

Climate change and tree genetic resource management: maintaining and enhancing the productivity and value of smallholder tropical agroforestry landscapes. A review

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Abstract Anthropogenic climate change has significant consequences for the sustainability and productivity of agroforestry ecosystems upon which millions of smallholders in the tropics depend and that provide valuable global services. We here consider the current state of knowledge of the impacts of climate change on tree genetic resources and implications for action in a smallholder setting. Required measures to respond to change include: (1) the facilitated translocation of environmentally-matched germplasm across appropriate geographic scales, (2) the elevation of effective population sizes of tree stands through the promotion of pollinators and other farm management interventions; and (3) the use of a wider range of ‘plastic’ species and populations for planting. Key bottlenecks to response that are discussed

here include limitations in the international exchange of tree seed and seedlings, and the absence of well-functioning delivery systems to provide smallholders with better-adapted planting material. Greater research on population-level environmental responses in indigenous tree species is important, and more studies of animal pollinators in farm landscapes are required. The development of well-functioning markets for new products that farmers can grow in order to mitigate and adapt to anthropogenic climate change must also consider genetic resource issues, as we describe.

Keywords Tropical smallholder agroforestry · Tree genetic resources · Climate change

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Introduction

Anthropogenic climate change caused by greenhouse gas emissions is altering the mean, range and seasonality of a series of climatic variables, resulting in rapid temperature increases, significantly different rainfall patterns and a greater frequency of extreme weather events in many regions (IPCC 2007). Current and predicted results include major changes in patterns of human disease, greater food insecurity and malnutrition, decreased water availability and worse sanitation (Costello et al. 2009; Nelson et al. 2009). These effects will disproportionately impact on the poor and will exacerbate current inequalities between high- and low-income nations. For example, a 2°C warming could result in permanent reductions in gross domestic product of 4% or more in Africa, a region that already suffers from extreme poverty (World Bank 2009). In the absence of appropriate mitigation and adaptation measures, there is a significant danger that climate change—together with other inter-related challenges such as high human population growth, fuel scarcity, deforestation, soil degradation and biodiversity loss—may result in catastrophic impacts (EC 2008; FAO 2006; Malhi et al. 2009).

Agroforestry—the practice of integrating a range of trees with annual crop cultivation and other farm activities—is an approach adopted by millions of smallholders to meet their needs for essential resources of food, medicine, timber, fuel, fodder and market commodities, and provides valuable environmental services such as soil fertility replenishment, water catchment protection, carbon sequestration, biodiversity conservation and landscape restoration (Garrity 2004; www.worldagroforestry.org). Worldwide, approximately 560 million people live in agricultural ecosystems with more than 10% tree cover, which equates to 31% of all humans inhabiting farm landscapes (Zomer et al. 2009). When an active tree planting culture exists in rural communities, hundreds of indigenous tree species can be found conserved *circa situ* in farmland (Acharya 2006; Kindt et al. 2006). A diversity of local and exotic trees and crops can improve the resilience of agricultural systems to environmental change if constituent species respond differently to disturbances (Kindt et al. 2006; Steffan-Dewenter et al. 2007). In addition, by providing alternative sources of products, tree cultivation has the potential to take pressure off extractive harvesting from natural forests, contributing

to in situ conservation, limiting deforestation and reducing greenhouse gas emissions, and fixing carbon in farmland (Jamnadas et al. 2010; Nair et al. 2009). Agroforestry is therefore seen as a key means of ‘climate-smart’ development, and understanding how to maximise the productivity of trees in agricultural landscapes under anthropogenic climate change is therefore essential in proactive management (World Bank 2009). In addition, in the context of climate change and other global challenges that result in the loss of natural forests, in the coming decades farmland will play an increasingly important role in conserving the biodiversity of tropical trees (Simons et al. 2000). This is because not only are in situ options limited, but alternative *ex situ* methods of conservation—in which species are stored as seed or as growing plants in ‘formal’ gene banks—are generally not practical for tropical trees. This is due to a range of factors, including the number of taxa involved, frequent seed recalcitrance, specific associations with micro-organisms that must be maintained for proper growth, and the prohibitive expense and time required to regenerate species with long generation intervals (Kindt and Lengkeek 1999).

Initial agroforestry-based responses to climate change can be envisaged as involving compositional adjustments between constituent tree species within farming systems. In this scenario, as climate changes, less well-performing species in farmland are replaced by other trees that are already present at low densities within systems and that are better-suited to new conditions (i.e., the relative abundance of different species in the landscape changes, and certain existing species in farmland may be lost; Lengkeek et al. 2005a, b). Compositional shifts to combat anthropogenic climate change will however be required beyond the level of species assemblages, and further crucial measures will involve maintaining, enhancing and better managing tree genetic resources at an intra-specific level within farm landscapes. It is these interventions that are the focus of this essay. We justify this focus by reviewing current knowledge on ‘genetic level’ responses by trees to environmental change (e.g., Aitken et al. 2008; Vinceti et al. 2009), in the specific context of how this knowledge can be translated into action for the particular case of smallholders’ agroforestry systems in the tropics. Our intention is to contribute to a wider discussion of how to better manage tree genetic resources in

smallholders' farms for more productive and sustainable practices (Dawson et al. 2009), in order to allow rural communities to face the range of pressing challenges to production that they are currently confronted with, of which climate change is one among many factors. In the below, we first consider germplasm translocation in agroforestry systems as a response to climate change, second consider the issue of local genetic adaptation, and third consider the role of plasticity in species performance. In the context of climate change, we summarise the needed germplasm-based interventions to deal with the constraints faced by farmers in tree planting in Table 1.

Germplasm translocation in agroforestry systems as a response to climate change

Although the 'demographic' and 'microclimatic' inertia (caused by longevity and the control of own climate, respectively) of trees need to be taken into account (Malhi et al. 2009), the consensus is that anthropogenic climate change will result in significant alterations to the geographic domains in which particular species can survive and thrive, and that this will occur relatively quickly (Petit et al. 2008). For natural forests in temperate regions, it has been estimated that migration rates of more than 1 km per year may be needed for tree species to overcome physiological mismatching and keep pace with current temperature and precipitation changes, a speed of migration ten-fold greater than that observed in the past under natural climate change for key taxa (Pearson 2006; data collected from pollen core studies and molecular marker analysis; see, e.g., McLachlan et al. 2005; Olago 2001; Pearson 2006; Petit et al. 2008). In tropical biomes, precipitation changes are likely to be more importance than temperature increases, as is evidenced by molecular marker studies that indicate dryness as a particular barrier to genetic exchange within tree species (e.g., see Muchugi et al. 2006, 2008 for the importance of the dry Rift Valley in limiting past migrations in East Africa). As with temperate regions, the needed rate of migration as a result of anthropogenic climate change will be considerably greater than that which can occur naturally (Malcolm et al. 2002), except for a small range of (invasive) trees that can respond more quickly to change because they are for example more

precocious, are dispersed further, or are quicker in reaching maturity. Rates of possible natural migration are reduced by forest cutting for agricultural development, although trees planted in buffer zones, corridors and as stepping stones in farmland provide opportunities for 'reconnecting' forest fragments, thereby allowing forest ecosystems to respond better to climate change (Bhagwat et al. 2008; Thuiller et al. 2008).

In the case of managed, agroforestry ecosystems, the 'facilitated translocation' of germplasm to respond to changes in climate (and associated changes in biotic factors such as the increased prevalence of particular pests and diseases; Konkin and Hopkins 2009; Moore and Allard 2008) is a possibility not available to natural forests. Facilitated translocation involves human movement of tree seed and seedlings, and possibly of associated micro-organisms (such as nitrogen-fixing bacteria essential for leguminous trees) and important animal pollinators, from existing ranges to sites expected to experience analogous environmental conditions in future years (Guariguata et al. 2008; McLachlan et al. 2007). Fundamental to human-facilitated translocation is the presumption that the global circulation models (GCMs) used to explain the environmental changes in temperature and rainfall profiles that result from anthropogenic climate change can be used to predict change with some certainty at given locations. Such predictions are not always straightforward, however, because of the divergence between different GCMs, which often come to different results especially for precipitation forecasts (Christensen et al. 2007). Second, predicting the future geographic 'domains' in which particular tree species will (if given the opportunity) grow well depends on understanding current species distributions, information which is often lacking (see, e.g., www.lifemapper.org), and the ecological niche model that is adopted (Peterson et al. 2008). Furthermore, projections are more difficult for perennials than for annual crops, as the long lifespans of trees mean that they can realise products and services (such as carbon storage) over considerable periods of time, possibly centuries from now when climatic conditions will depend on the effectiveness of current mitigation measures (IPCC 2007). Finally, since climate change is an ongoing process, the right interval for continued rounds of germplasm translocation needs to be established.

Table 1 Summary of smallholder constraints to tree planting, suggested interventions under existing challenges (see Dawson et al. 2009), and specific germplasm-based opportunities to address climate change

Constraint	Nature of constraint	Interventions under existing challenges	Specific germplasm-based opportunities under climate change
Lack of access to high-quality germplasm	Smallholders have to plant the tree seed and seedlings that they can obtain, even though this germplasm is frequently suboptimal in performance and function	<ul style="list-style-type: none"> • Improve access to germplasm through participatory domestication, by supporting small commercial seed and seedling dealers, through enhancing local networks for exchange, by establishment of seed production stands • Training in germplasm collection, production and farmland management of trees (e.g., in managing natural regeneration) at a local level • New introductions to farmers of more productive germplasm from elsewhere 	<ul style="list-style-type: none"> • In order to keep track with environmental shifts, link local germplasm suppliers with national tree seed programmes that can facilitate germplasm translocations at larger geographic scales, nationally and internationally. Ensure co-migrations of organisms (e.g., pollinators, microsymbionts) in mutual relationship with trees • Introduce new farm management methods to enhance pollination and maintain N_e, and bring into cultivation new varieties that are not as dependent on associations with particular animal pollinators • Ensure that new introductions of species and provenances are flexible (plastic) in responding to the extreme weather events caused by climate change. Do not, however, concentrate on only a small range of 'exotic' species
Absence of well-functioning markets	Market value chains are frequently biased against smallholder involvement, or are simply not present, and few opportunities exist for adding value through processing, etc.	<ul style="list-style-type: none"> • Improve access to markets through identifying new opportunities, sensitising consumers, increasing value chain transparency, and providing business training and credit for growers • Training in simple methods for adding value and introduction of necessary processing, etc., equipment 	<ul style="list-style-type: none"> • Ensure market opportunities for mitigation (e.g., carbon sequestration, biofuel production) can be met through new introductions of species and provenances that are productive for novel functions • Ensure that germplasm delivery systems are able to provide appropriate planting material to take advantage of newly developing markets to combat climate change health challenges (e.g., in order to provide medicines for disease treatment and foods to prevent malnutrition), in targeted geographic regions • Ensure that market opportunities for other local and global challenges are fully explored, so that 'climate change markets' do not result in a narrowing of production options, over-intensification and/or a tendency to monoculture that will weaken resilience to environmental change

Tree-site matching and genetic variation

Strategies for tree-site matching clearly depend on how climate-related intraspecific diversity is currently structured (Aitken et al. 2008). Field experiments indicate that considerable variation can be found among populations of any given tree species, with locally collected material often performing comparatively well (Aitken et al. 2008; Maranz et al. 2008; Rehfeldt et al. 2002). That local sourcing for planting is best (or at least was best before anthropogenic environmental change) cannot however be assumed, and the relative performance of different provenances needs to be evaluated on a species-by-species basis (Weber and Sotelo-Montes 2008).

Our current understanding of population-level environmental responses in smallholder-planted tree species is based primarily on field trials established before responding to anthropogenic environmental change was considered to be an important research issue. A small number of new trials have however recently been established to specifically consider climate change responses; for example, under the Sahelian Fruit Tree project (SAFRUIT, see www.safruit.org). In this initiative, trials on drought stress are being conducted in the semi-arid West African Sahel on important trees such as *Adansonia digitata* (baobab) and *Parkia biglobosa* (African locust bean). In nursery experiments, populations collected from locations with different rainfall levels are being exposed to a range of watering regimes (Sanou et al. 2007). The results of treatments on root development, seedling vigour and other characteristics are expected soon and will inform distribution strategies (Anders Ræbild, Forest and Landscape Denmark, personal communication).

More such trials are needed on a wider range of species important to farmers, in which emphasis is placed on sampling germplasm across existing environmental gradients and over vegetation zones (Aitken et al. 2008). During evaluation, more attention needs to be given to the physiological mechanisms underlying responses to climatic change. Attention to characteristics such as drought tolerance, water use efficiency, survival, salt tolerance, ability to withstand water-logging and response to elevated CO₂ levels, is required. In addition, ‘genomic’ studies, in which the quantitative trait loci believed

to control responses are studied at the gene level (Namroud et al. 2008; Neale and Ingvarsson 2008; Reusch and Wood 2007), could be applied. In the case of drought tolerance, which may be a particularly important feature in responding to new climatic conditions, candidate genes include those involved in the synthesis of abscisic acid, transcriptional regulators of drought-inducible pathways, and late embryogenesis abundant proteins; shifts at such loci have been linked to global warming (Hoffmann and Willi 2008). Such research needs to be extended from temperate to tropical trees, using modern approaches to study relationships between phenotype and genotype, such as whole genome scanning and association mapping (Pauwels et al. 2008).

Practical cases where climate change considerations have been taken into account in population-site matching for the tree component of agroforestry systems are to date limited. One good case is however provided by the seed distribution strategy adopted for *Prosopis africana* in the semi-arid West African Sahel, a region that became drier over the last decades (Sotelo-Montes and Weber 2009; Weber et al. 2008). Based on field trials measuring growth, survival and wood density in relation to rainfall patterns across seed collection sites, Weber et al. (2008) recommended that germplasm transfers of the species should only be undertaken in a single direction, from drier to (currently) wetter zones. A similar strategy was adopted for a recent International Fund for Agricultural Development (IFAD) agroforestry project in the same region (JCW and AK, personal observations). Different GCM vary in future predictions of rainfall in the region, with some indicating drier (e.g., Held et al. 2005) and some wetter (e.g., Shanahan et al. 2009) conditions. Given current uncertainties in climate change projections for the region, an emphasis on matching to the more limiting scenario of drier future conditions—and translocating germplasm from populations subject to a range of extreme conditions (e.g., from dry river beds subject to occasional flooding)—would appear to be the most risk-averse options.

With the uncertainties in projecting change at specific locations, one approach suggested by foresters’ for commercial plantation establishment is ‘composite provenancing’ in which germplasm taken from multiple, environmentally-different collection sites is mixed and then the worst-performing material

is thinned out in future years as climate trends become more evident (Bosselmann et al. 2008; Hubert and Cottrell 2007). Although at first examination this also appears an attractive approach for smallholder plantings, poor farmers generally plant trees at final density and will rarely thin out badly-performing individuals, so production gains through later selection are therefore not possible (Lengkeek 2003). Furthermore, as farmers frequently source future planting material from their existing trees (Lengkeek et al. 2005b), any outbreeding depression (breakdown of co-adapted gene combinations in individual sources; Ledig 1992) caused by interbreeding between constituent components of composite provenances may lead to progeny performing worse on average than parental material (Jamnadass et al. 2009).

Exchanging germplasm between countries

As geographic shifts in future climatic conditions are expected to be large (IPCC 2007), facilitated germplasm exchange between countries with different environments will be required, increasing international interdependency in tree genetic resources (Vinceti et al. 2009). Current international flows of tree seed and seedlings are difficult to quantify, but Koskela et al. (2009) found that trees important to smallholders are already very widely cultivated outside native ranges. Many introductions appear to have been haphazard and sub-optimal for existing conditions, and extant landraces are unlikely to perform optimally under changing environments (Koskela et al. 2009). Under climate change, greater emphasis on working with international suppliers to improve the quality of material exchanged between nations will therefore be required (Vinceti et al. 2009), whilst also taking into account the invasiveness potential of new introductions, which may be enhanced by altering environments (McLachlan et al. 2007; Peterson et al. 2008). Just when increased international movement of germplasm is required for research on tree-site matching, however, between-country transfer for research purposes is becoming increasingly difficult and costly as nations seek to conform to their commitments under the Convention on Biological Diversity; new approaches are therefore needed to allow the more effective exchange of germplasm for conducting experiments, possibly

through greater inclusion of tree genetic resources within multilateral agreements such as the International Treaty on Plant Genetic Resources for Food and Agriculture, and by the harmonisation of phytosanitary requirements (Koskela et al. 2009).

Delivering site-matched germplasm to smallholders

Any response to climate change that involves the facilitated translocation of germplasm across large distances, whether within or between countries, must consider how farmers gain access to this material. This means understanding how tree seed and seedling delivery systems currently work for them. ‘Centralised’ models of delivery, which are based around ‘formal’ institutions such as national tree seed centres (NTSCs), have generally proven ineffective in meeting the needs of small-scale farmers because of the high costs involved in reaching widely-dispersed clients with the small amounts of planting material that they require for any particular species (Graudal and Lillesø 2007). More successful, but lacking in investment, are ‘informal’ local commercial seed collectors and nursery operators that run small businesses that have low operating costs (Muriuki 2005). In the context of climate change, both these types of supplier are clearly needed. NTSCs must be revitalised to facilitate and coordinate the long distance transfers that are required to cope with the scale of change. They then need to engage with networks of small-scale commercial suppliers by providing them with exchanged germplasm, as well as supporting training in the technical and business skills needed to propagate good quality material, run profitable enterprises and reach farmers (Graudal and Lillesø 2007). Responses to climate change that are based on germplasm translocations across large distances will without such efforts have only limited impact.

Local adaptation in agroforestry systems as a response to climate change

An alternative response to the translocation of tree genetic resources is adaptation locally to altering environmental conditions. Field trials which indicate that local germplasm often performs best in prevailing conditions are indicative of past microevolution

in tree stands (see previous section). A number of features of natural tree stands in theory support local adaptation by ensuring high effective population sizes (N_e , the size of an ‘idealised’ population with the same genetic properties as those observed for a real population) (Petit and Hampe 2006). These features include: often high census numbers, high levels of genetic diversity, the outcrossing nature of most species, high seed yields; and the fact that pollen and seed can be dispersed over long distances allowing wide interbreeding. In smallholders’ farms, however, the evidence suggests that N_e values may be lower than in natural tree stands (Dawson et al. 2009). A number of reasons have been identified, including the narrow sampling practices of farmers and tree nursery managers when collecting seed and seedlings for cultivation (i.e., only a few parental trees sampled; Lengkeek et al. 2005a), and the ‘one-off’ nature of many introductions (i.e., once material has been introduced to smallholdings, farmers often rely upon it for future generations of planting; Lengkeek et al. 2005b), both of which reduce genetic diversity. In addition, particular tree species often demonstrate highly aggregated microgeographic distributions in farmland (i.e., clumping or clustering), and many species occur at only extremely low individual densities (Kindt et al. 2006), both of which factors reduce the overall connectivity between trees in agricultural landscapes, especially when connectivity depends on animal pollinators (e.g., ants, bees, birds and bats) and/or seed dispersers to facilitate gene flow (Nason and Hamrick 1997; Ward et al. 2005).

Supporting adaptation by maintaining and enhancing effective population sizes

A reduction in N_e in farm landscapes compared to natural stands means that the ability of tree populations to locally adapt to climate change in agroforestry systems is likely to be lower. In addition, climate change itself is likely to reduce N_e values further for those trees that are animal pollinated, especially in the case of species with specialised relationships with particular vectors (Bazzaz 1998). This is due to declining tree-pollinator interactions that limit gene flow, as climate change affects the life cycles of trees and pollinators differently and results in asynchronies (NRC 2007; FAO 2008a; Parmesan 2007). Measures to enhance the N_e of trees in

agricultural landscapes are already crucial to address current concerns on productivity (e.g., to prevent inbreeding depression; Charlesworth and Charlesworth 1987; Dawson et al. 2009; Lowe et al. 2005) and climate change clearly reinforces the importance of such interventions. Measures recommended to increase N_e include the greater involvement of ‘nodal’ farmers (those with a particular interest in diversity) in farmer-to-farmer exchange networks for tree seed and seedlings (Lengkeek 2003), and the distribution of germplasm through ‘diversity fairs’ (van der Steeg et al. 2004). The last approach is currently being applied to manage genetic diversity in fruit trees in the West African Sahel (JCW, personal observations). Suggested interventions also include the promotion of animal pollinators by activities such as bee-keeping (FAO 2008a), the protection of natural regeneration in farmland, and the training of farmers in proper tree seed collection and seed management techniques (Dawson et al. 2009).

More research is needed in order to understand better the level of the detrimental impact of climate change on pollinator-tree mutualisms in smallholder agroforestry systems. If interactions between trees and pollinators decline significantly, the ‘species carrying capacity’ of farmland (the number of tree species that can be maintained in farm landscapes) may be significantly reduced, because some interspecific diversity will need to be sacrificed in order to maintain N_e values through elevating census numbers of individual species. Carrying capacity is a crucial issue, as promoting greater interspecific diversity is in itself a recommended intervention for improving resilience to climate change (Kindt et al. 2006). Any loss of pollination services caused by climate change means that the scope for species diversification is limited, and an appropriate balance will need to be reached between inter- and intra-specific responses to environmental shifts (i.e., species diversification alone neglects the biological requirements for reproduction, maintenance of productivity and adaptation of individual species).

Individual species plasticity in agroforestry systems as a response to climate change

An alternative response to facilitated migration and local adaptation is the use of plastic tree species

and/or provenances with flexible morphology and physiology that grow at least reasonably well under a range of different environmental stresses without genetic change (Gienapp et al. 2008). As tree seed and seedlings have been distributed by humans from location to location around the world over the last centuries, it appears that anthropogenic selection has operated to choose relatively plastic, exotic species that grow well in a range of climates (Koskela et al. 2009). Good examples of plastic tree species are *Pinus patula* and *P. tecunumanii* originating from Central America; worldwide provenance trials show that these two widely planted pines grow well in environments much broader than their native ranges (van Zonneveld et al. 2009). Again, many *Eucalyptus* species originating from Australia are now grown by smallholders in a minimum of 25 countries worldwide, nations with often quite different environmental conditions (Koskela et al. 2009).

The selection of ‘generalist’ species and populations through multi-locational field trials and environmental data may be an important response to climate change, especially when greater variation in weather conditions is anticipated, such as combinations of increased drought and flooding. Under such circumstances, responses based on promoting local adaptation are limited because populations are unlikely to be able to evolve simultaneously to the range of different environmental stresses experienced (Jump and Penuelas 2005). In theory, planting of a relatively small number of highly plastic exotic species is an option for agroforestry production systems, but such species are often strongly competitive for water resources, displacing crop production and other trees (Osman-Elasha 2009). Furthermore, a key feature of smallholder agroforestry landscapes is the high biodiversity in indigenous tree species that they often contain (Kindt et al. 2006), and focusing on a few widespread exotics as a response to climate change could significantly reduce the conservation value of farmland. An understanding of the climatic requirements of a wider range of more ‘local’ tree species is therefore required, so that these also can be effectively promoted in planting programmes. Whilst it is relatively straightforward to identify plastic species, it is more difficult to determine generalist populations within species, although such evaluation is underway (e.g., the SAFRUIT project, see above).

Final considerations

The tree genetic resource-based responses to climate change possible in smallholder agroforestry systems include facilitated germplasm translocations to maintain physiological matching, the further promotion of N_e values to encourage local adaptation, and the use of a range of more plastic species and provenances to combat variability in conditions and uncertain trends (Table 1). Obviously, for proposed interventions to be successful, they must provide clear livelihood opportunities for local people, as otherwise measures will not be adopted (Franzel et al. 1996; Lengkeek and Carsan 2004). This means that there must be a focus on developing new market opportunities that are targeted toward smallholder involvement (Table 1). Whilst market mechanisms exist to reward the carbon sequestration function of agroforestry trees in mitigating global environmental change (Albrecht and Kandji 2003; Nair et al. 2009; Verchot et al. 2005), current payment mechanisms are generally inefficient and further attention to approaches is required if farmers are to benefit significantly (Jack et al. 2008). Even then, such payments are likely to be modest compared to the other products and services that trees provide (Roshetko et al. 2007). What is needed is to encourage the cultivation of trees that provide both sequestration benefits and high value products for sale. Trees such as *Allanblackia*, whose seed is a new commercial product in the edible oil market, and which is collected from trees without disturbing growth (i.e., non-destructive harvesting), provide particular opportunities. *Allanblackia* is currently the subject of intensive domestication efforts that include genetic analysis and the selection of the best performing provenances (Jamnadass et al. 2010; Russell et al. 2009).

Smallholder biofuel cultivation to potentially mitigate climate change and enhance energy security is another market opportunity (FAO 2008b). Planting of the small tree *Jatropha curcas* (jatropha), the seed of which yields biodiesel, has, for example, been promoted heavily in Africa, Asia and elsewhere (Achten et al. 2008). The cultivation of jatropha, which originates from Latin America, illustrates well the problems that farmers face in accessing superior germplasm: wide planting in Africa over the last few years has relied on sub-optimal landraces introduced into the mainland of the continent through Cape

Verde (Lengkeek 2007). Significant returns for African farmers and useful contributions to mitigation will only be possible with the coordinated introduction of massive quantities of more highly performing planting material, as well as the adoption of suitable farm management methods and proper attention to concerns of food crop displacement (FAO 2008b).

Climate change will result increasingly in the higher incidence of particular human diseases (e.g., malaria) in certain regions (Costello et al. 2009). Clearly, no one wants to see increased disease prevalence, but this situation could ironically provide farmers with new market opportunities, as rural communities in low-income countries rely heavily on locally-grown plant (often tree-based) remedies for their healthcare needs (World Bank 2001). Similarly, there are opportunities to increase fruit and nut production to address malnutrition linked to climate change (Costello et al. 2009). One approach to combat and realise opportunities from these developments is to undertake geographic projections of future challenges (e.g., malarial zones) and compare these with the projected future growth domains of plants that can be grown to provide the products to address challenges (e.g., trees that produce anti-malarial compounds in leaves, roots or bark). Market promotion of products, and the provision of suitable, superior germplasm, should then focus on geographic areas where projections overlap. At the same time, care must be taken not to promote any one product to the extent that it takes over farming systems and reduces the resilience of agricultural landscapes to climatic variability (Donald 2004; Kindt et al. 2006).

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