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OPINION ARTICLE

Tropical reforestation and climate change: beyond carbon

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Tropical reforestation (TR) has been highlighted as an important intervention for climate change mitigation because of its carbon storage potential. TR can also play other frequently overlooked, but significant, roles in helping society and ecosystems adapt to climate variability and change. For example, reforestation can ameliorate climate-associated impacts of altered hydrological cycles in watersheds, protect coastal areas from increased storms, and provide habitat to reduce the probability of species' extinctions under a changing climate. Consequently, reforestation should be managed with both adaptation and mitigation objectives in mind, so as to maximize synergies among these diverse roles, and to avoid trade-offs in which the achievement of one goal is detrimental to another. Management of increased forest cover must also incorporate measures for reducing the direct and indirect impacts of changing climate on reforestation itself. Here we advocate a focus on "climate-smart reforestation," defined as reforesting for climate change mitigation and adaptation, while ensuring that the direct and indirect impacts of climate change on reforestation are anticipated and minimized.

Key words: climate-smart, ecosystem service, forest, impact, livelihood, resilience, vulnerability, water

Implications for Practice

- Tropical reforestation has a clearly recognized potential for mitigating climate change, but its role in reducing vulnerability to climate change should also be acknowledged.
- Climate-smart reforestation should be promoted, that is, reforesting for climate change mitigation and adaptation, while ensuring that the direct and indirect impacts of climate change on reforestation are anticipated and minimized.
- Reforestation practices should be designed to avoid the implementation of one strategy (mitigation or adaptation) to the detriment of the other.
- Adequate climate policy or institutional arrangements and appropriate technical assistance and information are needed if managers are to pursue the objectives of climate-smart reforestation.
- Climate-smart reforestation should be integrated into broader disaster risk reduction programs, adaptation strategies, and landscape management plans.

Introduction

In many tropical regions where large areas of forest have historically been cleared for agriculture, reforestation, including natural regeneration, assisted restoration, enrichment planting, native tree plantations, commercial plantations, and agroforestry systems, is creating new opportunities and challenges in the context of climate change (Chazdon 2008). For example, the endorsers of the Declaration on Forests of the New York Climate Summit (September 2014) collectively committed to doing their part to restore 150 million hectares globally by 2020 and 350 million hectares by 2030. Another example is the Bonn Challenge (www.bonnchallenge.org), a global aspiration to restore 150 million hectares of the world's degraded and deforested lands by 2020.

Because tropical deforestation has been a large contributor of greenhouse gas emissions, reverting these lands to forests has a clearly recognized potential for recovering stocks of biomass-stored carbon (Houghton 2012). Compared with other climate mitigation practices, some forest restoration options can offer a low-cost approach to reducing greenhouse gas emissions (Turner et al. 2009). However, although many global commitments to reforestation are motivated by climate objectives, tree

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planting for mitigating climate change is still controversial, with recent debates on the cooling and warming effects of reforestation (Verchot 2014).

Viewing tropical reforestation (TR) primarily as a means of mitigating climate change through carbon sequestration overlooks a suite of other roles such as regulation of land–atmosphere interactions, ecosystem services mediated by biota (e.g. pollination), and societal adaptation to climate variability and change. These roles are particularly important because development, adaptation to climate change, the reduction of forest cover loss, and the conservation of ecosystem services present more challenges and opportunities in the tropics than elsewhere (Harvey et al. 2014).

In this "Policy Perspectives" paper, we argue that carbon sequestration is only one of multiple strategies for mitigating and adapting to climate change through reforestation. We describe the variety of links and feedbacks between reforestation and climate change in tropical regions, consider their importance to decision-making, introduce a conceptual framework for climate-smart reforestation, and discuss its management implications. We consider only carbon capture and storage briefly as our main purpose is to explore these other aspects rather than to review well-established information about carbon-focused reforestation.

TR for Mitigating Climate Change

Beyond its role in mitigating climate change through carbon storage, reforestation of tropical landscapes influences global and regional climates through a range of mechanisms (Table 1).

Reforestation has biophysical effects on climate, which, depending on their magnitude and direction, can contribute to climate change mitigation. Globally, these effects include changes in surface albedo, surface roughness, canopy conductance, evapotranspiration, and volatile organic compound emissions. The net overall result of all these changes can be either climatic warming (Kirschbaum et al. 2011) or cooling (Zhao & Jackson 2014), depending on latitude. In boreal forests, reforestation may cause a net increase in regional temperatures through albedo effects, whereas in the tropics, the most likely net effect is cooling (Anderson et al. 2011).

Large-scale reforestation can also affect precipitation locally, regionally, and in faraway places (Swann et al. 2012). At the regional and continental scale, forests recycle rainfall and generate flows of atmospheric water vapor (Ellison et al. 2012), which may also mitigate the effects of warming in arid regions, although generalizations are difficult to make and controversies are frequent (van der Ent et al. 2012). However, further research

Table 1. Types and examples of contributions of tropical reforestation (TR) to climate change mitigation and adaptation to climate variations (either climate variability or climate change), for which some evidence is available.

Type of Contribution	*Description of Contribution*	*Example Reference*
Mitigating climate change globally and regionally		
Carbon capture and storage	TR has high carbon sequestration potential	Silver et al. (2000)
Bioenergy and products	TR can reduce emissions by substituting plantation wood for fossil fuels or carbon-intensive materials	Righelato and Spracklen (2007)
Reduced pressure on forests	TR reduce harvesting pressure on remnant older growth forests and their carbon stocks	Carnus et al. (2006)
Biophysical cooling	TR creates regional cooling as a result of changes in evapotranspiration, surface roughness and albedo	Anderson et al. (2011)
Regional climate regulation	TR reduces warming and drying in arid regions	Oguntunde et al. (2014)
Protecting rural economies from impacts of climate variation		
Livelihood diversification	Livelihood diversification with forest products is an anticipatory strategy used by communities to reduce their sensitivity to climate variations	Paavola (2008)[a]
Safety nets	Forest products are used by communities during and after extreme events to cope and recover	McSweeney (2005)[a]
Microclimate and agriculture	TR improves the resilience of crop production to climate variations	Sendzimir et al. (2011)
Reducing impacts of climatic variation on water cycle and associated human uses		
Base flow conservation	TR increases dry season flow of streams and reduces impacts of drought	Scott et al. (2005)
Flood control	TR reduces frequency and severity of flood-related catastrophes	Bradshaw et al. (2007)[a]
Reducing local impacts of extreme weather events on society and ecosystems		
Heat waves	Urban trees moderate the health impacts of heat waves	Bowler et al. (2010)
Coastal protection	Planted mangroves protect coastal settlements against storms and waves	Adger (1999)
Landslide protection	Forest regeneration stabilizes hillsides and reduces landslides	Robledo et al. (2004)
Reducing impacts of climate change on biodiversity		
Landscape connectivity	Forested habitat corridors facilitate species dispersal under climate change scenarios	Imbach et al. (2013)[a]
Refugia and habitat provision	TR provides habitat refugia for climate-sensitive species of conservation significance	Shoo et al. (2011)

[a]These examples are not specific to reforestation but general to forests.

is needed to better understand the potential for undesirable feedbacks such as altered precipitation in other regions (Swann et al. 2012).

Reforestation can also contribute to climate change mitigation through the sustainable production and use of forest products. For example, wood or biofuels from tropical plantations can substitute for energy or materials that are currently responsible for large greenhouse gas emissions to the atmosphere (Lippke et al. 2011).

TR for Adapting to Climate Change

Well-managed reforestation can contribute to adaptation to climate change by reducing the vulnerability of people and ecosystems to current climate hazards and future climate change (Doswald et al. 2014). This may occur through a variety of pathways (Table 1). First, TR can enhance livelihood diversification, and thereby provide a safety net to increase the resilience of rural households to climate variations. For example, when agriculture is affected by drought, reforested areas can supply products such as firewood, wild fruits, mushrooms, and fodder to provide alternative sources of food, materials, and income (Pramova et al. 2012*b*).

Second, TR can buffer against climate change and variability and protect water supplies for agriculture and other human uses by stabilizing catchment hydrology, increasing base flow during drought, reducing flooding during rainfall events, and improving water quality. However, reforestation plans also need to recognize that reforestation of different types (i.e. successional stage, natural regrowth vs. plantations of native or exotic species) can lead to a variety of consequences for catchment-scale water cycles (Uriarte et al. 2011; Ponette-González et al. 2014). Reforestation often increases infiltration more than transpiration, increasing run-off and base flow during the dry season (Bruijnzeel 2004; Ogden et al. 2013). On the other hand, planting fast-growing exotic species with high transpiration rates often reduces run-off (Locatelli & Vignola 2009), which may cause water shortages, particularly in dry areas (Hodgman et al. 2012). The role of reforestation in reducing storm flow is unclear in large watersheds or for extreme rainfall events (Keenan & Van Dijk 2010). Greater understanding is needed of the effects of the type and the spatial location of reforestation on hydrological processes to enable better planning and management.

Third, TR can reduce the local impact of extreme weather events on society and ecosystems. Restoring forest cover to coastal areas and hillslopes can stabilize land against catastrophic movements associated with wave action and intense run-off during storms and flood events (Table 1). Restoration of even a sparse tree cover can also regulate microclimatic conditions, which can limit urban populations' exposure to heat waves through shade and evaporative cooling, and protect agricultural crops by controlling temperature, humidity, and exposure to winds (Bowler et al. 2010).

Fourth, some types of reforestation can contribute significantly to global biodiversity conservation by increasing species' resilience to climate change, which will otherwise magnify species' declines that are already occurring because of ongoing loss of forest habitat (Travis 2003). Increasing forest cover in climate refugia can improve long-term persistence of forest-dependent species, and reforestation can improve habitat connectivity to facilitate migration of species along climatic gradients (Carnus et al. 2006). Furthermore, biodiversity sustained by reforestation has the potential to improve the climate resilience of ecosystem services such as crop pollination and pest control, as well as increasing future options and as-yet-unknown benefits (e.g. from drug discovery), although research into these processes has so far been largely restricted to old growth rather than restored forest (Catterall et al. 2008; Pawson et al. 2013; Thompson et al. 2014).

The ability of reforestation to perform this range of climate-adaptation services will be influenced by the type of reforestation and associated level of biodiversity as well as by forest age, although these relationships are in need of further study. For example, non-timber forest products are scarce in industrial monoculture plantations but can be abundant in more biodiverse plantations (Pawson et al. 2013), which also provide better habitat quality for biodiversity conservation (Catterall et al. 2008).

Climatic Threats to TR and Possible Adaptations

Climate change affects TR in multiple ways (Table 2). An increased frequency of either very wet years or drought events may influence the potential for achieving long-term tree cover in areas that are marginal for forest growth (Holmgren et al. 2013). Altered temperature and precipitation, extreme events, and increased atmospheric CO_2 concentrations will all drive changes in forest structure and species composition, because new conditions will be physiologically unsuitable for some previously occurring species, while favoring others (Chazdon et al. 2005; Anderson-Teixeira et al. 2013). Climate change may lead ecosystems to alternate stable states where forests are replaced by shrublands or grasslands (Anderson-Teixeira et al. 2013).

These processes will directly affect TR through several mechanisms. Climate change may increase the likelihood of outbreaks of forest pests and diseases (Pawson et al. 2013). It could facilitate the spread of invasive species, potentially producing both positive and negative effects, including threats to forest recovery and contributions to the rate and volume of biomass growth in the reforestation of marginal lands (Lawson & Michler 2014). Another factor relates to the consequences of changes in local habitat suitability, which may require reconsidering the choice of locally appropriate species. Effects can also relate to disturbance regimes, such as the frequency or intensity of storms or fires, which may impair reforestation success (Pawson et al. 2013).

Indirectly, decreased suitability of some areas for agriculture may leave land available for future reforestation or increase the competition between agricultural and forest land uses in areas suitable for agriculture (Bradley et al. 2012), but in other locations agricultural abandonment could lead to forest regrowth.

Table 2. Examples of direct and indirect impacts of climate change and climate variability on tropical reforestation.

Exposure	*Direct Impacts on Reforestation*	*Indirect Impacts on Reforestation*
Climate change and variability	Changes in climate influence seedling establishment, tree growth and mortality, and the distribution and dynamics of invasive species, pests, seed dispersers, and pollinators	Human responses to climate change (e.g. migration, displacement of agriculture) affect areas available for reforestation
Climate-related policies and market changes	Forest-related climate policies (e.g. REDD+, adaptation plans) create a demand for carbon sequestration or adaptation services (e.g. watershed protection) and incentivize reforestation	Changes in energy policies and biofuel demand affect land availability for reforestation or create incentives for woody biomass production

In a changed climate, reforestation methods will benefit from a range of adjustments (Harris et al. 2006). Impacts can be reduced or buffered by interventions to manage fire and pests, irrigation and phytosanitary treatments (Guariguata et al. 2008); modifying silvicultural practices such as species selection, thinning, or tree density can reduce the sensitivity of reforestation to climate change and variability; and the resilience of plantation forests to disturbance events may be increased by actions such as incorporating increased diversity of tree species or habitats (Pawson et al. 2013; Thompson et al. 2014).

The emergence of forest-related policy and market mechanisms such as REDD+ or adaptation plans will also directly affect reforestation, by creating incentives and influencing choices of management practices or species. Furthermore, policies and markets will indirectly affect reforestation through societal efforts to deal with climate change in other spheres of activity (Pawson et al. 2013). For example, increasing demand for bioenergy as a mitigation option could either favor reforestation as a source of wood energy or reduce reforestation though increased land competition from biofuel crops (Brodie et al. 2012).

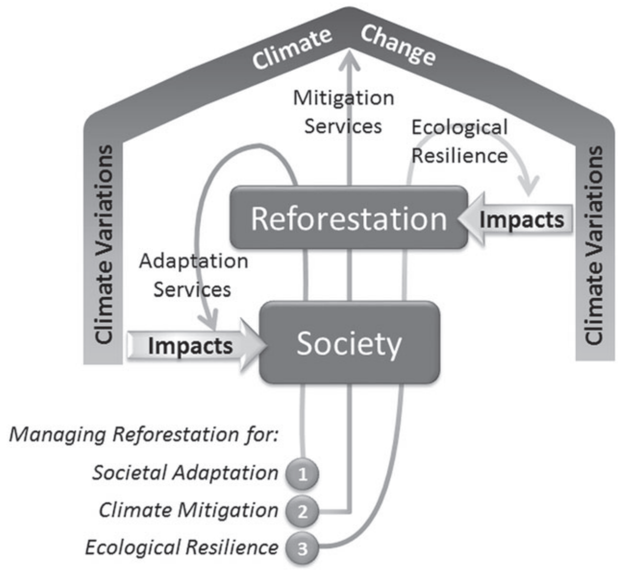

Figure 1. Conceptual framework of climate-smart reforestation: reforestation management contributes to the adaptation of society to climate variations (1) and climate change mitigation (2), while ensuring that reforestation is resilient to the direct and indirect impacts of climate variations (3).

Policies and Management for Climate-Smart Reforestation

Given the wide range of opportunities for reforestation to contribute to both adaptation and mitigation, together with the need to identify and minimize climate-related threats to reforestation processes, there is a pressing need to adjust reforestation practices and policies to suit a changing climate. Such adjustment constitutes the strategic adoption of "climate-smart reforestation," here defined as reforesting for climate change mitigation and adaptation, while ensuring that the direct and indirect impacts of climate change on reforestation are anticipated and minimized (Fig. 1). Given the multiple possible trade-offs, the challenge for climate-smart reforestation is to implement an effective combination of approaches to meet all three objectives: societal adaptation, climate mitigation, and ecological resilience.

Existing policy instruments address these three objectives individually and to differing extents. The role of TR in mitigation has been recognized by the Clean Development Mechanism (CDM) of the Kyoto Protocol, which has rewarded 55 afforestation and reforestation projects in developing countries (UNFCCC 2014). Currently high in the international agenda on climate change, the REDD+ initiative (Reducing Emissions from Deforestation and forest Degradation) includes the enhancement of forest carbon stocks, and many tropical countries have included reforestation activities in their REDD+ strategies (Salvini et al. 2014). The place of reforestation in adaptation policy is less developed, although several adaptation plans (such as the National Adaptation Programmes of Action, NAPAs, prepared by least developed countries) do consider the role of reforestation in adaptation. For example, Comoros' NAPA proposes watershed rehabilitation with multiple-use plantations, restoration of degraded forests, and agroforestry to respond to the identified vulnerability of local communities to climate variations and shortages of water, firewood, and timber (Pramova et al. 2012*a*). Some of these reforestation activities also integrate measures to improve ecological resilience (Reyer et al. 2009).

However, as most policies consider the three objectives of climate-smart reforestation separately, they often overlook possible trade-offs and synergies. For example reforestation projects managed with a carbon purpose could have detrimental consequences on water availability in the semi-arid tropics (Trabucco et al. 2008) or on biodiversity (O'Connor 2008). By contrast, reforestation that is explicitly climate smart uses a multi-objective planning focus that enables different objectives to reinforce each other so that their interactions produce synergies rather than trade-offs. For example, tree regeneration in Tanzania under the Ngitili resource management system achieves carbon storage together with improved watershed conservation and greater provision of natural resources (water, food, and fodder) for livelihoods (Duguma et al. 2014). A proposed adaptation project in Colombia aims to reforest with flood-resistant native tree species to reduce flood impacts on downstream communities (UNDP 2012). A project in Costa Rica is testing different mixes of species and silvicultural practices to reduce vulnerability to storms and fires while also achieving carbon storage (Locatelli et al. 2011).

Likewise, with respect to reforestation and restoration management practices, methods and guidelines have been developed with different objectives in mind (Ashton et al. 2001). Thus, a given method may exist to: enhance supporting services (e.g. improve nutrient cycling and soils by planting multiple tree species, fostering ground covers or inoculating with soil fauna from natural forests); conserve water (e.g. by ensuring a closed canopy or avoiding species with high water use); increase biomass production (with appropriate selection of species and management intensity); or ensure resilience (e.g. with diverse tree communities) (Thompson et al. 2014). Depending on the context, some of these methods could contribute to the three objectives of climate-smart reforestation, but trade-offs also need to be recognized and managed (Simonit & Perrings 2013). For example, tree mixes can store as much carbon as monocultures, be more resilient and provide additional ecosystem services (Hulvey et al. 2013) but can also have higher rates of water use (Kunert et al. 2012). To aid this process in the face of uncertainties, the implementation of reforestation management needs to be coupled with monitoring and adaptive management (Millar et al. 2007).

The implementation of climate-smart reforestation is limited by several knowledge gaps. One example is about the criteria that natural resources managers would use to select species for reforestation that meets multiple objectives. Many reforestation efforts in tropical regions have used a limited number of species (e.g. *Tectona grandis*, *Eucalyptus* spp., and *Pinus* spp.), in part because of limited available guidance for species selection and limited knowledge on other potentially productive and resilient species. The choice of exotic versus native species is an important topic, as there is an inherent tension between concerns of biodiversity and reforestation success (e.g. when native species cannot establish in degraded sites or when an exotic species appears more adapted to the future local climate than native ones). There is limited knowledge on the response of TR species and ecosystems to climate change, e.g. the characterization of effect and response traits (Suding et al. 2008), and on the ecosystem services produced by reforestation in the tropics (De Groot & Van der Meer 2010).

Capacity building would allow managers to examine outcomes of reforestation under a range of climate scenarios and to use improved knowledge, approaches, and tools for integrated assessments of issues such as biophysical and biogeochemical cooling or warming effects, effects on rainfall, and contributions to societal adaptation and biodiversity conservation. Capacity and tools would also allow them to decide among reforestation alternatives, e.g. between passive (i.e. natural regeneration) and active options.

In climate-smart reforestation, the scale of benefits is global for mitigation but local or regional for adaptation. As beneficiaries are generally different from reforestation managers, adequate climate policy and institutional arrangements, as well as involvement of local communities, are essential to ensure that this mismatch of scales does not limit achievement of benefits. Currently, policy instruments for climate change mitigation and adaptation provide limited incentives with often high transaction costs to reforestation managers, the Clean Development Mechanism being a clear example (Locatelli & Pedroni 2006). Timber value is often more valuable as an incentive than the value of the carbon stored, but, in some cases, carbon incentives can provide additional revenues that move a plantation project above a profitability threshold. In addition, the increasing recognition of the role of forests in adaptation, e.g. through watershed stabilization, has raised interest in the development of economic incentives, such as payment for ecosystem services for adaptation (Wertz-Kanounnikoff et al. 2011). Even though they are currently marginal, climate change incentives can influence decision-making about species or management practices (Olschewski & Benitez 2010) or allow an active management of spontaneous reforestation for enhancing the contribution of second growth forests to climate change adaptation and mitigation.

Climate-smart reforestation also has reciprocal relationships with other sectors of climate change adaptation and mitigation. The relative contribution of reforestation can be minor compared with these other sectors, but is often complementary to them. For example, coastal or watershed reforestation alone cannot guarantee complete protection from extreme events, but is effective as part of a broader disaster risk reduction, and adaptation strategy (Baird et al. 2009). The contribution of reforestation to mitigation is also linked to other sectors, e.g. building or energy sectors, through the production of bioenergy and biomaterials. These intersectoral links can also lead to the development of incentives for climate-smart reforestation such as payment for carbon or watershed protection.

Conclusions

Adaptation and mitigation are considered separately in international climate change policies, and in most national or subnational initiatives. However, some activities can significantly contribute to both objectives in a manner that may produce either synergies or trade-offs. TR is one such activity, and therefore needs to be managed with both adaptation and mitigation objectives in mind, to avoid the implementation of one strategy to the detriment of the other. Furthermore, the management of increased forest cover needs to incorporate measures for reducing the direct and indirect impacts of climate change and variability on reforestation. Yet the achievement of climate-smart reforestation is currently limited by a range of uncertainties and knowledge gaps. Improved knowledge will help managers make informed decisions adapted to local specificities.

Finally, larger climate-smart landscape management or rural development initiatives in tropical regions (Harvey et al. 2014) would be strengthened by the inclusion of a component aimed at climate-smart reforestation, based on the principles considered here. The Bonn Challenge and the Declaration on Forests of the New York Climate Summit are excellent opportunities for a global effort toward climate-smart reforestation.

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LITERATURE CITED

Adger WN (1999) Social vulnerability to climate change and extremes in coastal Vietnam. World Development 27:249–269

Anderson RG, Canadell JG, Randerson JT, Jackson RB, Hungate BA, Baldocchi DD, Ban-Weiss GA, Bonan GB, Caldeira K, Cao L (2011) Biophysical considerations in forestry for climate protection. Frontiers in Ecology and the Environment 9:174–182

Anderson-Teixeira KJ, Miller AD, Mohan JE, Hudiburg TW, Duval BD, DeLucia EH (2013) Altered dynamics of forest recovery under a changing climate. Global Change Biology 19:2001–2021

Ashton MS, Gunatilleke C, Singhakumara B, Gunatilleke I (2001) Restoration pathways for rain forest in southwest Sri Lanka: a review of concepts and models. Forest Ecology and Management 154:409–430

Baird AH, Bhalla RS, Kerr AM, Pelkey NW, Srinivas V (2009) Do mangroves provide an effective barrier to storm surges? Proceedings of the National Academy of Sciences 106:E111

Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010) Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landscape and Urban Planning 97:147–155

Bradley BA, Estes LD, Hole DG, Holness S, Oppenheimer M, Turner WR, Beukes H, Schulze RE, Tadross MA, Wilcove DS (2012) Predicting how adaptation to climate change could affect ecological conservation: secondary impacts of shifting agricultural suitability. Diversity and Distributions 18:425–437

Bradshaw CJA, Sodhi NS, Peh KSH, Brook BW (2007) Global evidence that deforestation amplifies flood risk and severity in the developing world. Global Change Biology 13:2379–2395

Brodie J, Post E, Laurance WF (2012) Climate change and tropical biodiversity: a new focus. Trends in Ecology & Evolution 27:145–150

Bruijnzeel LA (2004) Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture, Ecosystems and Environment 104:185–228

Carnus J-M, Parrotta J, Brockerhoff E, Arbez M, Jactel H, Kremer A, Lamb D, O'Hara K, Walters B (2006) Planted forests and biodiversity. Journal of Forestry 104:65–77

Catterall CP, Kanowski J, Wardell-Johnson GW (2008) Biodiversity and new forests: interacting processes, prospects and pitfalls of rainforest restoration. Pages 510–525. In: Stork N, Turton S (eds) Living in a dynamic tropical forest landscape. Wiley-Blackwell, Oxford, United Kingdom

Chazdon RL (2008) Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320:1458–1460

Chazdon RL, Redondo Brenes A, Vilchez Alvarado B (2005) Effects of climate and stand age on annual tree dynamics in tropical second-growth rain forests. Ecology 86:1808–1815

De Groot RS, Van der Meer PJ (2010) Quantifying and valuing goods and services provided by plantation forests. Pages 16–42. In: Bauhus J, Van der Meer P, Kanninen M (eds) Ecosystem goods and services from plantation forests. Earthscan, London, United Kingdom and Washington D.C.

Doswald N, Munroe R, Roe D, Giuliani A, Castelli I, Stephens J, Möller I, Spencer T, Vira B, Reid H (2014) Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. Climate and Development: 6:185–201

Duguma LA, Minang PA, van Noordwijk M (2014) Climate change mitigation and adaptation in the land use sector: from complementarity to synergy. Environmental Management 54:420–433

Ellison D, Futter MN, Bishop K (2012) On the forest cover–water yield debate: from demand- to supply-side thinking. Global Change Biology 18:806–820

Guariguata M, Cornelius JP, Locatelli B, Forner C, Sánchez-Azofeifa GA (2008) Mitigation needs adaptation: tropical forestry and climate change. Mitigation and Adaptation Strategies for Global Change 13:793–808

Harris JA, Hobbs RJ, Higgs E, Aronson J (2006) Ecological restoration and global climate change. Restoration Ecology 14:170–176

Harvey CA, Chacón M, Donatti CI, Garen E, Hannah L, Andrade A, Bede L, Brown D, Calle A, Chará J (2014) Climate-smart landscapes: opportunities and challenges for integrating adaptation and mitigation in tropical agriculture. Conservation Letters 7:77–90

Hodgman T, Munger J, Hall JS, Ashton MS (2012) Managing afforestation and reforestation for carbon sequestration: considerations for land managers and policy makers. Pages 227–255. In: Ashton MS, Tyrrell ML, Spalding D, Gentry B (eds) Managing forest carbon in a changing climate. Springer, New York, New York

Holmgren M, Hirota M, van Nes EH, Scheffer M (2013) Effects of interannual climate variability on tropical tree cover. Nature Climate Change 3:755–758

Houghton R (2012) Carbon emissions and the drivers of deforestation and forest degradation in the tropics. Current Opinion in Environmental Sustainability 4:597–603

Hulvey KB, Hobbs RJ, Standish RJ, Lindenmayer DB, Lach L, Perring MP (2013) Benefits of tree mixes in carbon plantings. Nature Climate Change 3:869–874

Imbach PA, Locatelli B, Molina LG, Ciais P, Leadley PW (2013) Climate change and plant dispersal along corridors in fragmented landscapes of Mesoamerica. Ecology and Evolution 3:2917–2932

Keenan RJ, Van Dijk A (2010) Planted forests and water. Pages 77–95. In: Bauhus J, Van der Meer P, Kanninen M (eds) Ecosystem goods and services from plantation forests. Earthscan, London, United Kingdom and Washington, D.C.

Kirschbaum MUF, Whitehead D, Dean SM, Beets PN, Shepherd JD, Ausseil AGE (2011) Implications of albedo changes following afforestation on the benefits of forests as carbon sinks. Biogeosciences 8:3687–3696

Kunert N, Schwendenmann L, Potvin C, Hölscher D (2012) Tree diversity enhances tree transpiration in a Panamanian forest plantation. Journal of Applied Ecology 49:135–144

Lawson SS, Michler CH (2014) Afforestation, restoration and regeneration—not all trees are created equal. Journal of Forestry Research 25:3–20

Lippke B, Oneil E, Harrison R, Skog K, Gustavsson L, Sathre R (2011) Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Management 2:303–333

Locatelli B, Evans V, Wardell A, Andrade A, Vignola R (2011) Forests and climate change in Latin America: linking adaptation and mitigation. Forests 2:431–450

Locatelli B, Pedroni L (2006) Will simplified modalities and procedures make more small-scale forestry projects viable under the Clean Development

Mechanism? Mitigation and Adaptation Strategies for Global Change 11:621–643
Locatelli B, Vignola R (2009) Managing watershed services of tropical forests and plantations: can meta-analyses help? Forest Ecology and Management 258:1864–1870
McSweeney K (2005) Natural insurance, forest access, and compounded misfortune: forest resources in smallholder coping strategies before and after Hurricane Mitch, eastern Honduras. World Development 33:1453–1471
Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17:2145–2151
O'Connor D (2008) Governing the global commons: linking carbon sequestration and biodiversity conservation in tropical forests. Global Environmental Change 18:368–374
Ogden FL, Crouch TD, Stallard RF, Hall JS (2013) Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama. Water Resources Research 49:8443–8462
Oguntunde PG, Abiodun BJ, Lischeid G, Merz C (2014) Modelling the impacts of reforestation on the projected hydroclimatology of Niger River Basin, West Africa. Ecohydrology 7:163–176
Olschewski R, Benitez PC (2010) Optimizing joint production of timber and carbon sequestration of afforestation projects. Journal of Forest Economics 16:1–10
Paavola J (2008) Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. Environmental Science & Policy 11:642–654
Pawson S, Brin A, Brockerhoff E, Lamb D, Payn T, Paquette A, Parrotta J (2013) Plantation forests, climate change and biodiversity. Biodiversity and Conservation 22:1203–1227
Ponette-González AG, Marín-Spiotta E, Brauman KA, Farley KA, Weathers KC, Young KR (2014) Hydrologic connectivity in the high-elevation tropics: heterogeneous responses to land change. Bioscience 64:92–104
Pramova E, Locatelli B, Brockhaus M, Fohlmeister S (2012a) Ecosystem services in the National Adaptation Programmes of Action. Climate Policy 12:393–409
Pramova E, Locatelli B, Djoudi H, Somorin OA (2012b) Forests and trees for social adaptation to climate variability and change. Wiley Interdisciplinary Reviews: Climate Change 3:581–596
Reyer C, Guericke M, Ibisch PL (2009) Climate change mitigation via afforestation, reforestation and deforestation avoidance: and what about adaptation to environmental change? New Forests 38:15–34
Righelato R, Spracklen DV (2007) Carbon mitigation by biofuels or by saving and restoring forests? Science 317:902
Robledo C, Fischler M, Patino A (2004) Increasing the resilience of hillside communities in Bolivia: has vulnerability to climate change been reduced as a result of previous sustainable development cooperation? Mountain Research and Development 24:14–18
Salvini G, Herold M, De Sy V, Kissinger G, Brockhaus M, Skutsch M (2014) How countries link REDD+ interventions to drivers in their readiness plans: implications for monitoring systems. Environmental Research Letters 9:074004
Scott DF, Bruijnzeel LA, Mackensen J (2005) The hydrological and soil impacts of forestation in the tropics. In: Bonell M, Bruijnzeel LA (eds) Forests, water, and people in the humid tropics: past, present, and future hydrological research for integrated land and water management. Cambridge University Press, Cambridge, U.K.
Sendzimir J, Reij CP, Magnuszewski P (2011) Rebuilding resilience in the Sahel: regreening in the Maradi and Zinder regions of Niger. Ecology and Society 16:1
Shoo LP, Storlie C, Vanderwal J, Little J, Williams SE (2011) Targeted protection and restoration to conserve tropical biodiversity in a warming world. Global Change Biology 17:186–193
Silver W, Ostertag R, Lugo A (2000) The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. Restoration Ecology 8:394–407
Simonit S, Perrings C (2013) Bundling ecosystem services in the Panama Canal watershed. Proceedings of the National Academy of Sciences 110:9326–9331
Suding KN, Lavorel S, Chapin FS, Cornelissen JH, Diaz S, Garnier E, Goldberg D, Hooper DU, Jackson ST, NAVAS ML (2008) Scaling environmental change through the community-level: a trait-based response-and-effect framework for plants. Global Change Biology 14:1125–1140
Swann AL, Fung IY, Chiang JC (2012) Mid-latitude afforestation shifts general circulation and tropical precipitation. Proceedings of the National Academy of Sciences of the United States of America 109:712–716
Thompson ID, Okabe K, Parrotta JA, Brockerhoff E, Jactel H, Forrester DI, Taki H (2014) Biodiversity and ecosystem services: lessons from nature to improve management of planted forests for REDD-plus. Biodiversity and Conservation 23:2613–2635
Trabucco A, Zomer RJ, Bossio DA, van Straaten O, Verchot LV (2008) Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. Agriculture, Ecosystems & Environment 126:81–97
Travis JMJ (2003) Climate change and habitat destruction: a deadly anthropogenic cocktail. Proceedings of the Royal Society B: Biological Sciences 270:467–473
Turner WR, Oppenheimer M, Wilcove DS (2009) A force to flight global warming. Nature 462:278–279
UNDP (2012) Reducing risk and vulnerability to climate change in the region of La Depresión Momposina in Colombia (Proposal 62507, Project 80029). Adaptation Fund and UNDP, Washington D.C.
UNFCCC (2014) Clean Development Mechanism project database. United Nations Framework Convention on Climate Change, Bonn, Germany. http://cdm.unfccc.int/Projects/projsearch.html (accessed 11 Oct 2014)
Uriarte M, Yackulic CB, Lim Y, Arce-Nazario JA (2011) Influence of land use on water quality in a tropical landscape: a multi-scale analysis. Landscape Ecology 26:1151–1164
van der Ent RJ, Coenders-Gerrits AMJ, Nikoli R, Savenije HHG (2012) The importance of proper hydrology in the forest cover-water yield debate: commentary on Ellison et al. (2012). Global Change Biology, 18, 806–820. Global Change Biology 18:2677–2680
Verchot L (2014) On forests' role in climate, New York Times op-ed gets it wrong. *Blog*, 22 September, 2014. http://blog.cifor.org/24311/ (accessed 15 January 2015)
Wertz-Kanounnikoff S, Locatelli B, Wunder S, Brockhaus M (2011) Ecosystem-based adaptation to climate change: what scope for payments for environmental services? Climate and Development 3:143–158
Zhao K, Jackson RB (2014) Biophysical forcings of land-use changes from potential forestry activities in North America. Ecological Monographs 84:329–353

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