and private funding.

Of course, appropriate methods for tree breeding must be fully integrated into effective tree seed delivery systems that supply growers with appropriate planting material. These delivery systems were the subject of an earlier ICRAF brief (Lillesø et al. 2021).

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