infobrief

CIFOR-ICRAF *infobriefs* provide concise, accurate, peer-reviewed information on current topics in forest research

CIFOR World Agroforestry

No. 383, April 2023

DOI: 10.17528/cifor-icraf/008850 | cifor-icraf.org

Operationalizing Climate Appropriate Portfolios of Tree Diversity

Roeland Kindt[1], Lars Graudal[1,2], Ramni Jamnadass[1], Fabio Pedercini[1,2], Stepha McMullin[1], Prasad S Hendre[1], Sammy Carsan[1], Soren Moestrup[2,4], Abrham Abiyu[4], Jens-Peter B Lillesø[2] and Ian K Dawson[1,3]

Key messages

- Climate Appropriate Portfolios of Tree Diversity (CAPTD) are mixes of tree species' planting materials, delivered to growers, that are environmentally-matched to planting sites and purpose-matched to planting requirements.
- CAPTD are necessary to respond to climate change in conjunction with other challenges that tree planting can help address.
- A possible pathway for the operationalization of CAPTD, outlined in this brief, involves a series of steps to define the portfolios and then implement them, drawing on different tree-knowledge resources, consultation approaches and planting material production methods.

Summary

In this brief we describe a pathway for operationalizing Climate Appropriate Portfolios of Tree Diversity. These portfolios of tree species for planting are necessary to respond to climate change along with other challenges that tree planting helps address. We describe what CAPTD consist of, and we outline different possible steps in their definition and implementation, although there is no 'one-size-fits-all' approach. There are seven steps in the pathway to operationalization that we present here: 1, to identify priority areas for tree planting; 2, to check tree species distributions (what can be planted where); 3, to consider planters' needs (what should be planted to meet these needs); 4, to check for existing adapted tree seed and seedling sources and their suppliers; 5, to invest in expanding tree seed and seedling systems; 6, to provide support to properly plant and manage selected trees species; and 7, to monitor progress and provide feedback in order to refine portfolio definition and implementation. Through adopting tools and approaches such as those we outline here, climate change mitigation and adaptation can be properly factored into tree planting, along with broader tree-planting goals.

Introduction

Tree planting is widely adopted to address climate change: it mitigates greenhouse gas emissions by sequestering carbon, and trees provide resilient sources of products and environmental services, even under the increasingly variable weather conditions that climate change creates. For planting, increasing evidence shows that a diversity of tree species is valuable, as this can provide more stable total productivity and greater sequestration of carbon. Genetic variation within tree species is important too, as it supports greater climate-adaptative potential and long-term stability, and enhances production.

Too often, however, the trees that are planted are the wrong types. Too few tree species are being used, leading to monocultures and environmental damage, which may be made worse when exotic tree species are planted, as often happens. In addition, genetically unadapted and otherwise low-quality tree seeds and seedlings are being relied upon that establish and grow only poorly. This leads to local communities' needs as regards tree planting not being properly addressed, as well as planting not providing intended 'global' environmental benefits such as carbon sequestration. These failures in the choice of planting material, along with the poor management of seeds, seedlings and trees, are some of the reasons why civil society and potential investors in tree planting now question whether it is worthwhile to become involved, just as tree planting becomes more vital.

Climate change complicates the choice about what trees to plant where, as the growth of the trees themselves is affected by the environment in which they are planted. This means that what species and what 'provenances' (or cultivars, lines, genotypes, etc.) can grow at any particular location alters with climate change. It also affects how the trees need to be managed at a planting site for them to establish and grow properly. Trees that grow well at one site now may not do so in the future, due to alterations in

1 CIFOR-ICRAF, Kenya

2 Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark

3 Scotland's Rural College (SRUC), Scotland

4 CIFOR-ICRAF, Ethiopia Office, Ethiopia

conditions that are 'abiotic' in nature (e.g. temperature and precipitation; drought, flood and fire frequencies) and/or are of 'biotic' origin (e.g. prevalence of pests and diseases). Climate change also affects the particular needs of the consumers of tree products and services. For example, to adapt to climate change, consumers may need new tree foods that substitute for annual crops that can no longer be grown. This in turn would mean that producers would need to switch to growing these new tree products and would need to understand how best to do so.

Evidently, getting 'what to plant where, when, and how' right is not a simple process in tree planting. This is especially so when planting is being used to tackle multiple pressing concerns that extend beyond climate change to food supplies, income provision, watershed protection, biodiversity conservation, etc., as there can be trade-offs as well as complementarities in addressing these different challenges. Science plays an important role in making better decisions, but the science needs to be successfully applied.

In this information brief, we look at a possible route to operationalize what we call Climate Appropriate Portfolios of Tree Diversity (CAPTD for short). The approach is designed to resolve the challenge of delivering the right tree planting material to the right place for the right purpose, to address climate change as well as other concerns. The approach we describe is practical as well as science based.

Steps in operationalizing Climate Appropriate Portfolios of Tree Diversity

Box 1 explains what CAPTD constitute. In this section, we consider aspects of operationalization. There is no 'one-size-fits-all' approach, but we present a pathway that involves seven steps. Our pathway is illustrated in the schematic of Figure 1. Each of the steps shown, from 1 to 7, is summarized in the current section, along with some of the CIFOR-ICRAF tools and approaches designed to facilitate each step, with hyperlinks and other references to these resources. These tools and approaches are targeted to a range of stakeholders that need to take action, including policymakers, land-use planners, investors, non-governmental organizations (NGOs), community groups and the actual planters. It should be emphasized that the pathway we describe here is not the only approach by which CAPTD can be operationalized – for example, the ordering of the shown steps may be changed, and some steps might be excluded or new ones included. The specific steps and their ordering will depend on the particular objectives of tree planting, the stakeholders involved and the wider context within which planting is taking place. Our example of operationalization can be built on by others.

Box 1. What are Climate Appropriate Portfolios of Tree Diversity?

Climate Appropriate Portfolios of Tree Diversity (CAPTD) are mixes of tree species' planting materials, delivered to growers, that are environmentally-matched to planting sites and purpose-matched to planting requirements. Both the 'environmental' and 'purpose' components of matching are crucial to CAPTD: the environmental component embraces both contemporary and predicted future climatic conditions at a planting site; while the purpose component covers the different functions for which trees are grown.

CAPTD place emphasis on tree species diversity at two levels. First, for any specific planting site, a range of tree species is promoted to strengthen resilience in delivering the multiple products and services that trees provide. Second, CAPTD are portfolios (plural) of diversity. This is because different, specifically composed groups of tree species are applicable for planting at different locations, depending on the specific environmental conditions and local growers' particular priorities.

In addition to the range of tree species promoted, a final aspect of diversity embraced by CAPTD is the genetic variation found among provenances, cultivars, lines, genotypes, etc., of any one tree species. This variation can determine the 'environmental adaptedness' and adaptability of the trees for growth at specific locations, as well as how well the trees provide particular products and services. This variation therefore also affects planting material choice.

The tree species involved in CAPTD may be exotic or native to a planting location or a combination of the two. The intention however is to encourage a greater component of native trees in portfolios, as this fits with conserving biodiversity along with supporting climate resilience and meeting other challenges. This focus on biodiversity is increasingly reflected in national governments' policies on climate change, the environment broadly, and development.

The growers to whom portfolios are delivered may be small-scale farmers practising agroforestry, large-scale plantation establishers and planters purposefully carrying out forest landscape restoration, among others.

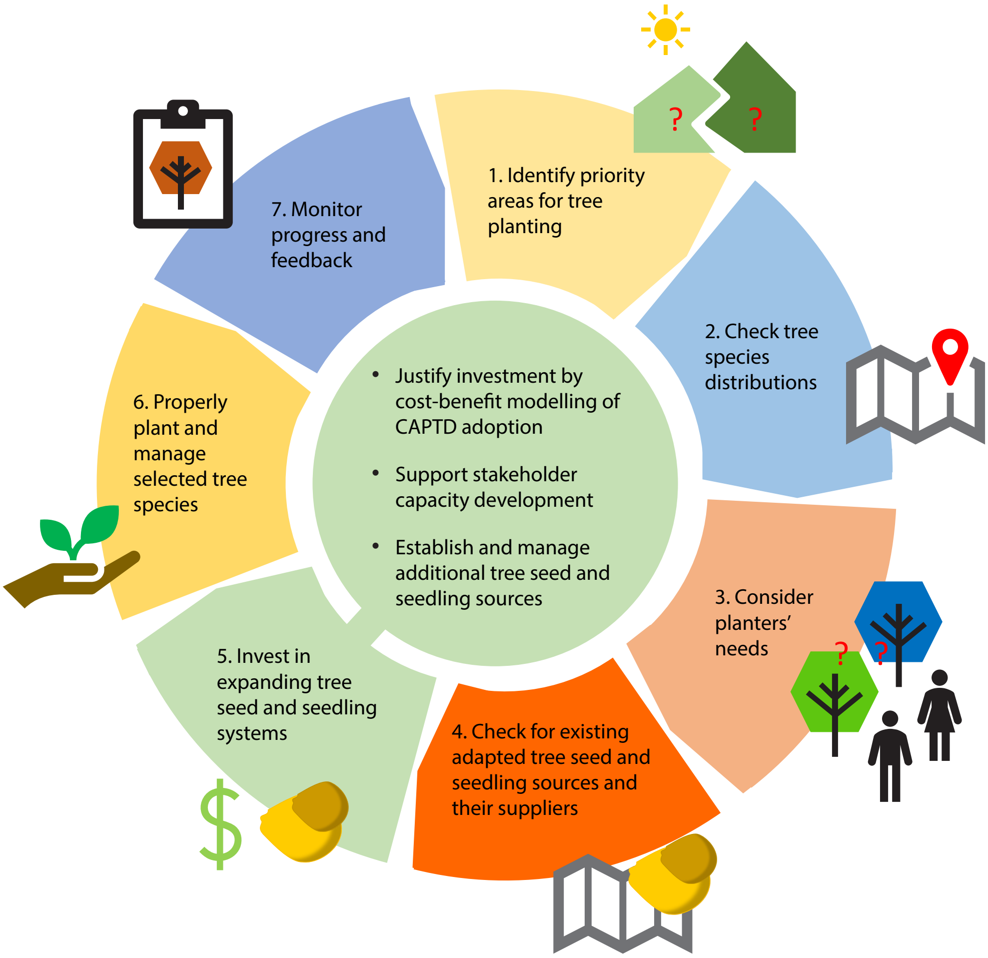

Figure 1. Schematic representing a possible pathway for operationalizing Climate Appropriate Portfolios of Tree Diversity (CAPTD).

The steps of CAPTD noted in the figure are discussed in the text using the reference numbers shown here. "1. Identify priority areas for tree planting" refers to the systematic application of appropriate indicators of the projected impact of planting to identify priority locations. "2. Check tree species distributions" refers to the modelling of tree species' ranges in contemporary and projected future climates. "3. Consider planters' needs" refers to participatory priority setting with growers to integrate their requirements from tree planting. "4. Check for existing adapted tree seed and seedling sources and their suppliers" refers to the identification of suitable sources of seeds and seedlings for planting. "5. Invest in expanding tree seed and seedling systems" refers to addressing challenges in tree seed and seedling supply. "6. Properly plant and manage selected tree species" refers to providing support for the adoption of appropriate nursery raising, field planting and further management methods by tree growers. "7. Monitor progress and feedback" refers to the refinement of the CAPTD approach. Because investment in the expansion of tree seed and seedling systems (step 5) is such a crucial part of CAPTD operationalization, we have highlighted in the centre of the schematic some of the key activities that support this.

1. Identify priority areas for tree planting

Objective determination of which are priority locations for where to plant trees is an important early step in tree-planting planning. Objective assessment requires the systematic application in geographic space of appropriate indicators of the projected impacts of planting, with reference to the particular challenges that are being addressed. Specifically with reference to the climate change challenge, one useful indicator that has been estimated for geospatially gridded map locations is climate change velocity (how quickly climate is changing), which can be used as a measure of the necessity of climate change adaptation at a location (high velocity = high priority). Another useful indicator calculated for gridded map locations is the potential to increase aboveground biomass, which can be taken as a measure of the climate change mitigation opportunity at a site (high potential = high priority).

CIFOR-ICRAF tools and approaches: CIFOR-ICRAF and partners have developed a multi-indicator approach for determining priority areas for tree planting (Pedercini et al. 2021). The approach was initially developed to support tree-planting-based landscape restoration. With suitable tweaks, however, it is applicable for the planning of any tree planting, including agroforestry broadly and horticulture. The approach starts with open-access maps of current land use patterns and potential natural vegetations, and then uses a wide range of other spatial datasets to set priority locations for planting interventions. A total of seven indicators that consider both the socioeconomic and environmental outcomes of planting are currently applied, but the indicator set can be adjusted. Specific climate-change-related indicators used currently by the approach are climate change velocity (comparing contemporary and predicted 2070 climates) and aboveground biomass increase potential. The other five current indicators relate to market access, tree cover change, productivity performance, soil erosion risk and the biodiversity value of sites. Information across indicators is combined using an integer linear programming algorithm to identify the areas that, overall, are planting priorities. The approach has so far been applied to Ethiopia, setting a selection intensity consistent with the 15 million hectares of the country that have been assigned under the Bonn Challenge as the national commitment for restoration. The methods are currently being extended to prioritize areas for tree planting in other East African countries. Pedercini et al.'s (2021) methods do not yet take into account the broader 'enabling human environment' for tree planting at specific locations, which is clearly a crucial practical issue guiding prioritization; future work will do so by integrating a wider range of indicators.

2. Check tree species distributions

When priority areas for tree planting have been settled upon, an understanding of which tree species grow well in these locations now, and which are expected (still) to grow well at these sites in the future, helps decide which trees to plant. Important information sources on which trees grow well currently at a location include geographic coordinate data of tree presence (from flora, inventories, genebank collection records, etc.) and vegetation maps. These information sources can be used to model contemporary and likely future tree species distributions, when combined with geospatial layers of current climate and predicted future climatic conditions, respectively. This modelling can then be used in three ways to narrow down what tree species to plant: first, by taking account of contemporary climate only; second, by considering future climate only; or, third, by considering both situations. In the last case, it is the tree species that are predicted to be present in the future (say, in the year 2050 or 2070) and that are present currently that are prioritized. This last option is an attractive one for both maximizing the probability of initial tree-planting success (establishment) and the likelihood of obtaining products and services from planted trees when these will only be fully realized decades later (e.g. when the product is timber or the service is carbon sequestration). This option also carries risks, however, in that it may narrow down species selection too quickly to only those trees with known broad environmental parameters for growth. This could work against the inclusion of native tree species as planting options, as these species have often not been tested across a wide range of environments. The testing of native trees under broad environmental conditions is therefore important.

CIFOR-ICRAF tools and approaches: CIFOR-ICRAF and partners have developed maps of the current and predicted future distributions of a substantial number of tree species. These maps are based on geographic point location data of trees collected from online databases and, where such data are limited, on maps of vegetation types. The Climate Change Atlas for Africa, for example, is based on point location data and the application of multiple global circulation models and greenhouse gas emission scenarios for the purpose of modelling future climatic conditions (Kindt et al. 2021). It shows the current and predicted year 2050 distributions of 127 tree species on the African continent. Similar 'current' and 'future' distribution maps are available in de Sousa et al. (2019) for 100 tree species in Central America. Based on vegetation patterns rather than point location records, the vegetationmap4africa (V4A) shows the expected distributions of over 700 tree species in 8 eastern Africa countries (van Breugel et al. 2015). CIFOR-ICRAF is continuing to scale out the development of these maps to embrace new locations and a broader range of tree species, with global maps of all tree species' distributions under current and predicted future climates being the ultimate objective.

3. Consider planters' needs

Once a 'long-list' of tree species that could be planted has been identified for a planting site, candidates on the list need to be considered against government priorities and planter needs. Considering the needs of local people who in most circumstances carry out tree planting and management is fundamental when prioritizing, both to support livelihoods and because if this is not done then there will be no incentive for them to become involved. In that case, tree-planting initiatives and the achievement of their wider objectives will fail. An understanding is needed of local peoples' preferences and priorities for particular products and services, and how these are affected by culture, gender, demography, market access, land tenure and other factors. From a climate change perspective, it means considering how climate change is in itself affecting local peoples' needs for the products and services that trees can provide.

CIFOR-ICRAF tools and approaches: CIFOR-ICRAF and partners have developed participatory approaches to tree species priority setting. These methods ask local stakeholders disaggregated by gender, age, etc., about what functions (food, timber, medicine, etc.) they need trees for, what tree species are currently used for these purposes, and what other tree species they would choose to fill current gaps in provision. CIFOR-ICRAF first applied participatory species priority setting methods in the 1990s to settle on which native food tree species to promote in Southern Africa (Franzel and Kindt 2012). More recently, participatory methods have been used to identify 'food tree portfolios' (McMullin et al. 2019). These are collections of tree species that produce edible fruits, nuts, seeds, etc., to fill seasonal hunger and nutrient gaps at particular locations, and 26 such portfolios have so far been developed in Africa. CIFOR-ICRAF has also developed online tree-knowledge resources that provide information on the uses of tree species. These include the Agroforestree Database, which contains data on tree products and services for over 600 tropical agroforestry tree species (Orwa et al. 2009). Also included is the Agroforestry Species Switchboard that makes available and visible a broad range of tree-use information resources (Kindt et al. 2022b). To promote the use of native tree species, CIFOR-ICRAF's GlobalUsefulNativeTrees database (GlobUNT) provides information on the uses of more than 14,000 tree species and indicates where these species occur naturally (Kindt et al. 2022c). CIFOR-ICRAF is currently refining the food tree portfolio approach to specifically address climate change challenges, so that it will be even more useful for species priority setting (e.g. so that food tree portfolios are fully climate resilient in nutrient provision).

4. Check for existing adapted tree seed and seedling sources and their suppliers

Once a target list of environmentally-matched and use-appropriate tree species has been identified for priority planting sites, suitable sources of planting material and their suppliers need to be found. As already noted in step 2 and Box 1, from a climate change perspective this may involve the sourcing of tree species, and suitable provenances and cultivars, etc., that are expected to be adapted to the predicted future environmental conditions at a planting site instead of, or as well as, to the contemporary conditions. Regardless, the source selection process normally relies on the assumption that extant natural sources of 'germplasm' are adapted to their specific prevailing environmental conditions. Thus, all else being equal, when choosing a germplasm source from within the range of environments experienced by a tree species, the source of that species that has the environment most closely matched to the planting site is chosen. This might be trees that are already at, or in close proximity to, the planned planting site (if thinking simply in terms of 'current' climate); but, if no such trees are found there, it means giving preference to germplasm collected from the most analogous site elsewhere. Clearly, once such germplasm sources have been identified, they also need to be protected so that they can continue to be accessed.

CIFOR-ICRAF tools and approaches: CIFOR-ICRAF and partners published the global Tree Seed Suppliers Directory in the 1990s. The printed directory, based on data collated from 'paper' lists of woody perennial species provided as seeds or as other propagules by 144 germplasm suppliers from across the world, contains 5,874 taxa (Kindt et al. 2002). Although the directory is still available online, the long period of time since its compilation means that it is now of only limited utility for identifying suppliers, as many no longer operate. Attempts have been made to update the directory, but devising a system to 'scrape' together the needed information from supplier websites is not straightforward. CIFOR-ICRAF has instead focused on cataloguing tree germplasm sources and suppliers at a national level, which is consistent with placing greater emphasis on planting native tree species (Box 1). The online What to Plant Where in Ethiopia selection tool provides guidance on the best-matched, nationally available tree seed sources and their suppliers for any given planting location in Ethiopia, for both contemporary and future climates (Kindt et al. 2022a). CIFOR-ICRAF is currently building similar tools to this for other countries that not only support seed access but allow conservation efforts to be targeted to key germplasm sources.

5. Invest in expanding tree seed and seedling systems

Existing constraints in tree seed and seedling delivery to growers are enormous and climate change makes the situation worse because of the 'moving target' of matching planting site environment with planting material. Investment in the expanding of effective 'tree seed and seedling systems' is a crucial driver for CAPTD operationalization. This investment is needed to effectively supply seeds and seedlings of most tree species, but for native trees investment is especially important because these have received little 'delivery' attention in the past. The implementation of tree seed and seedling systems is multifaceted, but in Box 2 we summarize three key areas where activity is needed in order to be able to operationalize CAPTD (see also the centre of the Figure 1 schematic).

CIFOR-ICRAF tools and approaches: CIFOR-ICRAF with the University of Copenhagen supports the systematic development of integrated tree seed and seedling systems that deliver high-quality germplasm of diverse tree species to planters. Support has included the development of a tool for modelling the costs and benefits of investing in high-quality tree seed delivery, including in terms of carbon sequestration benefits (Pedercini et al. 2022). Pedercini et al.'s (2022) tool can be applied to any tree species for which growth data and seed sourcing costs can be reasonably estimated. CIFOR-ICRAF and the University of Copenhagen have also developed, made available, and tested, assessment tools for understanding where interventions are most needed in the tree seed sector (Lillesø et al. 2018, 2021). These tools are supported by extensive training materials developed for tree seed sourcing and nursery seedling supply (available at the Resources for Tree Planting Platform; Schmidt et al. 2021). CIFOR-ICRAF and partners have also developed approaches for the production of tree seed in planted seed orchards, with equivalent designs for producing vegetative propagules when more appropriate. These approaches have recently been implemented at scale in Ethiopia, where work has included the establishment of breeding seedling orchards (BSOs) (PATSPO 2023). These BSOs not only produce seed, but allow for the evaluation of genotype-by-environment interactions in trees, for genetic improvement, and for the conservation of the tree genetic diversity that is needed for resilience. The BSO approach is currently being scaled regionally, with a focus on native tree species. Pedercini et al.'s (2022) methods so far only estimate CAPTD operationalization benefits on a species-by-species basis and do not yet account for diversification benefits such as increased resilience; future work will explore the integration of these benefits also.

6. Properly plant and manage selected tree species

Once the right tree germplasm has been sourced, it needs to be planted out, and the trees raised by growers in the right way. For native tree species especially, the knowledge growers have on how to plant out and then manage planted trees may be insufficient, as in the past wild trees were relied upon for product and service provision. Particular attention is therefore required to address this knowledge gap. Climate change itself poses particular risks and challenges for tree growing, such as more frequent drought periods or floods, and the planting and further management methods promoted to growers need to specifically address these challenges.

CIFOR-ICRAF tools and approaches: CIFOR-ICRAF and partners have developed a number of knowledge resources, including guidelines and training materials, that support the correct field planting and further field management of tree species within different contexts. One example is the Agroforestree Database that, as well as providing information on trees' uses (see step 3),

Box 2. Implementing tree seed and seedling systems for operationalizing Climate Appropriate Portfolios of Tree Diversity

Three areas of activity that are instrumental in making progress in tree seed and seedling system implementation to operationalize CAPTD are outlined below.

Justify investment by cost–benefit modelling of CAPTD adoption. Cost–benefit modelling is a key approach illustrating that high livelihood and environmental returns are possible with investments in tree seed and seedling systems. Modelling compares a 'business-as-usual' scenario for tree planting material supply with a scenario where better site-adapted and/or purpose-matched germplasm is made available. Costs are modelled in terms of the extra expense of sourcing high-quality planting material, and benefits are modelled in terms of the extra quantity of timber produced (an economic benefit) or the greater amount of carbon sequestered (an environmental benefit), etc., for each individual species in a portfolio, as well as the benefits achieved by species diversification (risk spreading, etc.).

Support stakeholder capacity development. Assessing the current infrastructural and technical capacities of the different stakeholders that make up a tree seed and seedling system is a crucial step for operationalizing improved tree planting material delivery to growers, because it allows support to be targeted to the filling of the revealed gaps. The current roles of small- and medium-sized enterprises, NGOs, national tree seed centres, government extension services and other stakeholders are determined through a sectoral assessment, and a more effective and equitable seed system is designed. Sectoral analysis often identifies a particular lack of knowledge among stakeholders in how to collect and handle seeds and other propagules of native tree species, and in how to raise their seedlings in nurseries. It frequently also reveals that support is needed to build communication between stakeholders, to better match tree planting material supply and demand.

Establish and manage additional tree seed and seedling sources. A key requirement for tree seed and seedling system implementation is to develop planted sources of high-quality seed, vegetative propagules, etc. This is to allow greater and more convenient planting material supply than just relying on existing germplasm sources (see step 4). The way that bespoke planted germplasm production stands are designed depends on the specific requirements of production. Designs may not only produce planting material, but conserve the trees, and allow the evaluation of genotype-by-environment interactions to support planting material–site matching. Stands that explore these interactions are particularly useful for responding to climate change, where altered environments at planting sites are created.

contains information on how to manage planted trees (Orwa et al. 2009). Another example is the Resources for Tree Planting Platform (see step 5), which includes many different sources of information on field planting and further management methods (Schmidt et al. 2021). These resources are being refined to specifically address the climate change challenges of planting and management, especially for native tree species.

7. Monitor progress and feedback

Crucial for scaling the adoption of CAPTD is to understand the results from their initial implementation, so that findings can be fed back to refine portfolio definition and further implementation. This means understanding the benefits that are achieved by the approach in terms of livelihoods and environmental services provision, paying attention to climate resilience and mitigation among other measures related to the broader goals of the tree planting. This requires adopting a range of indicators for assessing the success of intervention.

CIFOR-ICRAF tools and approaches: CIFOR-ICRAF is currently designing a transformative partnership platform with tree planters, researchers and investors that will explore the benefits of improving quality in tree seed and seedling sourcing in large-scale planting initiatives, including the benefits measured in terms of carbon sequestration and climate resilience. In work on tree genetic improvement, CIFOR-ICRAF has suggested a shift from 'production' alone to a broader range of indicators for measuring breeding success (Graudal et al. 2022), and some of these indicators will be considered for monitoring CAPTD implementation.

Conclusion

In this information brief, we have explained some possible steps for operationalizing Climate Appropriate Portfolios of Tree Diversity (CAPTD) to support climate mitigation and adaptation benefits from tree planting, as well as to achieve broader goals from growing trees. We have also outlined some of the relevant CIFOR-ICRAF tools and approaches that support this operationalization. These include tools and approaches for identifying priority areas for tree planting; for checking what trees will grow well at specific planting locations now and likely in the future; for considering growers' needs in planting, especially those of the local people who typically manage the planted trees; for identifying existing suitable sources of planting material and their suppliers; for investing in the expansion of tree seed and seedling systems; for properly managing the planting out and growing of trees; and for monitoring the progress of implementation to refine the application of CAPTD. From the perspective of policy, the starting point for the wider adoption of CAPTD is to provide incentives that ensure that climate change impacts, and the possible responses, are properly integrated into all aspects of tree-planting decision-making, with emphasis given to the role of tree species and genetic diversity in achieving impactful responses.

Acknowledgements

Current support for CIFOR-ICRAF's work on CAPTD comes from Norway's International Climate and Forest Initiative through its funding of the Provision of Adequate Tree Seed Portfolios (PATSPO) project for improving Ethiopia's tree seed supply, and from Germany's International Climate Initiative through its initial funding for development of the Right Tree in the Right Place proposal (RTRP-Seed) for improving native tree species' seed supply in sub-Saharan Africa (full-proposal preparation phase funds). In addition, the Green Climate Fund (GCF) provides support through the IUCN-led Transforming the Eastern Province of Rwanda through Adaptation (TREPA) project. The GCF Readiness Programme also supports the development of CAPTD in Burkina Faso. CIFOR-ICRAF also gratefully acknowledges the support of CGIAR funding partners through the CGIAR Research Program on Forests, Trees and Agroforestry (2011–2021) and the CGIAR Genebank Platform led by the Crop Trust.

References

de Sousa K, van Zonneveld M, Holmgren M, Kindt R, Ordoñez JC. 2019. The future of coffee and cocoa agroforestry in a warmer Mesoamerica. *Scientific Reports* 9: article 8828. https://doi.org/10.1038/s41598-019-45491-7

Franzel S, Kindt R. 2012. Species priority setting procedures. *In* Dawson I, Harwood C, Jamnadass R, Beniest J, eds. *Agroforestry tree domestication: a primer*. Nairobi, Kenya: World Agroforestry. Pp. 36–45. https://www.worldagroforestry.org/publication/agroforestry-tree-domestication-primer

Graudal L, Dawson IK, Hale I, Powell W, Hendre P, Jamnadass R. 2022. 'Systems approach' plant breeding illustrated by trees. *Trends in Plant Science* 27:158–165.

Kindt R, Abiyu A, Borchardt P, Dawson I, Demissew S, Graudal L, Jamnadass R, Lillesø J-PB, Moestrup S, Pedercini F, et al. 2021. *A climate change atlas for Africa of tree species prioritized for forest landscape restoration in Ethiopia*. Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://atlas.worldagroforestry.org/

Kindt R, Abiyu A, Dawson IK, Graudal L, Lillesø J-PB, Mengesha Y, Moestrup S, Nørgard C, van Breugel P. 2022a. *What to plant where in Ethiopia*. Nairobi, Kenya and Addis Ababa, Ethiopia: World Agroforestry. Accessed 7 April 2023. https://worldagroforestry.org/output/what-to-plant-where-in-ethiopia

Kindt R, Graudal L, Lillesø J-P, Pedercini F, Smith P, Jamnadass R. 2022b. *GlobalUsefulNativeTrees: country-*

specific selections of native tree species for forest landscape restoration and biodiverse plantings. Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://www.worldagroforestry.org/output/globalusefulnativetrees

Kindt R, John I, Dawson IK, Graudal L, Lillesø J-P B, Ordonez J, Jamnadass R. 2022c. *Agroforestry species switchboard: a synthesis of information sources to support tree research and development activities.* Version 3.0. Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://www.worldagroforestry.org/output/agroforestry-species-switchboard-30

Kindt R. Mutua A, Muasya SN, Kimotho J. 2002. *Tree seed suppliers directory: sources of seeds and microsymbionts.* Nairobi, Kenya: World Agroforestry. Accessed 7 April 2023. https://www.worldagroforestry.org/output/tree-seed-suppliers-directory

Lillesø J-PB, Dawson IK, Graudal L, Jamnadass R. 2021. *Quality seed for tree planting: supporting more effective agroforestry and forest landscape restoration by learning from crop Integrated Seed System Development.* ICRAF Policy Brief No. 54. Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://www.worldagroforestry.org/publication/quality-seed-tree-planting-supporting-more-effective-agroforestry-and-forest-landscape

Lillesø J-PB, Harwood C, Derero A, Graudal L, Roshetko JM, Kindt R, Moestrup S, Omondi WO, Holtne N, Mbora A, et al. 2018. Why institutional environments for agroforestry seed systems matters. *Development Policy Review* 36:O89–O112

McMullin S, Njogu K, Wekesa B, Gachuiri A, Ngethe E, Stadlmayr B, Jamnadass R, Kehlenbeck K. 2019. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: a new approach for providing year-round micronutrients to smallholder farmers. *Food Security* 11:1355–1372

Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A. 2009. *Agroforestree database: a tree reference and selection guide.* Version 4.0. Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://www.worldagroforestry.org/output/agroforestree-database

PATSPO. 2023. *Provision of adequate tree seed portfolio in Ethiopia*. Nairobi, Kenya: World Agroforestry. Accessed 7 April 2023. https://worldagroforestry.org/project/provision-adequate-tree-seed-portfolio-ethiopia-patspo-ii-phase-2

Pedercini F, Dawson IK, Kindt R, Tadesse W, Moestrup S, Abiyu A, Lillesø J-PB, van Schoubroeck F, McMullin S, Carsan S, et al. 2021. *Priority landscapes for tree-based restoration in Ethiopia*. ICRAF Working Paper No. 320. Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://doi.org/10.5716/WP21037.PDF

Pedercini F, Dawson IK, Lillesø J-PB, Moestrup S, Nørgaard CT, Abiyu A, Eshete G, Jamnadass R, Graudal L. 2022. *Cost benefit analysis for Grevillea robusta in Ethiopia: linking establishment of a breeding seedling orchard to the economic returns of quality plantings.* CIFOR-ICRAF Working Paper No. 6. Bogor, Indonesia: CIFOR, and Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://doi.org/10.17528/cifor-icraf/008579

Schmidt LH, Barsotti D, Moestrup S, Abiyu A, Graudal L, Jamnadass R, Dawson IK, Lillesø J-PB, Carsan S, Kindt R, et al. 2021. *The resources for tree planting platform: delivering high-quality tree-planting material to growers*. Copenhagen, Denmark: University of Copenhagen, and Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://tree.worldagroforestry.org/

Van Breugel P, Kindt R, Lillesø J-PB, Bingham M, Demissew S, Dudley C, Friis I, Gachathi F, Kalema J, Mbago F, et al. 2015. *Potential natural vegetation of eastern Africa (Burundi, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia)*. Version 2.0. Copenhagen, Denmark: Forest & Landscape Denmark, and Nairobi, Kenya: World Agroforestry. Accessed 6 April 2023. https://vegetationmap4africa.org

NICFI Norway's International Climate and Forest Initiative
PATSPO II Provision of adequate tree seed portfolios
GREEN CLIMATE FUND
IUCN
TREPA Transforming Eastern Province through Adaptation

cifor-icraf.org

cifor.org | worldagroforestry.org

CIFOR-ICRAF
The Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF) envision a more equitable world where trees in all landscapes, from drylands to the humid tropics, enhance the environment and well-being for all. CIFOR and ICRAF are CGIAR Research Centers.

CGIAR