New Forests
DOI 10.1007/s11056-015-9500-x

Future landscapes: opportunities and challenges

John A. Stanturf[1]

Received: 11 March 2015 / Accepted: 1 July 2015
© Springer Science+Business Media Dordrecht(outside the USA) 2015

Abstract The global magnitude of degraded and deforested areas is best approached by restoring landscapes. Heightened international perception of the importance of forests and trees outside forests (e.g., woodlands, on farms) demands new approaches to future landscapes. The current need for forest restoration is two billion ha; most opportunities are mosaic restoration in the Tropical and Temperate Zones where human pressure is moderate. A rapidly changing global environment introduces uncertainty, however, that questions the usefulness of success criteria based on present or past ecosystems conditions. Considerable uncertainty arises from future climate and the timing of significant departures from current conditions, social system responses to drivers of global change, and ecosystem responses to changes in coupled socio-ecological systems. Three active approaches to reducing vulnerability and increasing adaptive capacity (incremental, anticipatory, transformational adaptation) differ in their future orientation but share similar objectives of favoring genotypes adapted to future conditions; resisting pathogens; managing herbivory to ensure adequate regeneration; encouraging species and structural diversity at the stand-level, landscape-level, or both; and providing connectivity and reducing fragmentation. Integrating attempts to restore landscapes and mitigate and adapt to climate change may synergistically increase adaptive capacity. Behavioral, institutional, and/or social barriers to implementing change can stop or delay adaptation. Stratagems for overcoming these barriers include conducting "risky" research that pushes the bounds of knowledge and practice and developing plant materials adapted to future conditions.

Keywords Functional restoration · Adaptation · Climate change · Socio-ecological systems

✉ John A. Stanturf
jstanturf@fs.fed.us

[1] Center for Forest Disturbance Science, Southern Research Station, US Forest Service, 320 Green St., Athens, GA 30602, USA

Published online: 12 July 2015

Introduction

An estimated 25 % of the world's land area is degraded (FAO 2011). Responses from the international community include the Changwon Initiative of the United Nations Convention to Combat Desertification that aims to achieve land degradation neutrality by 2030 and the Aichi Declaration of the Convention on Biological Diversity that set a goal of restoring 15 % of degraded lands by 2020. An estimated two billion ha of degraded forest land needs restoration (Minnemayer et al. 2011; Seddon et al. 2014) and the international response was the Bonn Challenge to restore 150 million ha by 2020. Recently the New York Declaration increased the challenge to restore 350 million ha of degraded forest land by 2030. One attempt to locate degraded forest land (Hansen et al. 2010) used remotely sensed data to partition the global landscape into areas where restoration could occur in remote, mosaic, or wide-scale fashion (Minnemayer et al. 2011). Many of the current forest restoration opportunities exist in the Tropics and Temperate Zones, mostly for mosaic restoration in areas of moderate human pressure (between 10 and 100 people km^2) (Fig. 1).

The heightened perception in international policy arenas of the importance of forests and trees outside forests (woodlands, savannas, on farms) is leading to a change in the way we approach future landscapes (Menz et al. 2013; Zomer et al. 2008). A renewed awareness of the importance of forests for human well-being stems from efforts to mitigate and adapt to climate change (Biagini et al. 2014); from an awareness of the importance of forests in sustainable development (Macqueen et al. 2014; Minang et al. 2015; Ordonez et al. 2014); and from the sheer magnitude of deforestation and degradation we have achieved (FAO 2011; Minnemayer et al. 2011; Zalasiewicz et al. 2010). Given the scope of the global restoration challenge in the twenty-first century, approaches that focus on restoring functioning landscapes are the most likely to succeed (Minnemayer et al. 2011; Stanturf et al. 2014a). Landscapes are socio-ecological

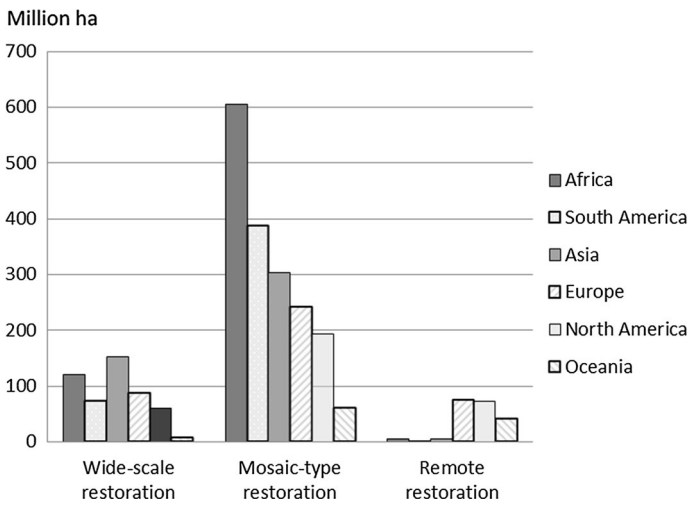

Fig. 1 An estimated 2 billion ha globally of deforested and degraded forest land present the greatest opportunities for restoration in mosaic landscapes with moderate human pressure (between 10 and 100 people km^2). Lesser opportunity occurs for remote restoration in unpopulated areas (density < 1 person km^2 within a 500 km radius) or wide-scale restoration (in areas with <10 people km^2) (*Source* Minnemayer et al. 2011)

systems (SES) (Liu et al. 2007; Ostrom 2009), mosaics of land cover and land use caused by the interplay of ecological possibilities and socio-economic constraints (Lamb et al. 2012; Parrott and Meyer 2012).

The nature of future landscapes will be determined by the success of interventions to restore degraded lands including degraded forests and deforested areas. The uncertainty introduced by a rapidly changing global environment, however, questions the usefulness of success criteria based on present or past ecosystem conditions (Hobbs 2013). Incomplete understanding of the effects on landscapes from temporal and spatial changes in climate and socio-ecological systems has produced a cascade of uncertainty (Wilby and Dessai 2010) resulting in "spatiotemporal chaos" (Pielke et al. 2013) that precludes realistic predictions of where and when significant changes will occur. My objectives are to outline the uncertain future as it affects landscape restoration and to suggest ways to integrate landscape restoration with climate change mitigation and adaptation. My emphasis is on landscapes where forests, woodlands, and agroforestry are important if not dominant land uses. I draw on the adaptation literature, which is oriented toward avoiding degradation caused by global change. My focus, however, is on the large land area already deforested or degraded, and the landscapes that may become degraded under altered climate. Inasmuch as many of the same strategies and methods apply to both current and future restoration needs (Keenan 2015; Millar et al. 2007), the distinction is not sharp.

Uncertain future

Future uncertainty stems from changing climate and the timing of significant departures from current conditions (Mora et al. 2013; Rummukainen 2012); social system responses to drivers of global change, which include but are not restricted to changing climate (Arneth et al. 2014; Wilby and Dessai 2010); and ecosystem responses to changes in coupled socio-ecological systems (Keskitalo 2011; Liu et al. 2007; Seidl and Lexer 2013). Coupled ocean/atmospheric general circulation models (AOGCM) have provided the scientific basis for concerns about climate change. These models, however, provide only a coarse-resolution view of global climate and each model differs in how it represents the physical forces driving climate, resulting in different levels of skill in modeling historic or present climate, especially short-term extremes (Becker et al. 2013).

Population increases (Gerland et al. 2014), changing consumption patterns as a consequence of rising standards of living, and migrations are the demographic drivers of land-use change (Lambin and Meyfroidt 2011; Pretty 2013). Climate change impacts on humans will elicit responses that will indirectly impact ecological systems by altering the way land and natural resources are utilized (Chapman et al. 2014). One downside of a more integrated world is the facilitated movement of pests and invasive plants (Bradley et al. 2011; Logan et al. 2003; Sturrock et al. 2011).

Examples of the potential effects of the interacting drivers of change can be seen today in the Tropics where biodiversity and the potential for mosaic restoration are high (Fig. 1) (Bellard et al. 2014; Dirzo et al. 2014; Visconti et al. 2011; Williams 2013). Generally, these areas are in countries with the highest population growth vulnerable to climate change and a rural populace that is susceptible to food insecurity (Dixon et al. 2003; McMichael et al. 2006; Patz et al. 2005; Thornton et al. 2014; WHO 2014). Farmers dependent on rain fed agriculture and who lack the capital to intensify (Pretty and

Bharucha 2014) may respond to lower crop yields because of climate change through extensification of agriculture at the expense of forests (Seto et al. 2012; Zabel et al. 2014).

Ecosystems and species have adapted to dynamically changing climatic conditions for millennia (Jackson and Overpeck 2000; Millar 2014). Plant populations will respond to future moderate shifts in habitat by tolerating and persisting, migrating, or dying out (Aitken et al. 2008). The nature and rapidity of changing conditions caused by anthropogenic forcing could overwhelm natural adaptation processes, including the dispersal rates needed for species to adapt (Burrows et al. 2014; Corlett and Westcott 2013; Jump and Peñuelas 2005). Predicting the effects of climate change on natural systems, in particular long-lived woody species such as forest trees is important for restoration because abrupt changes will increase the area requiring restoration interventions and ecosystem responses to changed conditions influences what interventions are needed, adaptive, and affordable. At the species level, attempts to project the nature of future landscapes will face a variety of sources of uncertainty, including

- How will a species respond to climate change within its present range (Pacifici et al. 2015; Park et al. 2014)?
- What other changes in addition to direct climate effects will occur in a species' present location and how vulnerable will it be to indirect effects (Chapman et al. 2014; Pacifici et al. 2015)?
- Where might other locations be with a suitable future climate (Vos et al. 2008)?
- How will a species respond to dispersing or being moved to a new location with a suitable future climate (Breed et al. 2013; Fitzpatrick and Hargrove 2009; Lunt et al. 2013; Rout et al. 2013)?
- What effect will an introduced species have on the receiving ecosystem (Hewitt et al. 2011; Laikre et al. 2010; McLachlan et al. 2007; Pedlar et al. 2012)?

Views of the future

Climate and weather are inherently variable and vegetation has adapted to the regional and local range of multi-decadal as well as inter-annual temperatures, precipitation, wind, etc. (Nicotra et al. 2010; Valladares et al. 2014). The most recent projections are for a warmer 2100 world (IPCC 2012) characterized by decreases in cold days and nights and increases in unusually warm days and nights. Land areas will experience increases in the frequency, duration, and/or intensity of warm spells or heat waves. Average precipitation is projected to decrease in some regions and increase in others with more frequent heavy precipitation events, or more of the total precipitation occurring as heavy events. Higher latitudes and tropical regions will be particularly affected, as well as winter precipitation in mid-latitudes in the Northern hemisphere.

Most climate models project changes 50–100 years in the future with an implication that change will be gradual and linear, but projections of extreme events suggest more abrupt shifts will occur along the trajectory (Cai et al. 2014; Leadley et al. 2014). Knowing when to expect significant departure from historic climatic conditions is critical for deciding whether to alter current management strategies, such as species selection and spatial prioritization of target areas for restoration and in forests, rotation length. Mora et al. (2013) examined the timing of departures from current climates, roughly equivalent to the novel or no-analog climates of Williams et al. (2007). The projected near-surface

temperature of the average location would exceed the historic range of variability by 2047 under the business-as-usual RCP85 scenario (Van Vuuren et al. 2011) and by 2069 under the RCP45 (rapid mitigation scenario). The earliest occurrence of unprecedented climate occurred in the Tropics; even though the magnitude of warming was small the current annual and seasonal temperature variability was low. These novel climates could give rise to no-analog plant communities that may be transient within the lifespan of long-lived forests tree species (Williams and Jackson 2007).

In the very near-term (0–30 years), on-going pressures from human demographic shifts, land use change, and introduced pests from globalization of trade will greatly affect ecosystems (Cochrane and Laurance 2008; Kiage 2013; Lambin and Meyfroidt 2011; Laurance et al. 2014). The long-term synergistic effect of human and climate induced change will be significant (Barnosky et al. 2012; Hughes et al. 2013; Leadley et al. 2014; Schröter et al. 2005). For example, forests are important to the terrestrial carbon cycle and measures to mitigate climate change have focused on maintaining and increasing carbon stocks by increasing C-sequestration and reducing emissions. Restoring future landscapes likely will play an increasing role in climate change mitigation and adaptation. Approaches to restoration are not without controversy, particularly in terms of objectives or desirable endpoints (Stanturf et al. 2014a, b) and vegetation patterns altered by climate change will add additional opportunities for debate. For example, afforestation (planting trees on land that was used for purposes other than forests) is a restoration practice and by increasing forest area and carbon stocks, achieves climate change mitigation goals. Creating closed canopy forest on grassy biomes may compromise ecosystem services (Veldman et al. 2015). Under future climates and altered fire regimes, forest/grassland transitions may shift, adding to the complexity of restoration decisions. On one hand, altered climate may favor grassland and cause degradation of forest or woodland and attempting to restore forest or woodland would go against ecological forces. On the other hand, future climate may favor woody species and afforestation would be adaptive to future conditions but may be opposed by the public as degrading current grasslands.

Mitigation and adaptation

Concerns about climate change and loss of biodiversity underscore the importance of forest land cover and trees in the landscape for mitigation and adaptation strategies (Mayaux et al. 2013; Rudel 2013). Mitigation aims at causes of climate change, the emission of green house gases (GHG) and their accumulation in the atmosphere. Mitigation interventions either reduce the sources, or enhance the sinks for GHG (IPCC 2003). Mitigation has been regarded as an international issue (Locatelli et al. 2011); the benefits of mitigation accrue globally, over the long-term because of the inertia of the climate system. Adaptation is local in nature, focusing on the effects of climate change on natural and social systems. Integrating landscape restoration with climate change mitigation and adaptation means squarely facing the diversity of ecological conditions and socio-cultural contexts (Liu et al. 2007). Adaptation strategies must be robust under a broader range of potential climatic conditions than those faced by managers in the past (Hallegatte 2009). Adaptation is essentially about managing the effects of climate change; therefore it is a continuing process (Stein et al. 2013). Inasmuch as many interventions are long-term commitments, restoration decisions including species selections will be made under uncertainty.

Mitigation

Mitigation activities (Table 1) include carbon conservation and increasing sequestration, offsets through substitution for fossil fuels or unsustainably harvested wood, and offsets from use of wood products rather than steel, cement, or plastic (Ravindranath 2007). Land use change, including deforestation and forest degradation, is a major cause of GHG emissions (Cochrane and Laurance 2008; Mahmood et al. 2013; Pielke et al. 2011) and despite the stability of total global forest cover (FAO 2010), deforestation is regionally

Table 1 Mitigation opportunities relevant to forest landscape restoration

Climate change goal	Objective	Mechanism	Restoration activity
Mitigation	Sequester carbon	Increase forest landscape area	Recolonization Farmer-assisted natural regeneration Agroforestry (agroforestation) Afforestation
		Increase biomass/unit area	Increase productivity Introduce longer-lived species Lengthen rotation
		Increase soil carbon	Introduce species with greater rooting depth Implement soil conservation measures that reduce erosion Add biochar
	Reduce fossil fuel emissions	Bioenergy	Firewood, charcoal, and forest residues Bioenergy plantations
		Substitute materials with greater carbon footprint	Producing wood-based bioproducts (e.g. construction materials, bioplastics)
	Reduce emissions from biomass burning	Control GHG emissions from wildfire	Prescribed burning and holistic fire management Convert to fire resistant species
		Increase biofuel use efficiency	More efficient stoves, powerplants and conversion technology Improve charcoal production
	Reduce emissions from land use change	Reduce deforestation drivers	Policy reforms to promote increasing trees in the landscape (e.g., secure tenure) Effective protection (e.g., conservation easements, improved enforcement) Reduce illegal logging Prevent agricultural encroachment Reduce escaped fire Manage or exclude grazing Increase agriculture, agroforestry, pasture productivity and profitability Improve community forest management (e.g., management efficiency, equity) Improve smallholder access to climate-adapted inputs and markets

Table 2 Adaptation opportunities relevant to forest landscape restoration (Adapted from Bolte et al. 2009a; Janowiak et al. 2014; Keskitalo 2011; Kolström et al. 2011; Lindner et al. 2014; Spittlehouse and Stewart 2004; Stanturf et al. 2014b)

Climate change goal	Objective	Mechanism	Restoration activity
Adaptation (Incremental and anticipatory)	Maintain forest area	Reduce deforestation drivers	Policy reforms to promote increasing trees in the landscape (e.g., secure tenure) Effective protection (e.g., conservation easements, improved enforcement) Reduce illegal logging Prevent agricultural encroachment Reduce escaped fire Manage or exclude grazing Increase agriculture, agroforestry, pasture productivity and profitability Improve community forest management (e.g., management efficiency, equity) Improve smallholder access to climate-adapted inputs and markets
	Maintain carbon stocks	Reduce degradation	Sustainable forest landscape management Improve community forest management (e.g., management efficiency, equity) Improve smallholder access to climate-adapted inputs and markets Policy reforms to promote increasing trees in the landscape (e.g., secure tenure) Increase agriculture, agroforestry, and pasture productivity and profitability Effective protection (e.g., conservation easements, improved enforcement) Reduce illegal logging Prevent agricultural encroachment Manage or exclude grazing Reduce escaped fire Increase structural diversity in the landscape Increase species diversity in the landscape Restore natural disturbance processes (e.g., fire, flooding) Increase connectivity between forested patches Rehabilitate degraded stand composition Rehabilitate degraded stand structure Use low-impact logging
	Maintain other forest functions	Improve biodiversity	Afforest, reforest, or agroforest with mixed species Silvicultural interventions to increase species diversity Manage for threatened, endangered, and species of concern Manage hunting (protect seed dispersers or control herbivory)

Table 2 continued

Climate change goal	Objective	Mechanism	Restoration activity
		Improve hydrology	Install or repair check dams and contour trenches Plant stream buffers Restore stream hydroperiod
		Improve rural economy	Improve timber productivity Improve production of non-timber forest products Improve recreational and subsistence hunting Improve tourism aesthetics
	Reduce vulnerability	Increase resistance and resilience to stressors	Integrated pest management Thin to increase drought resistance Introduce new species or more climate-adapted provenances of existing species
		Overcome regeneration barriers	Genetically diverse seed sources available in the landscape for natural regeneration/colonization/agroforestry planting Develop genetically diverse germplasm that is climate-adapted (e.g., seed sources, provenances, or functionally equivalent non-native species) Introduce genetically diverse germplasm that is climate-adapted Enhance dispersal by removing barriers and creating connectivity
		Assist migration	Expand population within the historic range Expanding range
		Create refugia	Identify and create microclimate refugia for in situ conservation of climate-threatened species
	Reduce vulnerability	Increase resistance and resilience to stressors	Integrated pest management Thin to increase drought resistance Introduce new species or more climate-adapted provenances of existing species
		Overcome regeneration barriers	Genetically diverse seed sources available in the landscape for natural regeneration/colonization/agroforestry planting Develop genetically diverse germplasm that is climate-adapted (e.g., seed sources, provenances, or functionally equivalent non-native species) Introduce genetically diverse germplasm that is climate-adapted Enhance dispersal by removing barriers and creating connectivity
		Assist migration	Expand population within the historic range Expanding range

Table 2 continued

Climate change goal	Objective	Mechanism	Restoration activity
		Create refugia	Identify and create microclimate refugia for in situ conservation of climate-threatened species
Transformation	Manage novel ecosystems	Manage spontaneous ecosystems	Manage new species combinations that emerge (e.g., non-natives, altered dominance of natives)
		Create ecosystems	Translocate species Create and plant new species that are climate-adapted (using synthetic biology) with desired functional traits Rewilding (re-introduce extirpated or extinct species) Ecosystem with novelty (replace native species with non-natives having desired functional traits) Neo-native ecosystems (moving communities of native species) Novel ecosystems (combinations of native and non-native species with desired functional traits; designer ecosystems)

significant and continues unabated in the Tropics (Kelatwang and Garzuglia 2006; Kim et al. 2015). Attempts to mitigate climate change have addressed forest loss in the Tropics through Reduced Emissions from Deforestation and Degradation (REDD+), an effort to protect and increase forested area (Nepstad et al. 2013). Increasing bioenergy use and efficiency are other ways to offset fossil fuel emissions (Creutzig et al. 2014).

Mitigation activity may be situated on the landscape to improve connectivity among patches of intact forests and reduce fragmentation, aiding dispersal, migration, and gene flow among populations of plants and animals (Table 1). New or rehabilitated forest areas around intact forests, especially protected areas, may act as buffers and reduce pressure on native forests. Examples of landscape-scale restoration designs are given in Stanturf et al. (2014a). These include corridor plantings that connect patches of intact forests or as riparian buffers in agricultural fields. Dispersed plantings, usually of species with limited dispersal capability, planted as individuals or in clumps near intact forest remnants may over time be augmented by other species dispersed from the forest. Nucleation and cluster plantings within an agricultural matrix are similar plantings (Corbin and Holl 2012; Schönenberger 2001).

Adaptation

Adaptation emphasizes robust solutions that increase resilience of forest ecosystems (Dumroese et al. 2015). Reconstructing forests (e.g., afforestation) can be done in a way that achieves mitigation, provides biodiversity and other ecosystem services, benefits local communities, and increases adaptive capacities of the forest and local community (Table 2). Restoring degraded forests by altering composition, structure, or ecological processes, singly or in combination (Löf et al. 2012; Stanturf et al. 2014a), can be done with an eye toward future climate (Table 2). Some guiding principles are to maintain or improve ecosystem processes (Bolte et al. 2009a; Janowiak et al. 2014; Keenan 2015; Spittlehouse and Stewart 2004) and to promote species, genetic, structural, and age-class diversity (Millar et al. 2007; Oliver et al. 2012) in order to spread risk (Ando and Mallory 2012; Crowe and Parker 2008; Yemshanov et al. 2013).

Passively responding to climate change by accepting what develops and accommodating to the change can be a reversible adaptation strategy (Hallegatte 2009), in that active approaches can be adopted later if the changes are deemed unacceptable. As a restoration method, a passive response is not cost-free (Zahawi et al. 2014) but may be justified if one or more of the following conditions are met: (1) the risk of degradation is low, (2) the social and ecological values at risk are low, hence the costs of degradation are bearable, (3) the costs of acting are high relative to the benefits, and (4) especially if limited resources must be directed toward higher-valued ecosystems that are at greater risk. After a drought-induced insect outbreak, for example remote areas could be allowed to regenerate naturally without intervention even if an herbaceous or shrub-dominated assemblage develops. Notwithstanding, higher-valued stands could be replanted with species or provenances better adapted to future climate (Bolte et al. 2009a; Keenan 2015).

Three active approaches to reducing vulnerability and increasing adaptive capacity are (Table 2) incremental, anticipatory, or transformational adaptation (Joyce et al. 2013; Kates et al. 2012). Incremental adaptation is a short-term coping strategy (Moser and Ekstrom 2010) that seeks to avoid disruptions and maintain forest ecosystems at their current locations, essentially managing for persistence (Kates et al. 2012; Stein et al. 2013).

Incremental adaptations may be extensions of current adaptive practices (Heltberg et al. 2009) that might also reduce vulnerability or avoid loss under altered conditions (Hobbs et al. 2011; Joyce et al. 2009; Kates et al. 2012). Restoration to some measure of historical fidelity (Burton and Macdonald 2011; SERI 2004; Tierney et al. 2009) or range of natural variability (Agee 2003; Keane et al. 2009) are incremental approaches that rely on projections of a stable climate or that the resistance or resilience of healthy ecosystems will enable them to persist under altered climate (Chapman et al. 2014; Stein et al. 2013). Anticipatory adaptations require more substantial adjustments but stop short of transforming the system (Kates et al. 2012). They incorporate some aspects of an incremental approach but are more future-oriented in terms of goals and expectations of altered climate. Transformational adaptations attempt to anticipate climate change and respond in ways that are larger in scale or more intense than anticipatory adaptations, or they are novel by their nature or new to a region or resource system (Hobbs et al. 2011; Joyce et al. 2013; Kates et al. 2012).

The three active adaptation strategies differ in their future orientation but share similar objectives of maintaining vigor at stand level by favoring genotypes that are adapted to local conditions; resisting pathogens; managing herbivory to ensure adequate regeneration; encouraging species and structural diversity at the stand-level, landscape-level, or both; and providing connectivity and reducing landscape fragmentation (Bolte et al. 2009a; Janowiak et al. 2014; Keenan 2015; Lindner et al. 2014; Spittlehouse and Stewart 2004). The approach to reaching these objectives, however, may differ among the strategies (Table 3). Restoration focused on resilient forests under future climate conditions may utilize any of the strategies or some combination on the landscape (Bormann and Kiester 2004; Park et al. 2014). The appropriateness of any of these adaptation strategies will depend on the actual rate and nature of climate change and the vulnerability of species or ecosystems of interest (Park et al. 2014).

Table 3 Comparison of the features of incremental, anticipatory, and transformation adaptation strategies

Features	Adaptation strategies		
	Incremental	Anticipatory	Transformational
Vulnerability Target	Reduce vulnerability to current stressors	Reduce vulnerability to current and future stressors	Reduce vulnerability to current and future stressors
Restoration Paradigm	Ecological restoration: historic fidelity	Functional restoration	Intervention ecology
Species	Native	Native, or exotic with functional equivalencies	Native, exotic, or designer species
Genetics	Local sources, natural evolution	Conventional breeding or biotechnology for clones or provenances with adaptive traits	Transgenic for keystone species, cloning extinct species
Invasive Species	Prevent or remove	Accept those that are functional analogs to extirpated natives	Accept as novel
Novel Ecosystems	Prevent or avoid	Accept and manage neo-native (emergent) assemblages	Manage novel and emergent ecosystems (exotics dominate)

Incremental adaptation

Incremental adaptation focuses on historic fidelity using native species from local sources that may adapt to changing climate through natural evolutionary mechanisms (Table 3). This strategy has a low degree of novelty (Perring et al. 2014) and is likely to be motivated by the ecological restoration paradigm (Stanturf et al. 2014b). Nevertheless, assisted population migration may be a feature of incremental adaptation to the extent of moving seed sources climatically or geographically within the current range of a species (Breed et al. 2013; Janowiak et al. 2014; Williams and Dumroese 2013). Favoring species and genotypes better adapted to future conditions provides a safety margin (Bolte et al. 2009a; Hallegatte 2009; Janowiak et al. 2014; Keenan 2015). This is most easily accomplished by outplanting or sowing germplasm from a wide geographic range (Janowiak et al. 2014; Williams and Dumroese 2013). Maintaining minor species in natural regeneration systems is another safety margin provided at little or no "cost." For example, species currently in low abundance but potentially adapted to even the most extreme future conditions could be maintained or favored by silvicultural practices (Dumroese et al. 2015).

Unique habitats and species of concern can be conserved within existing natural or protected areas, or by enlarging existing areas (Janowiak et al. 2014). Other adaptive activities include favoring multiple species plantings at the stand-level (Gamfeldt et al. 2013; Kelty 2006; Lockhart et al. 2008) and developing structure/age diversity in the landscape (Millar et al. 2007; Oliver et al. 2012). Avoiding consequences of climate change can be accomplished by reducing rotation length or planting species or varieties that grow rapidly to maturity (Park et al. 2014). Short-rotation bioenergy plantings have an additional mitigation benefit (Agostini et al. 2015) and may be combined with a slower growing species in a nurse crop system for restoration (Löf et al. 2014; Stanturf et al. 2009, 2014a).

Establishing new forests or restoring degraded forests must balance sustainability under current climate conditions and adaptability to future climates; thus choice of species, stand structure, and management regime may require trade-offs (Seidl and Lexer 2013). Lowered productivity may result because adaptation to future conditions could be sub-optimal under current climate (Hallegatte 2009; Keenan 2015). Restoration that strives for rapid revegetation and quick site capture (Pichancourt et al. 2014; Stanturf et al. 2001) can avoid negative effects of accelerated soil erosion or invasion by non-native plants (D'Antonio and Vitousek 1992; Janowiak et al. 2014). The greatest opportunities for incremental adaptation exist where active forest management already occurs and adequate infrastructure and technical capacity exists (Guldin 2013; Spittlehouse and Stewart 2004).

Anticipatory adaptation

Anticipatory adaptation is future-oriented and the underlying paradigm is functional restoration, which emphasizes restoration of abiotic and biotic processes rather than fidelity to historic structure or composition (Stanturf et al. 2014a, b). While the starting point for anticipatory adaptation is the same suite of incremental activities described above (Janowiak et al. 2014; Spittlehouse and Stewart 2004), there is greater tolerance for novelty and for non-native species that are functional analogs to native species (Davis et al. 2011; Hobbs et al. 2009; Lugo 2009). Novelty is a matter of degree (Hobbs et al. 2013); replacing a maladapted genotype of a native species with a better-adapted provenance (incremental

adaptation) is an example of low degree of novelty. Replacement with a non-native species with desired functional traits, or a genetically modified clone of a native species, would constitute a greater degree of novelty and fall into anticipatory adaptation (Table 3). Neo-native or hybrid ecosystems could arise spontaneously as assemblages of native species in new combinations or by intentionally moving communities of native species to a new location in anticipation of climate change (Hobbs et al. 2013; Perring et al. 2013; Rout et al. 2013). Extending the historic range of species in advance of extirpation is another anticipatory adaptation (Williams and Dumroese 2013). New refugia for sensitive species can be identified and established within the climatically stable portion of geographic range or beyond (De Frenne et al. 2013; Dobrowski 2011; Janowiak et al. 2014; Keppel and Wardell-Johnson 2012).

Transformational adaptation

Transformational adaptation may be planned or arise spontaneously (Alig et al. 2004; Joyce et al. 2013). Assisted migration of a species far beyond its historical range (Lunt et al. 2013; McLachlan et al. 2007; Pedlar et al. 2012), introduction of non-native species (Davis et al. 2011), or genetic modification to restore keystone species (Jacobs et al. 2013; Seddon et al. 2014) are transformational adaptations. Prominent ecologists and conservationists recently called for intervention ecology, a transformational approach to restoration of degraded ecosystems (Hobbs et al. 2009, 2011; Sarr and Puettmann 2008) that acknowledges the dynamic nature of ecosystems, the prospect for even more rapid change under altered climate, and the infeasibility of complete restoration (Clement and Junqueira 2010; Hobbs 2013). Considerable planning (especially in advance of extreme events; Beatty and Owen 2005; Hallegatte 2009; Stanturf et al. 2007), experimentation, and monitoring will be required for transformation to be successful (Joyce et al. 2009).

Species extinctions and loss of ecosystem services caused by climate change are likely more susceptible to extreme events and climate variability than changes in climate means (Seppälä et al. 2009). Extreme events are inherent in climate variability (Rummukainen 2012); as disturbances they shape ecosystems (Sprugel 1991; Turner 2010). Increases in frequency, intensity, and duration of heat waves and heavy precipitation are expected under climate change. Droughts are projected to increase in different parts of the world, including central and southern Europe, central North America, Central America and Mexico, northeast Brazil, southern Africa, Australia, and Southeast Asia (Dai 2011; IPCC 2012; Rummukainen 2012; Thornton et al. 2014). Many wind-related disturbances such as tornadoes, thunder storms, and derechos are significant for forest ecosystems (Peterson 2000); they occur, however, at a small scale and are not yet represented in either GCMs or RCMs (Regional Climate Model) (Diffenbaugh and Field 2013; Hawkins et al. 2014; Kunkel et al. 2013; Mora et al. 2013).

Extreme events can create a window of opportunity for transformation (Pelling and Dill 2010), temporarily lowering institutional and social barriers to change (Nelson et al. 2007). Prolonged drought, insect outbreaks, wildfire, and wind disturbances that reach the level of a natural disaster (Stanturf et al. 2014b; Van Aalst 2006) provide impetus for transformational adaptation. Extreme events are expected to increase in frequency and intensity under climate change (Allen 2009; Allen et al. 2010; Cai et al. 2014; Meehl et al. 2005; Reichstein et al. 2013); even so, windows for transformational adaptation associated with extreme events likely will be narrow because the usual reaction is to restore to the familiar (Travis 2010).

A way forward

At the landscape level, little or no ability exists to reduce exogenous drivers of global change. Socio-ecological systems, however, are amenable to reducing vulnerability and the negative effects of global change (Füssel 2007; Heltberg et al. 2009; Sarewitz et al. 2003). Outcome vulnerability, a top-down analysis, and contextual vulnerability, a bottom-up analysis, are two different perspectives (Pielke et al. 2013; Weaver et al. 2013). The top-down approach works best when addressing well-constrained problems where probabilities can be attached to the likelihood of different outcomes (Lempert et al. 2004). Top-down climate change vulnerability assessments lead either to decision-making ahead of evidence or alternatively, deferring decisions until uncertainty is reduced by improved climate projections (Pielke et al. 2013). Although the latter "wait and see" approach defers decisions and potential costs of adaptive measures; it risks the danger that the climate system will reach or exceed a tipping point of irreversible change before convincing evidence emerges resulting in greater costs of sustaining SES and mitigating the damage (Adams 2013; Lenton et al. 2008).

Decision-making under uncertainty is a necessary part of life; managing risk, reducing vulnerability, and focusing on increasing adaptive capacity may be a better way to cope with climate change trends that currently may be undetectable but are nonetheless real (Kates et al. 2012; Pielke et al. 2013). Bottom-up analysis yields an assessment of contextual vulnerability (Fig. 2) by examining the multiple stressors affecting socio-ecological

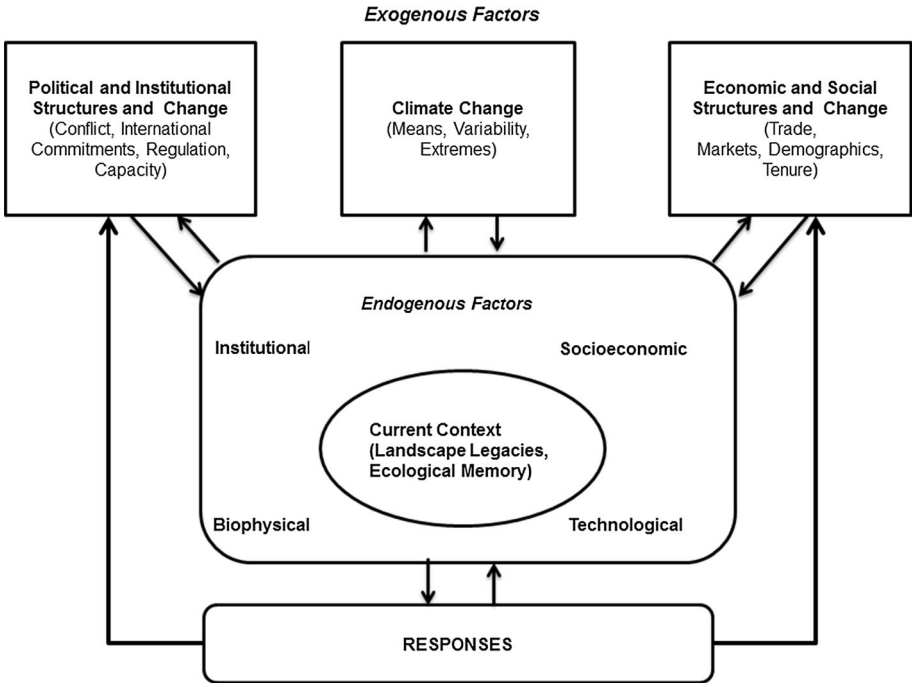

Fig. 2 Contextual vulnerability is a bottom-up approach that includes exogenous (political and institutional structures, economic and social institutions, and climate) and endogenous (biophysical, socioeconomic, institutional, and technological) drivers of land use change in landscapes that have legacies and ecological memory (Adapted from Pielke et al. 2013)

systems. Changes in exogenous drivers include climate, political and institutional structures, and socioeconomic structures (Fig. 2). The lingering effects of historical events that confer an exceptional nature on a landscape are recognized as landscape legacies including ecological memory (Parrott and Meyer 2012; Turner 2010).

Modeling capabilities will improve over time, but because people will change behavior in light of projections and new experience (e.g., extreme events), thus coupled SES are unlikely to become truly predictable (Liu et al. 2007; Parrott and Meyer 2012). Despite this uncertainty, our accumulated silvicultural and ecological knowledge provides the ability to act now and react in the future as more information becomes available (Keenan 2015; Lindner et al. 2014; Park et al. 2014; Pinkard et al. 2015). In the meantime, adapting to climate change requires improved coping strategies or reduced exposure to known threats (Moser and Ekstrom 2010; Wilby and Dessai 2010). Regardless of adaptation strategy (Tables 2 and 3), improved coping ability will require strategic and institutional flexibility and structured feedback (monitoring and evaluation) to facilitate course changes (Choi et al. 2008; Dow et al. 2013; Hobbs et al. 2006).

Integrate landscape restoration with climate change mitigation and adaptation

A central premise has been that the magnitude of degraded and deforested landscapes is best approached at a landscape scale. Landscape restoration incorporates consideration of all land uses, not just forests, which adds considerable complexity (Lamb et al. 2012; Lindenmayer et al. 2008; Sayer et al. 2013). Land use dynamics reflect current demand for land; future demand will increase for agriculture, forestry, energy, and conservation resulting in more intense competition (Lambin and Meyfroidt 2011; Smith et al. 2010). In addition to large areas of already degraded landscapes, the effects of climate change on SES pose additional threats to future forests. Integrating attempts to restore landscapes and mitigate and adapt to climate change may synergistically increase adaptive capacity.

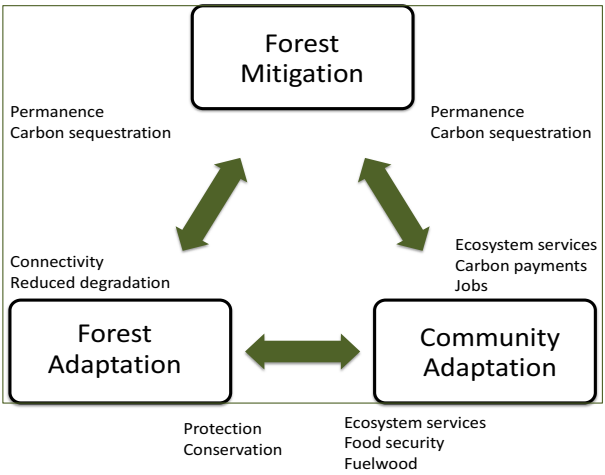

Fig. 3 Linkages among mitigation, forest adaptation, and community adaptation to climate change illustrate a linked socio-ecological system in a landscape, with reciprocal benefits from mitigation and adaptation (Adapted from Locatelli et al. 2011)

Forest landscapes are a linked socio-ecological system (Locatelli et al. 2011; Ostrom and Cox 2010). Potential synergies from linkages among mitigation, forest adaptation, and social adaptation to climate change can be illustrated at a local level by a community adjacent to a protected area that participates in a carbon benefit scheme such as REDD+ (Fig. 3). A mitigation planting connects the protected area to remnant forests outside through a corridor, enhancing connectivity. Forest adaptation measures are crucial to ensuring permanence of carbon fixed in mitigation forests (Galik and Jackson 2009; Hurteau et al. 2008) and may increase carbon sequestration in native forests (inside and outside the protected area) through improved forest management. The local community benefits from payments for carbon and other ecosystem services. In addition to payments, the carbon project has provided other benefits in the interim including improved agricultural seed and technical assistance to increase crop yields that reduce pressure on native forests (Blay et al. 2008; Schelhas et al. 2010).

Restoration planning and evaluation

Many natural resources organizations have well-established strategic and operational planning frameworks to guide future activities (Oliver et al. 2012). Planning methods that incorporate risk and assume a stationary climate will be challenged by the uncertainty of future climate (Bettinger et al. 2013). The following presents some features that could be incorporated to better adapt to climate change (Fig. 2).

Building a conceptual model of the landscape as a complex system means bringing diverse interests to a common understanding of the system and the wider context of exogenous environmental and social variables. Formally modeling the system may be attempted but if resources are insufficient to construct a quantitative model, a simple diagram may suffice. The starting point is evaluating current conditions and identifying significant landscape components and their sensitivity to current climate stimuli (Millar 2014). The next step is determining what changes in climate would have a significant effect on important landscape components (Daron et al. 2015; Pielke et al. 2013). These steps are iterative and may involve linking climate models and resource models, realizing this increases the uncertainty of projections (Maslin and Austin 2012; Wilsey et al. 2013). The estimated likelihood of these changes occurring should accompany recommendations to decision makers and stakeholders (Pielke et al. 2013).

Projections of future climate at an appropriate scale are necessary (Daron et al. 2015) and an ensemble of several (>10) AOGCMs gives better estimates of future conditions than using one or more "best" models (Mote et al. 2011). Current AOGCMs are better than older models at hindcasting historical temperature and precipitation at finer temporal and spatial scales (Sakaguchi et al. 2012; Wilsey et al. 2013). Publically available downscaled projections reduce the technical capacity needed to incorporate climate change projections into restoration planning (Girvetz et al. 2009; Groves et al. 2012). Nevertheless, expertise is needed to interpret model output and dynamical downscaling (rather than statistical) will be necessary to provide adequate spatial resolution in tropical areas where meteorological data are sparse or lacking.

Well-defined expectations are a hallmark of successful restoration (Stanturf et al. 2014a, b) and include in addition to the desired endpoint, the mechanism and trajectory of change (Burton 2014; Dey and Schweitzer 2014; Toth and Anderson 1998). Historic conditions as endpoints (e.g., reference sites) or regaining historical trajectories of ecosystem

development as a guide (SERI 2004; Suding et al. 2015) may not be adapted to future conditions (Balaguer et al. 2014; Millar 2014; Stanturf et al. 2014b; Stein et al. 2013). A diversity of forest and non-forest conditions may be best suited to meet multiple social needs (Oliver et al. 2012; Sayer et al. 2013). Restoration is the opposite of degradation and indicators of successful restoration can be the reverse of degradation indicators (Stanturf et al. 2014b). Positive restoration indicators may be increasing such as forest area maintained or enlarged or decreasing such as encroachment or fragmentation (Table 4). Some

Table 4 Restoration indicators, ▲ indicates an increase and ▼ a decrease in an indicator but both are positive outcomes (Adapted from Stanturf et al. 2014a)

Sustainability attributes	Restoration indicators	Landscape	Stand	Species
Forest extent	Area maintained	▲	▲	
	Area increased	▲	▲	
	Crown extent	▲	▲	▲
	Stocking		▲	▲
	Species number	▲	▲	▲
	Species diversity	▲	▲	▲
	Structural complexity	▲	▲	
	Fragmentation	▼	▼	
	Encroachment of non-forest uses	▼	▼	
Forest health and vitality	Crown extent	▲	▲	▲
	Growth	▲	▲	▲
	Seed dispersers	▲	▲	▲
	Pollinators	▲	▲	▲
	Mortality	▼	▼	▼
	Stem and root rots		▼	▼
Biodiversity	Area designated for habitat conservation	▲	▲	▲
	Richness	▲	▲	▲
	Connectivity	▲	▲	
	Species of concern	▲	▲	▲
	Genetic diversity within populations	▲	▲	▲
	Dispersal barriers	▼	▼	▼
	Invasive species	▼	▼	▼
Protective functions	Area designated for protective purposes	▲		
	Surface cover	▲	▲	
	Soil loss	▼	▼	
	Sediment delivery	▼	▼	
Productive functions	Site potential	▲	▲	
	Nutrient cycling	▲	▲	
	Stocking		▲	▲
	Valuable species		▲	▲
	Growing stock	▲	▲	▲
	Regeneration	▲	▲	▲
	Wildfire regime	▲	▲	
	Invasive species	▼	▼	▼

indicators are relevant at several scales (landscape, stand, and species) or singly. The indicators in Table 4 relate to current conditions (reversing past degradation) and many apply to adaptation to future climate but additional indicators are needed that focus on traits and adaptations of individual species to altered climate and to the non-forest elements in the landscape.

Trajectories and intermediate states are components of defined expectations (Toth and Anderson 1998). Key variables can be used for a temporal monitoring and evaluation system (Hutto and Belote 2013) within a spatial hierarchy (species, stand, landscape), stratified by significant habitats or landforms (Herrick et al. 2006; Sayer et al. 2007). The monitoring system would document successful adaptation and detect emerging threats. New information arising would be evaluated to determine if additional or innovative actions were needed because adaptation had not met expectations or altered conditions had changed vulnerability. Additional approaches to reduce risk from climate change and other impacts will likely arise and merit adoption (Kates et al. 2012).

A major question remains: when, or rather how quickly to act? Scenario planning captures the uncertainty surrounding the impacts of decisions and choices (Peterson et al. 2003). Characterizing when climate is likely to become sufficiently different so that action is needed is one way to set trigger points for pursuing more aggressive strategies (Travis 2010). Incremental adaptation is the default mode in restoration and initially a "no-regrets" approach (Heltberg et al. 2009) is the rational choice. Managers need to consider how actions affect the adaptive capacities of landscape components (Millar et al. 2007; Stephens et al. 2010). Managing for a portfolio of stand composition and structures across the landscape provides the flexibility to intervene and adapt to future conditions (Ando and Mallory 2012; Crowe and Parker 2008; Millar et al. 2007; Yemshanov et al. 2013). Stanturf et al. (2014a) provided a summary of available restoration methods; summarized by restoration objectives and starting points.

Restoration interventions

Cost-effective and low-cost methods are preferred in order to restore as much area as possible but without sacrificing benefits that could be secured by using more intensive methods, at least in some parts of the landscape (e.g., Stanturf et al. 2001). Passive restoration is a low-cost (but not necessarily free) method and useful where appropriate (Zahawi et al. 2014). Importantly, the long time needed for passive restoration to affect visible change might be seen as failure and cause premature termination of the effort or interpreted as abandonment and an invitation to encroachment (Zahawi et al. 2014). Significant opportunity costs of passive versus active restoration are incurred by the delay in delivering ecosystem services and foregone benefits (e.g., Stanturf et al. 2001).

Native recolonization of non-forest land or natural regeneration in degraded forests are lower-cost alternatives to more intensive planting methods but require adequate seed sources, advance regeneration, or sprouts on-site or within effective dispersal distance (Ashton et al. 2014; Chazdon 2008; Vieira and Scariot 2006). Low-intensity methods are unreliable, however, if threatened by ungulate herbivory or competing vegetation. Recolonization and natural regeneration rely on locally adapted genetic material, thus losing the opportunity to introduce new provenances or species better adapted to changing climatic conditions. Natural regeneration can be augmented by planting or sowing a desired species mix or stem density and in the event, non-local material more adapted to

changing climate can be introduced (Stanturf et al. 2014a). If local climate is likely to remain stable or change slowly, however, species may have sufficient phenotypic plasticity or genetic variation to acclimate or adapt through natural selection (Corlett and Westcott 2013; Keenan 2015; Park et al. 2014). Conversely, species already in decline or at risk because of isolation or under attack by introduced pests are poor candidates to survive climate change and likely will require active adaptation (Aitken et al. 2008; Jump and Peñuelas 2005).

Moving individuals of a species to locations where it has not occurred in the Holocene remains controversial (e.g., Laikre et al. 2010). Variously termed assisted migration, managed relocation, or assisted colonization, this strategy may be anticipatory or transformational, depending upon the distance a species is moved (Dumroese et al. 2015). Assisted migration is considered replacement in functional restoration (Stanturf et al. 2014a). Controversy aside, a key question is when and where to move species. Answers will vary over time as climate and landscape conditions change (Williams and Dumroese 2013). Methods are needed to identify species at risk, identify suitable habitat, and prioritize translocations. Assessing contextual vulnerability (Fig. 2) requires combining genetic information, bioclimatic models, and downscaled climate projections, augmented by historical records and experimental evidence from provenance testing (Rout et al. 2013; Williams and Dumroese 2013). This approach is information intensive and best applied for a defined region; a similar approach can be used to broadly identify where species at risk are likely to be found (Watson et al. 2013). In highly degraded ecoregions (the target of forest landscape restoration) likely to undergo significant climate shifts, a combination of assisting out-migration of species at risk and in-migration of climate-adapted species will be needed.

Implementing a decision to translocate a species requires using seed sources with the lowest risk of maladaptation and inbreeding or outbreeding depression over time (Breed et al. 2013; Williams and Dumroese 2013). A framework using climate change projections and genetic and environmental information was developed by Breed et al. (2013) to guide decisions about deploying provenances under various levels of uncertainty. Predictive provenancing is suitable for high-value species because of the cost of acquiring necessary data from provenance growth trials and population genetics (Crowe and Parker 2008). Uncertainty of climate projections, however, suggests that the risk of failure increases beyond 2050 (Williams and Dumroese 2013). Admixture provenancing (mixtures of seeds drawn from large populations across different environments) is the suggested strategy when genetic data are lacking and climate conditions are uncertain (Breed et al. 2013; Williams and Dumroese 2013). Sites to test provenancing strategies are needed (Breed et al. 2013) and degraded forest landscapes provide ample widely dispersed habitats for experiments.

Long-distance assisted migration raises questions, including whether it is worth the cost, financially and in terms of potential ecological risks at the introduction site (Hewitt et al. 2011). Rout et al. (2013) provided a quantitative approach to these questions as well as questions about the costs associated with the failure of the introduction and extinction risk of the source population. Extensions to their method could include the probability of dispersal and spontaneous colonization by the target species. Even in situations where insufficient information makes it uncomfortable to apply probabilities to stochastic events, they suggested that decisions based on an explicit, structured framework are preferable to ad hoc decision-making (Rout et al. 2013).

Implementing change

Implementing change is not free or immune from resistance by entrenched interests and institutional and behavioral barriers that favor the status quo (Kates et al. 2012). There are limits to adaptation by social actors, whether the focus is on individuals, businesses, or governments (Dow et al. 2013; Moser and Ekstrom 2010). The uncertainties about risks and benefits are compounded by the differing perceptions of risk by different actors (Klinke and Renn 2002) that influences their willingness to act (Dow et al. 2013), which is also determined by their ability to implement change and the amount of influence they have to overcome barriers (Moser and Ekstrom 2010). Nevertheless, climate variability and extreme events will require institutions to be proactive and flexible (Dow et al. 2013; Gupta et al. 2010). Adaptation should reduce risks to things of value and keep damage to tolerable levels (Dow et al. 2013).

Institutional inertia includes the generally ponderous, top-down, hierarchical nature of bureaucratic processes (Game et al. 2014). Policy sluggishness and regulatory inflexibility inhibit innovation (Keenan 2015) and guidelines, best practices, and tacit or explicit rules of thumb that are based on practices and experience proven successful in the past but may become maladaptive under future conditions (Kates et al. 2012). Nevertheless, aversion to using non-native species (Shackelford et al. 2013), stressing collection from local sources (Breed et al. 2013; McKay et al. 2005), or the debate about assisted migration (McLachlan et al. 2007; Pedlar et al. 2012; Williams and Dumroese 2013) are flashpoints in climate change adaptation. Within organizations, norms emerge from frames of reference that will be maintained, even in the face of new evidence that runs counter to these norms (Berkhout et al. 2006). Organizations appear more receptive to climate change adaptation when core business or core competencies are engaged (Berkhout et al. 2006). Individuals may respond in similar fashion. For example, Blennow et al. (2012) found that personal experience of perceived local climate change or its effects explained attitudes of private forest owners toward adaptation. Forestry professionals in Germany were likewise receptive to undertaking adaptive measures (Yousefpour and Hanewinkel 2015). In contrast, conservation professionals were less receptive (Hagerman and Satterfield 2014). Similarly, studies of individuals and their attitudes toward climate change have shown that political persuasion is more predictive than knowledge (Kahan 2015).

Social resistance to anticipatory and transformational adaptation is likely if actions contravene popular beliefs and values (Moser and Ekstrom 2010). For example the naturalness paradigm still dominates policy and public perception of restoration goals (Stanturf et al. 2014b). Native species, historic structure, and natural disturbance regimes are widely held tenets of ecological restoration (Burton and Macdonald 2011; Hobbs 2013) as well as close-to-nature silviculture (Brang et al. 2014). Another facet of the naturalness paradigm is the aversion to deploying genetically modified organisms (GMO) into native ecosystems (Laikre et al. 2010; Strauss and Bradshaw 2004). The ability to develop plant materials better adapted to new climatic conditions will be severely constrained if GMOs cannot be widely deployed (Dumroese et al. 2015).

The uncertain costs of climate change adaptation have been identified as a barrier (Moser and Ekstrom 2010) and what we know of the costs of large-scale restoration is daunting. For example, the 20+ year project to restore the Everglades ecosystem in Florida, USA has cost an estimated $13.4 billion. Guldin (2013) provided another example; he speculated on the financial hurdle of changing species composition of forests in the southern USA, based on a history of planting degraded land and converting naturally

regenerated stands to pine plantations. Briefly, a century was required to convert a fourth of the 100 million ha of forest for commercial purposes; the approximately $US16 billion spent to convert 250,000 ha annually on private land was under reasonably certain conditions (Guldin, 2013). This estimate did not account for the millions invested in research and development by public and private entities (e.g., Stanturf et al. 2003). Generally, there is little credible information on average costs of restoration (Holl and Howarth 2001). The cost of implementing the Bonn Challenge of restoring 150 million ha by 2020 (Minnemayer et al. 2011) is estimated at US$18 billion per year, with a return of US$84 billion per year to the global economy (Menz et al. 2013). Meeting global biodiversity conservation needs is estimated to cost US$76.1 billion annually (McCarthy et al. 2012).

Stratagems to overcome barriers

In order to move beyond incremental adaptation, we need "risky" research that pushes the boundaries of knowledge and accepted practice. Silvicultural and ecological knowledge of important relationships underlying successful adaptation to current climate can be the basis for speculative experiments that test the limits of important variables (Park et al. 2014). For example, warming experiments would provide needed information on the thermal tolerance of valued species. No doubt many of these experiments will fail, but even a few successful outcomes would provide needed information on species adaptation and appropriate management systems (Bormann and Kiester 2004).

More information about available provenances is needed as well as breeding programs to develop entirely new material. Modifying seed transfer zones and common garden experiments with commercial tree species are underway in the USA and Canada (Park et al. 2014; Williams and Dumroese 2013) and some European countries have considerable experience with non-native species (Bolte et al. 2009a; Isaac-Renton et al. 2014). Past efforts have concentrated on current climate or small increases in average temperature (Bolte et al. 2009b; Park et al. 2014) and more speculative experiments are needed to match the higher limits of projected warming (>5 °C). Moving provenances greater distances will have limited success for species that have limited genetic variation (Aitken et al. 2008) or have been decimated by non-native pests (Jacobs et al. 2013). Developing new climate-resilient plant material, through traditional breeding or genetic modification (Borland et al. 2015); will provide needed adaptations to warmer and drier conditions as well as defenses against novel pests (Dumroese et al. 2015).

Current species distribution models can be improved by incorporating more information on a host of species traits (Fitzpatrick and Hargrove 2009; Keenan 2015; Travis et al. 2013) and even better if more information is available at the genotype or provenance level (Bolte et al. 2009a, b). Better models will improve prioritizing species and habitats targeted for assisted migration (McKenney et al. 2007; Pedlar et al. 2012; Williams and Dumroese 2013). The ability to design adapted species mixtures in neo-native and novel ecosystems will depend upon trait-based approaches with species and provenances. Because climate sensitivity is likely to be greatest in the regeneration phase, ameliorating harsh conditions for seedling survival and establishment using underplanting or nurse crops could be included in speculative experiments testing provenancing strategies (Breed et al. 2013; Park et al. 2014).

Future landscapes pressured by radically different climate, twice as much humanity to feed and clothe, and greater global interconnectedness that facilitates the spread of

innovation as well as threats to natural systems, requires an unprecedented effort to restore past degradation and avoid future maladaptation. Perceptions of the future based on projections of the past are no longer tenable. Producing significant research results is important for academic advancement and science-based management but does not guarantee that the information produced will enter into policy formulation or management decisions. Methods to improve science-based adaptation include transdisciplinary teams with embedded managers and stakeholders (Pennington et al. 2013), communities of practice (Barlow et al. 2011; Hendriks et al. 2012) or knowledge hubs (Bidwell et al. 2013). In some cases, establishing research sites with an eye toward demonstrating how innovations compare to current best practices can yield unexpected benefits (Gardiner et al. 2008).

Acknowledgments This paper is based on a presentation made at the 2nd IUFRO Restoring Forests Conference "What constitutes success in the 21st Century", held 14–16 October 2014 in Lafayette, Indiana, USA. I thank the conference organizers for supporting my attendance and Douglass Jacobs for the invitation. The ideas expressed are my own and do not represent the official position of the US Forest Service or any other entity. I thank many colleagues for valuable discussions over the years that helped to formulate my ideas, in particular Kas Dumroese, Palle Madsen, David Lamb, Brian Palik, Magnus Löf, Andreas Bolte, Kalev Jögiste, Chad Oliver, and Emile Gardiner. Thanks also to two anonymous reviewers for helpful comments.

Conflict of interest I declare that I have no conflict of interest.

References

Adams MA (2013) Mega-fires, tipping points and ecosystem services: managing forests and woodlands in an uncertain future. For Ecol Manag 294:250–261

Agee JK (2003) Historical range of variability in eastern Cascades forests, Washington, USA. Landsc Ecol 18:725–740

Agostini F, Gregory A, Richter G (2015) Carbon sequestration by perennial energy crops: Is the jury still out? Bioenerg Res. doi:10.1007/s12155-014-9571-0

Aitken SN, Yeaman S, Holliday JA, Wang T, Curtis-McLane S (2008) Adaptation, migration or extirpation: climate change outcomes for tree populations. Evol Appl 1:95–111

Alig RJ, Adams D, Joyce L, Sohn-Gen B (2004) Climate change impacts and adaptation in forestry: responses by trees and markets. Choices 19:1–7

Allen C (2009) Climate-induced forest dieback: an escalating global phenomenon. Unasylva 231:60

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim J-H, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684

Ando AW, Mallory ML (2012) Optimal portfolio design to reduce climate-related conservation uncertainty in the Prairie Pothole Region. Proc Nat Acad Sci USA 109:6484–6489

Arneth A, Brown C, Rounsevell M (2014) Global models of human decision-making for land-based mitigation and adaptation assessment. Nat Clim Change 4:550–557

Ashton MS, Gunatilleke C, Gunatilleke I, Singhakumara B, Gamage S, Shibayama T, Tomimura C (2014) Restoration of rain forest beneath pine plantations: a relay floristic model with special application to tropical South Asia. For Ecol Manag 329:351–359

Balaguer L, Escudero A, Martín-Duque JF, Mola I, Aronson J (2014) The historical reference in restoration ecology: re-defining a cornerstone concept. Biol Conserv 176:12–20

Barlow J, Ewers RM, Anderson L, Aragao LEOC, Baker TR, Boyd E, Feldpausch TR, Gloor E, Malhi Y, Milliken W, Mulligan M, Parry L, Pennington T, Peres CA, Phillips OL, Roman-Cuesta RM, Tobias JA, Gardner TA (2011) Using learning networks to understand complex systems: a case study of biological, geophysical and social research in the Amazon. Biol Rev 86:457–474

Barnosky AD, Hadly EA, Bascompte J, Berlow EL, Brown JH, Fortelius M, Getz WM, Harte J, Hastings A, Marquet PA, Martinez ND, Mooers A, Roopnarine P, Vermeij G, Williams JW, Gillespie R, Kitzes J,

Marshall C, Matzke N, Mindell DP, Revilla E, Smith AB (2012) Approaching a state shift in earth's biosphere. Nature 486:52–58
Beatty S, Owen B (2005) Incorporating disturbance into forest restoration. In: Stanturf J, Madsen P (eds) Restoration of boreal and temperate forests. CRC Press, Boca Raton, pp 61–76
Becker EJ, Van Den Dool H, Peña M (2013) Short-term climate extremes: prediction skill and predictability. J Clim 26:512–531
Bellard C, Leclerc C, Leroy B, Bakkenes M, Veloz S, Thuiller W, Courchamp F (2014) Vulnerability of biodiversity hotspots to global change. Global Ecol Biogeogr 23:1376–1386
Berkhout F, Hertin J, Gann DM (2006) Learning to adapt: organisational adaptation to climate change impacts. Clim Change 78:135–156
Bettinger P, Siry J, Merry K (2013) Forest management planning technology issues posed by climate change. For Sci Tech 9:9–19
Biagini B, Bierbaum R, Stults M, Dobardzic S, McNeeley SM (2014) A typology of adaptation actions: a global look at climate adaptation actions financed through the global environment facility. Glob Environ Change 25:97–108
Bidwell D, Dietz T, Scavia D (2013) Fostering knowledge networks for climate adaptation. Nat Clim Change 3:610–611
Blay D, Appiah M, Damnyag L, Dwomoh FK, Luukkanen O, Pappinen A (2008) Involving local farmers in rehabilitation of degraded tropical forests: some lessons from Ghana. Environ Dev Sustain 10:503–518
Blennow K, Persson J, Tome M, Hanewinkel M (2012) Climate change: believing and seeing implies adapting. PLoS ONE 7:e50182
Bolte A, Ammer C, Löf M, Madsen P, Nabuurs G-J, Schall P, Spathelf P, Rock J (2009a) Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. Scan J For Res 24:473–482
Bolte A, Ammer C, Löf M, Nabuurs G-J, Schall P, Spathelf P (2009b) Adaptive forest management: a prerequisite for sustainable forestry in the face of climate change. In: Spathelf P (ed) Sustainable forest management in a changing world. Springer, Dordrecht, pp 115–139
Borland AM, Wullschleger SD, Weston DJ, Hartwell J, Tuskan GA, Yang X, Cushman JC (2015) Climate-resilient agroforestry: physiological responses to climate change and engineering of crassulacean acid metabolism (CAM) as a mitigation strategy. Plant Cell Environ (in press). doi:10.1111/pce.12479
Bormann BT, Kiester AR (2004) Options forestry: acting on uncertainty. J Forestry 102:22–27
Bradley BA, Blumenthal DM, Early R, Grosholz ED, Lawler JJ, Miller LP, Sorte CJB, D'Antonio CM, Diez JM, Dukes JS (2011) Global change, global trade, and the next wave of plant invasions. Front Ecol Environ 10:20–28
Brang P, Spathelf P, Larsen JB, Bauhus J, Boncčina A, Chauvin C, Drössler L, García-Güemes C, Heiri C, Kerr G (2014) Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. Forestry 87:492–503
Breed MF, Stead MG, Ottewell KM, Gardner MG, Lowe AJ (2013) Which provenance and where? Seed sourcing strategies for revegetation in a changing environment. Conserv Genet 14:1–10
Burrows MT, Schoeman DS, Richardson AJ, Molinos JG, Hoffmann A, Buckley LB, Moore PJ, Brown CJ, Bruno JF, Duarte CM (2014) Geographical limits to species-range shifts are suggested by climate velocity. Nature 507:492–495
Burton PJ (2014) Considerations for monitoring and evaluating forest restoration. J Sustain For 33:S149–S160
Burton PJ, Macdonald SE (2011) The restorative imperative: challenges, objectives and approaches to restoring naturalness in forests. Silva Fenn 45:843–863
Cai W, Borlace S, Lengaigne M, Van Rensch P, Collins M, Vecchi G, Timmermann A, Santoso A, McPhaden MJ, Wu L (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. Nat Clim Change 4:111–116
Chapman S, Mustin K, Renwick AR, Segan DB, Hole DG, Pearson RG, Watson JE (2014) Publishing trends on climate change vulnerability in the conservation literature reveal a predominant focus on direct impacts and long time-scales. Diver Distrib 20:1221–1228
Chazdon RL (2008) Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320:1458–1460
Choi YD, Temperton VM, Allen EB, Grootjans AP, Halassy M, Hobbs RJ, Naeth MA, Torok K (2008) Ecological restoration for future sustainability in a changing environment. Ecoscience 15:53–64
Clement CR, Junqueira AB (2010) Between a pristine myth and an impoverished future. Biotropica 42:534–536
Cochrane MA, Laurance WF (2008) Synergisms among fire, land use, and climate change in the Amazon. Ambio 37:522–527

Corbin JD, Holl KD (2012) Applied nucleation as a forest restoration strategy. For Ecol Manag 265:37–46
Corlett RT, Westcott DA (2013) Will plant movements keep up with climate change? Trends Ecol Evol 28:482–488
Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, Cherubini F, Chum H, Corbera E, Delucchi M, Faaij A, Fargione J, Haberl H, Heath G, Lucon O, Plevin R, Popp A, Robledo-Abad C, Rose S, Smith P, Stromman A, Suh S, Masera O (2014) Bioenergy and climate change mitigation: an assessment. GCB Bioenergy. doi:10.1111/gcbb.12205
Crowe KA, Parker WH (2008) Using portfolio theory to guide reforestation and restoration under climate change scenarios. Clim Change 89:355–370
Dai A (2011) Drought under global warming: a review. WIREs Clim Change 2:45–65
D'Antonio CM, Vitousek PM (1992) Biological invasions by exotic grasses, the grass/fire cycle, and global change. Ann Rev Ecol Syst 23:63–87
Daron JD, Sutherland K, Jack C, Hewitson BC (2015) The role of regional climate projections in managing complex socio-ecological systems. Reg Environ Change 15:1–12
Davis MA, Chew MK, Hobbs RJ, Lugo AE, Ewel JJ, Vermeij GJ, Brown JH, Rosenzweig ML, Gardener MR, Carroll SP (2011) Don't judge species on their origins. Nature 474:153–154
De Frenne P, Rodríguez-Sánchez F, Coomes DA, Baeten L, Verstraeten G, Vellend M, Bernhardt-Römermann M, Brown CD, Brunet J, Cornelis J (2013) Microclimate moderates plant responses to macroclimate warming. Proc Nat Acad Sci USA 110:18561–18565
Dey DC, Schweitzer CJ (2014) Restoration for the future: endpoints, targets, and indicators of progress and success. J Sustain For 33:S43–S65
Diffenbaugh NS, Field CB (2013) Changes in ecologically critical terrestrial climate conditions. Science 341:486–492
Dirzo R, Young HS, Galetti M, Ceballos G, Isaac NJ, Collen B (2014) Defaunation in the Anthropocene. Science 345:401–406
Dixon RK, Smith J, Guill S (2003) Life on the edge: vulnerability and adaptation of African ecosystems to global climate change. Mitig Adapt Strat Gl 8:93–113
Dobrowski SZ (2011) A climatic basis for microrefugia: the influence of terrain on climate. Ann Rev Ecol Syst 17:1022–1035
Dow K, Berkhout F, Preston BL, Klein RJ, Midgley G, Shaw MR (2013) Limits to adaptation. Nat Clim Change 3:305–307
Dumroese RK, Williams MI, Stanturf JA, St. Clair JB (2015) Considerations for restoring temperate forests of tomorrow: forest restoration, assisted migration, and bioengineering. New For (in press)
FAO (2010) Global forest resources assessment 2010, forestry paper 163. Food and Agriculture Organization, Rome
FAO (2011) The state of the world's land and water resources for food and agriculture (SOLAW)—managing systems at risk. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London
Fitzpatrick MC, Hargrove WW (2009) The projection of species distribution models and the problem of non-analog climate. Biodivers Conserv 18:2255–2261
Füssel H-M (2007) Vulnerability: a generally applicable conceptual framework for climate change research. Glob Environ Change 17:155–167
Galik CS, Jackson RB (2009) Risks to forest carbon offset projects in a changing climate. For Ecol Manag 257:2209–2216
Game ET, Meijaard E, Sheil D, McDonald-Madden E (2014) Conservation in a wicked complex world; challenges and solutions. Conserv Lett 7:271–277
Gamfeldt L, Snäll T, Bagchi R, Jonsson M, Gustafsson L, Kjellander P, Ruiz-Jaen MC, Fröberg M, Stendahl J, Philipson CD (2013) Higher levels of multiple ecosystem services are found in forests with more tree species. Nat Commun 4:1340
Gardiner E, Stanturf J, Leininger T, Hamel P, Dorris L, Portwood J, Shepard J (2008) Establishing a research and demonstration area initiated by managers: the Sharkey restoration research and demonstration site. J For 106:363–369
Gerland P, Raftery AE, Ševčíková H, Li N, Gu D, Spoorenberg T, Alkema L, Fosdick BK, Chunn J, Lalic N, Bay G, Buettner T, Heilig GK, Wilmoth J (2014) World population stabilization unlikely this century. Science 346:234–237
Girvetz EH, Zganjar C, Raber GT, Maurer EP, Kareiva P, Lawler JJ (2009) Applied climate-change analysis: the climate wizard tool. PLoS ONE 4:e8320
Groves CR, Game ET, Anderson MG, Cross M, Enquist C, Ferdana Z, Girvetz G, Gondor A, Hall KR, Higgins J (2012) Incorporating climate change into systematic conservation planning. Biodivers Conserv 21:1651–1671

Guldin JM (2013) Adapting silviculture to a changing climate in the Southern United States. In: Vose JM, Klepzig KD (eds) Climate change adaptation and mitigation management options: a guide for natural resource managers in southern forest ecosystems. CRC Press, Boca Raton, pp 173–192

Gupta J, Termeer C, Klostermann J, Meijerink S, van den Brink M, Jong P, Nooteboom S, Bergsma E (2010) The adaptive capacity wheel: a method to assess the inherent characteristics of institutions to enable the adaptive capacity of society. Environ Sci Policy 13:459–471

Hagerman SM, Satterfield T (2014) Agreed but not preferred: expert views on taboo options for biodiversity conservation, given climate change. Ecol Appl 24:548–559

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. Glob Environ Change 19:240–247

Hansen MC, Stehman SV, Potapov PV (2010) Quantification of global gross forest cover loss. Proc Nat Acad Sci USA 107:8650–8655

Hawkins E, Anderson B, Diffenbaugh N, Mahlstein I, Betts R, Hegerl G, Joshi M, Knutti R, McNeall D, Solomon S (2014) Uncertainties in the timing of unprecedented climates. Nature 511:E3–E5

Heltberg R, Siegel PB, Jorgensen SL (2009) Addressing human vulnerability to climate change: toward a 'no-regrets' approach. Glob Environ Change 19:89–99

Hendriks RJ, Boot RG, de Haas W, Savenije HJ (2012) Forest landscape restoration in the Netherlands: policy aspects and knowledge management. In: Stanturf J, Madsen P, Lamb D (eds) A goal-oriented approach to forest landscape restoration. Springer, Dordrecht, pp 21–40

Herrick JE, Schuman GE, Rango A (2006) Monitoring ecological processes for restoration projects. J Nat Conserv 14:161–171

Hewitt N, Klenk N, Smith A, Bazely D, Yan N, Wood S, MacLellan J, Lipsig-Mumme C, Henriques I (2011) Taking stock of the assisted migration debate. Biol Conserv 144:2560–2572

Hobbs RJ (2013) Grieving for the past and hoping for the future: balancing polarizing perspectives in conservation and restoration. Restor Ecol 21:145–148

Hobbs RJ, Arico S, Aronson J, Baron JS, Bridgewater P, Cramer VA, Epstein PR, Ewel JJ, Klink CA, Lugo AE (2006) Novel ecosystems: theoretical and management aspects of the new ecological world order. Glob Ecol Biogeogr 15:1–7

Hobbs RJ, Higgs E, Harris JA (2009) Novel ecosystems: implications for conservation and restoration. Trends Ecol Evol 24:599–605

Hobbs RJ, Hallett LM, Ehrlich PR, Mooney HA (2011) Intervention ecology: applying ecological science in the twenty-first century. Bioscience 61:442–450

Hobbs RJ, Higgs ES, Hall CM (2013) Defining novel ecosystems. In: Hobbs RJ, Higgs ES, Hall CM (eds) Novel ecosystems. Wiley-Blackwell, Oxford, pp 58–60

Holl KD, Howarth RB (2001) Paying for restoration. Restor Ecol 8:260–267

Hughes TP, Linares C, Dakos V, van de Leemput IA, van Nes EH (2013) Living dangerously on borrowed time during slow, unrecognized regime shifts. Trends Ecol Evol 28:149–155

Hurteau MD, Koch GW, Hungate BA (2008) Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. Front Ecol Environ 6:493–498

Hutto RL, Belote R (2013) Distinguishing four types of monitoring based on the questions they address. For Ecol Manag 289:183–189

IPCC (2003) Definitions and methodological options to inventory emissions from direct human induced degradation of forests and devegetation of other vegetation types. In: Penman J et al (eds) IPCC national greenhouse gas inventories programme. Hayama, Japan

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA

Isaac-Renton MG, Roberts DR, Hamann A, Spiecker H (2014) Douglas-fir plantations in Europe: a retrospective test of assited migration to address climate change. Ann Rev Ecol Syst 20:2607–2617

Jackson ST, Overpeck JT (2000) Responses of plant populations and communities to environmental changes of the late quaternary. Paleobiology 26:194–220

Jacobs DF, Dalgleish HJ, Nelson CD (2013) A conceptual framework for restoration of threatened plants: the effective model of American chestnut (*Castanea dentata*) reintroduction. New Phytol 197:378–393

Janowiak MK, Swanston CW, Nagel LM, Brandt LA, Butler PR, Handler SD, Shannon PD, Iverson LR, Matthews SN, Prasad A (2014) A practical approach for translating climate change adaptation principles into forest management actions. J For 112:424–433

Joyce LA, Blate GM, McNulty SG, Millar CI, Moser S, Neilson RP, Peterson DL (2009) Managing for multiple resources under climate change: national forests. Environ Manage 44:1022–1032

Joyce LA, Briske DD, Brown JR, Polley HW, McCarl BA, Bailey DW (2013) Climate change and North American rangelands: assessment of mitigation and adaptation strategies. Rangeland Ecol Manag 66:512–528

Jump AS, Peñuelas J (2005) Running to stand still: adaptation and the response of plants to rapid climate change. Ecol Lett 8:1010–1020
Kahan DM (2015) Climate-science communication and the measurement problem. Polit Psychol 36:1–43
Kates RW, Travis WR, Wilbanks TJ (2012) Transformational adaptation when incremental adaptations to climate change are insufficient. Proc Nat Acad Sci USA 109:7156–7161
Keane RE, Hessburg PF, Landres PB, Swanson FJ (2009) The use of historical range and variability (HRV) in landscape management. For Ecol Manag 258:1025–1037
Keenan RJ (2015) Climate change impacts and adaptation in forest management: a review. Ann For Sci 72:145–167
Kelatwang S, Garzuglia M (2006) Changes in forest area in Africa 1990–2005. Int For Rev 8:21–30
Kelty MJ (2006) The role of species mixtures in plantation forestry. For Ecol Manag 233:195–204
Keppel G, Wardell-Johnson GW (2012) Refugia: keys to climate change management. Ann Rev Ecol Syst 18:2389–2391
Keskitalo ECH (2011) How can forest management adapt to climate change? Possibilities in different forestry systems. Forests 2:415–430
Kiage LM (2013) Perspectives on the assumed causes of land degradation in the rangelands of Sub-Saharan Africa. Prog Phys Geog 37:664–684
Kim D-H, Sexton JO, Townshend JR (2015) Accelerated deforestation in the Humid tropics from the 1990s to the 2000s. Geophys Res Lett. doi:10.1002/20/2014GL062777
Klinke A, Renn O (2002) A New approach to risk evaluation and management: risk-based, precaution-based, and discourse-based strategies. Risk Anal 22:1071–1094
Kolström M, Lindner M, Vilén T, Maroschek M, Seidl R, Lexer MJ, Netherer S, Kremer A, Delzon S, Barbati A (2011) Reviewing the science and implementation of climate change adaptation measures in European forestry. Forests 2:961–982
Kunkel KE, Karl TR, Brooks H, Kossin J, Lawrimore JH, Arndt D, Bosart L, Changnon D, Cutter SL, Doesken N (2013) Monitoring and understanding trends in extreme storms: state of knowledge. B Am Meteorol Soc 94:499–514
Laikre L, Schwartz MK, Waples RS, Ryman N, Group GW (2010) Compromising genetic diversity in the wild: unmonitored large-scale release of plants and animals. Trends Ecol Evol 25:520–529
Lamb D, Stanturf J, Madsen P (2012) What is forest landscape restoration? In: Stanturf J, Lamb D, Madsen P (eds) forest landscape restoration. Springer, Dordrecht, pp 3–23
Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. Proc Nat Acad Sci USA 108:3465–3472
Laurance WF, Sayer J, Cassman KG (2014) Agricultural expansion and its impacts on tropical nature. Trends Ecol Evol 29:107–116
Leadley P, Proença V, Fernández-Manjarrés J, Pereira HM, Alkemade R, Biggs R, Bruley E, Cheung W, Cooper D, Figueiredo J, Gilman E, Guénette S, Hurtt G, Mbow C, Oberdorff T, Revenga C, Scharlemann JPW, Scholes R, Smith MS, Sumaila UR, Walpole M (2014) Interacting regional-scale regime shifts for biodiversity and ecosystem services. Bioscience 64:665–679
Lempert R, Nakicenovic N, Sarewitz D, Schlesinger M (2004) Characterizing climate-change uncertainties for decision-makers. An editorial essay. Clim Change 65:1–9
Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ (2008) Tipping elements in the Earth's climate system. Proc Nat Acad Sci USA 105:1786–1793
Lindenmayer D, Hobbs RJ, Montague-Drake R, Alexandra J, Bennett A, Burgman M, Cale P, Calhoun A, Cramer V, Cullen P (2008) A checklist for ecological management of landscapes for conservation. Ecol Lett 11:78–91
Lindner M, Fitzgerald JB, Zimmermann NE, Reyer C, Delzon S, van der Maaten E, Schelhaas M-J, Lasch P, Eggers J, van der Maaten-Theunissen M (2014) Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? J Environ Manage 146:69–83
Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J (2007) Complexity of coupled human and natural systems. Science 317:1513–1516
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
Lockhart BR, Gardiner E, Leininger T, Stanturf J (2008) A stand-development approach to oak afforestation in the Lower Mississippi Alluvial Valley. South J Appl For 32:120–129
Löf M, Brunet J, Hickler T, Birkedal M, Jensen A (2012) Restoring broadleaved forests in southern Sweden as climate changes. In: Stanturf J, Madsen P, Lamb D (eds) A goal-oriented approach to forest landscape restoration. Springer, Dordrecht, pp 373–391

Löf M, Bolte A, Jacobs DF, Jensen AM (2014) Nurse trees as a forest restoration tool for mixed plantations: effects on competing vegetation and performance in target tree species. Restor Ecol 22:758–765

Logan JA, Regniere J, Powell JA (2003) Assessing the impacts of global warming on forest pest dynamics. Front Ecol Environ 1:130–137

Lugo AE (2009) The emerging era of novel tropical forests. Biotropica 41:589–591

Lunt ID, Byrne M, Hellmann JJ, Mitchell NJ, Garnett ST, Hayward MW, Martin TG, McDonald-Maddden E, Williams SE, Zander KK (2013) Using assisted colonisation to conserve biodiversity and restore ecosystem function under climate change. Biol Conserv 157:172–177

Macqueen D, Milledge I, Reeves J (2014) SD goals from a forest perspective: Transformative, universal and integrated? IIED discussion paper. International Institute for Environment and Development, London

Mahmood R, Pielke RA, Hubbard KG, Niyogi D, Dirmeyer PA, McAlpine C, Carleton AM, Hale R, Gameda S, Beltrán-Przekurat A (2013) Land cover changes and their biogeophysical effects on climate. Int J Climatol 34:929–953

Maslin M, Austin P (2012) Uncertainty: climate models at their limit? Nature 486:183–184

Mayaux P, Pekel J-F, Desclée B, Donnay F, Lupi A, Achard F, Clerici M, Bodart C, Brink A, Nasi R, Belward A (2013) State and evolution of the African rainforests between 1990 and 2010. Philos T R Soc Biol Sci 368:1–10

McCarthy DP, Donald PF, Scharlemann JP, Buchanan GM, Balmford A, Green JM, Bennun LA, Burgess ND, Fishpool LD, Garnett ST (2012) Financial costs of meeting global biodiversity conservation targets: current spending and unmet needs. Science 338:946–949

McKay JK, Christian CE, Harrison S, Rice KJ (2005) "How local is local?"—a review of practical and conceptual issues in the genetics of restoration. Restor Ecol 13:432–440

McKenney DW, Pedlar JH, Lawrence K, Campbell K, Hutchinson MF (2007) Beyond traditional hardiness zones: using climate envelopes to map plant range limits. Bioscience 57:929–937

McLachlan JS, Hellmann JJ, Schwartz MW (2007) A framework for debate of assisted migration in an era of climate change. Conserv Biol 21:297–302

McMichael AJ, Woodruff RE, Hales S (2006) Climate change and human health: present and future risks. Lancet 367:859–869

Meehl GA, Washington WM, Collins WD, Arblaster JM, Hu A, Buja LE, Strand WG, Teng H (2005) How much more global warming and sea level rise? Science 307:1769–1772

Menz MH, Dixon KW, Hobbs RJ (2013) Hurdles and opportunities for landscape-scale restoration. Science 339:526–527

Millar CI (2014) Historic variability: informing restoration strategies, not prescribing targets. J Sustain For 33:S28–S42

Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17:2145–2151

Minang PA, van Noordwijk M, Freeman OE, Mbow C, de Leeuw J, Catacutan D (eds) (2015) Climate-smart landscapes: multifunctionality in practice. World Agroforestry Centre (ICRAF), Nairobi

Minnemayer S, Laestadius L, Sizer N (2011) A world of opportunity. World Resource Institute, Washington, DC

Mora C, Frazier AG, Longman RJ, Dacks RS, Walton MM, Tong EJ, Sanchez JJ, Kaiser LR, Stender YO, Anderson JM (2013) The projected timing of climate departure from recent variability. Nature 502:183–187

Moser SC, Ekstrom JA (2010) A framework to diagnose barriers to climate change adaptation. Proc Nat Acad Sci USA 107:22026–22031

Mote P, Brekke L, Duffy PB, Maurer E (2011) Guidelines for constructing climate scenarios. Eos Trans Am Geophys Union 92:257–258

Nelson DR, Adger WN, Brown K (2007) Adaptation to environmental change: contributions of a resilience framework. Annu Rev Environ Resour 32:395

Nepstad DC, Boyd W, Stickler CM, Bezerra T, Azevedo AA (2013) Responding to climate change and the global land crisis: REDD+, market transformation and low-emissions rural development. Philos Trans R Soc B 368:20120167

Nicotra AB, Atkin OK, Bonser SP, Davidson AM, Finnegan E, Mathesius U, Poot P, Purugganan MD, Richards C, Valladares F (2010) Plant phenotypic plasticity in a changing climate. Trends Plant Sci 15:684–692

Oliver CD, Covey K, Hohl A, Larsen D, McCarter JB, Niccolai A, Wilson J (2012) Landscape management. In: Stanturf J, Lamb D, Madsen P (eds) Forest landscape restoration. Springer, Dordrecht, pp 39–65

Ordonez JC, Luedeling E, Kindt R, Tata HL, Harja D, Jamnadass R, van Noordwijk M (2014) Constraints and opportunities for tree diversity management along the forest transition curve to achieve multifunctional agriculture. Curr Opin Enviro Sustain 6:54–60

Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. Science 325:419–422
Ostrom E, Cox M (2010) Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. Environ Conserv 37:451–463
Pacifici M, Foden WB, Visconti P, Watson JEM, Butchart SHM, Kovacs KM, Scheffers BR, Hole DG, Martin TG, Akcakaya HR, Corlett RT, Huntley B, Bickford D, Carr JA, Hoffmann AA, Midgley GF, Pearce-Kelly P, Pearson RG, Williams SE, Willis SG, Young B, Rondinini C (2015) Assessing species vulnerability to climate change. Nat Clim Change 5:215–224
Park A, Puettmann K, Wilson E, Messier C, Kames S, Dhar A (2014) Can boreal and temperate forest management be adapted to the uncertainties of 21st century climate change? Crit Rev Plant Sci 33:251–285
Parrott L, Meyer WS (2012) Future landscapes: managing within complexity. Front Ecol Environ 10:382–389
Patz JA, Campbell-Lendrum D, Holloway T, Foley JA (2005) Impact of regional climate change on human health. Nature 438:310–317
Pedlar JH, McKenney DW, Aubin I, Beardmore T, Beaulieu J, Iverson L, O'Neill GA, Winder RS, Ste-Marie C (2012) Placing forestry in the assisted migration debate. Bioscience 62:835–842
Pelling M, Dill K (2010) Disaster politics: tipping points for change in the adaptation of sociopolitical regimes. Prog Hum Geog 34:21–37
Pennington DD, Simpson GL, McConnell MS, Fair JM, Baker RJ (2013) Transdisciplinary research, transformative learning, and transformative science. Bioscience 63:564–573
Perring MP, Standish RJ, Hobbs RJ (2013) Incorporating novelty and novel ecosystems into restoration planning and practice in the 21st century. Ecol Process 2:1–8
Perring MP, Audet P, Lamb D (2014) Novel ecosystems in ecological restoration and rehabilitation: Innovative planning or lowering the bar? Ecol Processes 3:8
Peterson CJ (2000) Catastrophic wind damage to North American forests and the potential impact of climate change. Sci Total Environ 262:287–311
Peterson GD, Cumming GS, Carpenter SR (2003) Scenario planning: a tool for conservation in an uncertain world. Conserv Biol 17:358–366
Pichancourt JB, Firn J, Chadès I, Martin TG (2014) Growing biodiverse carbon-rich forests. Ann Rev Ecol Syst 20:382–393
Pielke RA, Pitman A, Niyogi D, Mahmood R, McAlpine C, Hossain F, Goldewijk KK, Nair U, Betts R, Fall S (2011) Land use/land cover changes and climate: modeling analysis and observational evidence. WIREs Clim Change 2:828–850
Pielke RA, Wilby R, Niyogi D, Hossain F, Dairuku K, Adegoke J, Kallos G, Seastedt T, Suding K (2013) Dealing with complexity and extreme events using a bottom-up, resource-based vulnerability perspective. In: Sharma AS, Bunde A, Dimri VP, Baker DN (eds) Extreme events and natural hazards: the complexity perspective. American Geophysical Union, Washington, DC, pp 345–359
Pinkard E, Battaglia M, Bruce J, Matthews S, Callister AN, Hetherington S, Last I, Mathieson S, Mitchell C, Mohammed C, Musk R, Ravenwood I, Rombouts J, Stone C, Wardlaw T (2015) A history of forestry management responses to climatic variability and their current relevance for developing climate change adaptation strategies. Forestry 88:155–171
Pretty J (2013) The consumption of a finite planet: well-being, convergence, divergence and the nascent green economy. Environ Resour Econ 55:475–499
Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114:1571–1596
Ravindranath N (2007) Mitigation and adaptation synergy in forest sector. Mitig Adapt Strat Gl 12:843–853
Reichstein M, Bahn M, Ciais P, Frank D, Mahecha MD, Seneviratne SI, Zscheischler J, Beer C, Buchmann N, Frank DC, Papale D, Rammig A, Smith P, Thonicke K, van der Velde M, Vicca S, Walz A, Wattenbach M (2013) Climate extremes and the carbon cycle. Nature 500:287–295
Rout TM, McDonald-Madden E, Martin TG, Mitchell NJ, Possingham HP, Armstrong DP (2013) How to decide whether to move species threatened by climate change. PLoS ONE 8:e75814
Rudel TK (2013) The national determinants of deforestation in sub-Saharan Africa. Philos Trans R Soc B. doi:10.1098/rstb.2012.0405
Rummukainen M (2012) Changes in climate and weather extremes in the 21st century. WIREs Clim Change 3:115–129
Sakaguchi K, Zeng X, Brunke MA (2012) The hindcast skill of the CMIP ensembles for the surface air temperature trend. J Geophys Res-Atmos 117:D16113. doi:10.1029/2012JD017765
Sarewitz D, Pielke R, Keykhah M (2003) Vulnerability and risk: some thoughts from a political and policy perspective. Risk Anal 23:805–810

Sarr DA, Puettmann KJ (2008) Forest management, restoration, and designer ecosystems: integrating strategies for a crowded planet. Ecoscience 15:17–26

Sayer J, Campbell B, Petheram L, Aldrich M, Perez MR, Endamana D, Dongmo Z-LN, Defo L, Mariki S, Doggart N (2007) Assessing environment and development outcomes in conservation landscapes. Biodivers Conserv 16:2677–2694

Sayer J, Sunderland T, Ghazoul J, Pfund J-L, Sheil D, Meijaard E, Venter M, Boedhihartono AK, Day M, Garcia C (2013) Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. Proc Nat Acad Sci USA 110:8349–8356

Schelhas J, Samar S, Johnson C, Asamadu A, Tease F, Stanturf J, Blay D (2010) Opportunities and capacity for community-based forest carbon sequestration and monitoring in Ghana. Nat Faune 25:41–45

Schönenberger W (2001) Cluster afforestation for creating diverse mountain forest structures—a review. For Ecol Manag 145:121–128

Schröter D, Cramer W, Leemans R, Prentice IC, Araújo MB, Arnell NW, Bondeau A, Bugmann H, Carter TR, Gracia CA (2005) Ecosystem service supply and vulnerability to global change in Europe. Science 310:1333–1337

Seddon PJ, Griffiths CJ, Soorae PS, Armstrong DP (2014) Reversing defaunation: restoring species in a changing world. Science 345:406–412

Seidl R, Lexer MJ (2013) Forest management under climatic and social uncertainty: trade-offs between reducing climate change impacts and fostering adaptive capacity. J Environ Manage 114:461–469

Seppälä R, Buck A, Katila P (eds) (2009) Adaptation of forests and people to climate change: a global assessment report. IUFRO World Series 22, International Union Forest Research Organizations, Helsinki, Finland

SERI (2004) The SER International primer on ecological restoration. Society for Ecological Restoration International. http://www.ser.org/resources/resources-detail-view/ser-international-primer-on-ecological-restoration

Seto KC, Güneralp B, Hutyra LR (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc Nat Acad Sci USA 109:16083–16088

Shackelford N, Hobbs RJ, Heller NE, Hallett LM, Seastedt TR (2013) Finding a middle-ground: the native/non-native debate. Biol Conserv 158:55–62

Smith P, Gregory PJ, Van Vuuren D, Obersteiner M, Havlík P, Rounsevell M, Woods J, Stehfest E, Bellarby J (2010) Competition for land. Philos Trans R Soc Biol Sci 365:2941–2957

Spittlehouse DL, Stewart RB (2004) Adaptation to climate change in forest management. J Ecosyst Manag 4:1–11

Sprugel DG (1991) Disturbance, equilibrium, and environmental variability: What is 'natural'vegetation in a changing environment? Biol Conserv 58:1–18

Stanturf JA, Schoenholtz SH, Schweitzer CJ, Shepard JP (2001) Achieving restoration success: myths in bottomland hardwood forests. Restor Ecol 9:189–200

Stanturf JA, Kellison RC, Broerman FS, Jones SB (2003) Innovation and forest industry: domesticating the pine forests of the southern United States, 1920–1999. For Pol Econ 5:407–419

Stanturf JA, Goodrick SL, Outcalt KW (2007) Disturbance and coastal forests: a strategic approach to forest management in hurricane impact zones. For Ecol Manag 250:119–135

Stanturf JA, Gardiner ES, Shepard JP, Schweitzer CJ, Portwood CJ, Dorris LC Jr (2009) Restoration of bottomland hardwood forests across a treatment intensity gradient. For Ecol Manag 257:1803–1814

Stanturf J, Palik B, Dumroese RK (2014a) Contemporary forest restoration: a review emphasizing function. For Ecol Manag 331:292–323

Stanturf JA, Palik BJ, Williams MI, Dumroese RK, Madsen P (2014b) Forest restoration paradigms. J Sustain For 33:S161–S194

Stein BA, Staudt A, Cross MS, Dubois NS, Enquist C, Griffis R, Hansen LJ, Hellmann JJ, Lawler JJ, Nelson EJ (2013) Preparing for and managing change: climate adaptation for biodiversity and ecosystems. Front Ecol Environ 11:502–510

Stephens SL, Millar CI, Collins BM (2010) Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. Environ Res Lett 5:024003

Strauss SH, Bradshaw HD (2004) The bioengineered forest: challenges for science and society. Resources for the Future, Washington DC

Sturrock R, Frankel S, Brown A, Hennon P, Kliejunas J, Lewis K, Worrall J, Woods A (2011) Climate change and forest diseases. Plant Path 60:133–149

Suding K, Higgs E, Palmer M, Callicott JB, Anderson CB, Baker M, Gutrich JJ, Hondula KL, LaFevor MC, Larson BMH, Randall A, Ruhl JB, Schwartz KZS (2015) Committing to ecological restoration. Science 348:638–640

Thornton PK, Ericksen PJ, Herrero M, Challinor AJ (2014) Climate variability and vulnerability to climate change: a review. Ann Rev Ecol Syst 20:3313–3328
Tierney GL, Faber-Langendoen D, Mitchell BR, Shriver WG, Gibbs JP (2009) Monitoring and evaluating the ecological integrity of forest ecosystems. Front Ecol Environ 7:308–316
Toth LA, Anderson DH (1998) Developing expectations for ecosystem restoration. In: Transactions of the North American Wildlife and Natural Resources Conference, 1998. Wildlife Management Institute, pp 122–134
Travis WR (2010) Going to extremes: propositions on the social response to severe climate change. Clim Change 98:1–19
Travis JM, Delgado M, Bocedi G, Baguette M, Bartoń K, Bonte D, Boulangeat I, Hodgson JA, Kubisch A, Penteriani V (2013) Dispersal and species' responses to climate change. Oikos 122:1532–1540
Turner MG (2010) Disturbance and landscape dynamics in a changing world. Ecology 91:2833–2849
Valladares F, Matesanz S, Guilhaumon F, Araújo MB, Balaguer L, Benito-Garzón M, Cornwell W, Gianoli E, van Kleunen M, Naya DE, Nicotra AB, Poorter H, Zavala MA (2014) The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. Ecol Lett 17:1351–1364
Van Aalst MK (2006) The impacts of climate change on the risk of natural disasters. Disasters 30:5–18
Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F (2011) The representative concentration pathways: an overview. Clim Change 109:5–31
Veldman JW, Overbeck GE, Negreiros D, Mahy G, Le Stradic S, Fernandes GW, Durigan G, Buisson E, Putz FE, Bond WJ (2015) Tyranny of trees in grassy biomes. Science 347:484–485
Vieira DL, Scariot A (2006) Principles of natural regeneration of tropical dry forests for restoration. Restor Ecol 14:11–20
Visconti P, Pressey RL, Giorgini D, Maiorano L, Bakkenes M, Boitani L, Alkemade R, Falcucci A, Chiozza F, Rondinini C (2011) Future hotspots of terrestrial mammal loss. Philos Trans R Soc B Biol Sci 366:2693–2702
Vos CC, Berry P, Opdam P, Baveco H, Nijhof B, O'Hanley J, Bell C, Kuipers H (2008) Adapting landscapes to climate change: Examples of climate-proof ecosystem networks and priority adaptation zones. J Appl Ecol 45:1722–1731
Watson JE, Iwamura T, Butt N (2013) Mapping vulnerability and conservation adaptation strategies under climate change. Nat Clim Change 3:989–994
Weaver CP, Lempert RJ, Brown C, Hall JA, Revell D, Sarewitz D (2013) Improving the contribution of climate model information to decision making: The value and demands of robust decision frameworks. WIREs Clim Change 4:39–60
WHO (2014) Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. World Health Organization, Geneva
Wilby RL, Dessai S (2010) Robust adaptation to climate change. Weather 65:180–185
Williams JN (2013) Humans and biodiversity: population and demographic trends in the hotspots. Popul Environ 34:510–523
Williams MI, Dumroese RK (2013) Preparing for climate change: forestry and assisted migration. J For 114:287–297
Williams JW, Jackson ST (2007) Novel climates, no-analog communities, and ecological surprises. Front Ecol Environ 5:475–482
Williams JW, Jackson ST, Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. Proc Nat Acad Sci USA 104:5738–5742
Wilsey CB, Lawler JJ, Maurer EP, McKenzie D, Townsend PA, Gwozdz R, Freund JA, Hagmann K, Hutten KM (2013) Tools for assessing climate impacts on fish and wildlife. J Fish Wildlife Manage 4:220–241
Yemshanov D, Koch FH, Ducey M, Koehler K (2013) Mapping ecological risks with a portfolio-based technique: incorporating uncertainty and decision-making preferences. Diver Distrib 19:567–579
Yousefpour R, Hanewinkel M (2015) Forestry professionals' perceptions of climate change, impacts and adaptation strategies for forests in south-west Germany. Clim Change 130:273–286
Zabel F, Putzenlechner B, Mauser W (2014) Global agricultural land resources—a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. PLoS ONE 9:e107522
Zahawi RA, Reid JL, Holl KD (2014) Hidden costs of passive restoration. Restor Ecol 22:284–287
Zalasiewicz J, Williams M, Steffen W, Crutzen P (2010) The new world of the Anthropocene. Environ Sci Technol 44:2228–2231
Zomer RJ, Trabucco A, Bossio DA, Verchot LV (2008) Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agric Ecosyst Environ 126:67–80