ISSN: 1877-3435

More than CO_2: A broader paradigm for managing climate change and variability to avoid ecosystem collapse

Authors: McAlpine, C.A. [1*], Ryan, J.G., [1] Seabrook, L. [1], Thomas, S.[2] , Dargusch, P. J.[2], Syktus, J.I. [3], Pielke, R.A. Sr.[4], Etter, A.E.[5], Fearnside, P.M.[6] and Laurance W.F.[7].

1. The University of Queensland, School of Geography, Planning and Environmental Management, Brisbane, Australia 4072.
2. The University of Queensland, School of Integrative Systems, Brisbane, Australia 4072.
3. Queensland Climate Change Centre of Excellence, Queensland Department of Environment and Natural Resources, Brisbane, Queensland, Australia 4068
4. Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, Colorado.
5. Departamento de Ecología y Territorio, Universidad Javeriana, Bogotá, Colombia.
6. National Institute for Research in the Amazon (INPA), C.P. 478, CEP 69.011-970, Manaus, Amazonas, Brazil.
7. School of Marine and Tropical Biology, James Cook University, Cairns, Australia 4870.

*Corresponding Author: Clive McAlpine c.mcalpine@uq.edu.au

Abstract: Climate change policies currently focus on reducing the concentration of industrial atmospheric greenhouse gases due to burning fossil fuels and deforestation, but pay limited attention to feedbacks between the land surface and the climate system. In tropical and sub-tropical regions, forests and woodlands play an important role in the climate system by buffering climate extremes, maintaining the hydrological cycle and sequestering carbon. Despite the obvious significance of these feedbacks to the functioning of the climate system, deforestation continues apace. It is critical, therefore, that a broader focus be developed that includes the restoration of feedbacks between vegetation and climate. In this paper, we present a synthesis of the best available, policy-relevant science on the feedbacks between the land surface and the climate system, with a focus on tropical and sub-tropical regions. Based on this science, we argue for a stronger integration of land-use and climate-change policies. These policies need to include a virtual halt to all deforestation and an acceleration of investment in strategic reforestation, supported by a comprehensive global forest monitoring program. Without these actions, the degradation of the Earth's ecosystems will become exacerbated as their resilience is eroded by accelerated changes in temperature, precipitation and extreme weather events.

KEYWORDS: complex systems; clean development mechanism (CDM), climate feedbacks; climate policy; land use/land cover change, land-use change and forestry (LULUCF); reduced emissions from deforestation and forest degradation (REDD).

Introduction

There is a global recognition for strong and urgent policy actions to prevent atmospheric concentrations of CO_2, due to the burning of industrial fossil fuels and deforestation, from rising much above their present levels [1, *2, 3]. Despite the hopeful expectations of a concerned global population, the 15th Conference of the Parties (COP15) in Copenhagen made very modest progress towards reducing concentrations of CO_2 in the atmosphere and addressing issues of deforestation and forest degradation, particularly in developing countries. The failure to secure a binding global agreement at COP15 means further negotiations are required before real, quantifiable, progress can be achieved to "stabilise greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous anthropogenic interference with the climate system" [4].

Even if effective global action on mitigating greenhouse-driven climate change is forthcoming, communities may still be grappling with adverse changes to climate precisely because policy makers remain overwhelmingly focused on CO_2 reductions and continue to ignore other anthropogenic modifiers of climate systems. To date, climate models such as those used for the 4AR of the IPCC have failed to adequately capture the full range of human-influenced climate forcings impacting the climate system, [4, **5, 6]. This has resulted in an emphasis on industrial CO_2 emissions in climate policy frameworks, and much less emphasis on other human-influenced climate forcings.

In reality, there is a range of human-influenced climate forcings, including changing concentrations of industrial anthropogenic greenhouse gases, stratospheric ozone depletion, changes in atmospheric aerosol loadings and deposition, and biophysical feedbacks of land use/land cover change (LUCC) on the Earth's climate [3, 6, 7, 8, 9, 10]. The Earth's climate behaves as a complex adaptive system, continually responding to numerous forcings and feedbacks across a range of spatial and temporal scales [11, 12]. The climate system is highly nonlinear: inputs and outputs are not proportional, and change is often episodic and abrupt, rather than slow and gradual [13]. Even if humans find ways to reverse the rapid progress of climate change through technology, it may be impossible to revert to historical climates due to inertia in the climate system and ongoing LUCC.

A number of studies point toward the links between historical LUCC and concurrent changes in climate across many regions of the Earth [*14, *15, *16, 17, 18, **19, 20, 21]. Contemporary LUCC is likely to generate further changes in climate and ecosystem functioning, as there is a considerable time lag between the responses of ecosystems to climate change [22]. Forests and woodlands around the world are known to play a significant role in moderating climate variability and climate change, conserving biodiversity and providing essential ecosystem services [18, 23, 24, 25, 26, 27, 28]. Yet, deforestation is continuing at alarming rates in many tropical and sub-tropical regions. Between 1996 and 2009, Brazil deforested an average of ~17,000 km^2 annually, while Indonesia deforested ~20,000 km^2 [29].

The aim of this paper is to highlight the need to broaden the current paradigm for managing climate change and variability to include feedbacks between the land surface and the climate system. First, we provide a short synthesis of impacts of LUCC on the climate, and the vulnerability of terrestrial ecosystems and society to these impacts, followed by a synthesis of current international climate policy mechanisms and their capacity to mitigate the adverse impacts of LUCC on climate. Finally, we identify a set of priority actions for including land-atmosphere forcings and feedbacks in regional and global climate change policies.

How forest and woodland clearing affects climate

By the end of the 20th century, approximately 35% of Earth's terrestrial ecosystems had already been converted to cropland, pasture and urban land uses [30, 31]. These conversions resulted in decreased moisture recycling at scales of the landscape and biosphere [32, 33], and a diminished capacity for landscapes to buffer extreme weather events, increasing climate variability and climate change [**34]. Most intact native forests and woodlands provide essential links between climate and water, energy and carbon cycles, but this is especially true for tropical regions [35]. These forests recycle large volumes of water vapour between the land surface and the lower atmosphere [33], which is a positive feedback to the generation of further precipitation [36]. Forests and woodlands also reduce sensible heat flux and contribute to increased atmospheric instability and convection that leads to the formation of clouds, which are important mechanisms for buffering climatic extremes [Figure 1; 37, 38, 39]. For example, dense cloud cover reflects significant amounts of long-wave radiation back into space, a process that regulates local surface temperatures [**34, *40]. Tropical forests have a much higher leaf area index than perennial crops and pastures, and this (along with their deep roots) promotes the transpiration of water vapour and subsequent cloud development. In Amazonia and other forest ecosystems, volatile organic compounds emitted by the forest provide cloud-condensation nuclei that are key elements in cloud formation [41, *42].

[Figure 1 approx here]

In sub-tropical regions, native forests and woodlands also play a major role in enhancing the hydrological cycle and moderating temperatures and climate extremes [*14, **19, 43, *44].

The wet phase of the El Niño Southern Oscillation (ENSO) cycle triggers periodic resource recovery and renewal processes for many sub-tropical ecosystems. Across Australia, for example, ‘La Niña’ (wet phase) events are linked to periods of above-average rainfall that allow ecosystems to regenerate following drought [45]. However, if climate change amplifies and increases the frequency of extreme temperatures and droughts, there is a real danger that native forests and woodlands may begin to lose their auto-regenerative capacities. These changes would then reduce an ecosystem’s resilience to climate extremes and increase the risk of resource degradation and ecosystem collapse [*44, 46, 47, *48].

Risks and vulnerability

Terrestrial ecosystems and the climate system are closely coupled, with multiple interactions and feedbacks occurring across a range of scales [7, 34, 47]. This is because the Earth and its ecosystems are organised as complex adaptive systems, where feedbacks between a large number of components maintain ecological functioning despite continual variance in inputs (e.g. solar radiation, rainfall). Small perturbations to these systems can cause much greater changes than the perturbation itself would suggest. Perturbations are also often non-linear, meaning that changes may be abrupt or take decades to manifest themselves. This means that the Earth has numerous possible future pathways depending on the type and timing of land use changes and climate change mitigation actions undertaken decades prior (Figure 2). As the climate shifts, feedbacks may become impaired, modified or destroyed, further weakening ecosystem resilience (Figure 2, path ‘A’). In addition, dramatic shifts in and/or collapse of the hydrological cycle and ecosystem services in many regions may still occur based purely on the historical legacy of LUCC and emissions (Figure 2, path ‘B’). To maximise options available to manage complex climatic and landscape systems alike, we must define and act on ‘leverage points’ that result in major change for small input (Figure 2, path ‘C’). Timely intervention can create a future where LUCC and climate change is managed for resilience (t1), whereas the same change a decade later may have little benefit (t2). Alternatively, if we, as a global society, wait for the more severe impacts of climate change to occur, then extreme shifts in climate and wide-spread ecosystem collapse are assured.

It is critical that clearing of native forests and woodlands in tropical and sub-tropical regions be dramatically reduced, as these ecosystems have a significant capacity to sequester carbon and also underpin the hydrological cycle. Tropical forests absorb about 18% of all carbon dioxide added by fossil fuels, annually processing about six times as much carbon via photosynthesis and respiration as humans emit from fossil fuel use [11, 49, 50]. If society fails to act soon, severe shifts in ecosystem functioning as a result of changes to the climate system due to human and natural climate forcings may mean that the narrow window of opportunity to use the regenerative capabilities of native forests and woodlands is lost. Likewise, it is almost impossible to plant forests over such vast areas and to expect them to survive under continually drying conditions. These factors make it imperative that policy actions prevent further large-scale or ad-hoc deforestation in all biomes (not only carbon-rich tropical forests) and provide for the strategic, broad-scale restoration of forests and woodlands in addition to reducing industrial CO_2 emissions. Due to the inertia in the climate system, these actions must be implemented decades before 2050 changes begin to manifest (Figure 2, path ‘C’). The year 2050 has been identified by a number of studies as an approximate date by which continued business-as-usual emissions would provoke catastrophic impacts, such as Amazon forest collapse [51].

[Figure 2 approx here]

Current policy mechanisms

LULUCF

The policy framework that has evolved to address the challenges posed by greenhouse-driven climate change has established carbon as the standard of exchange in a market designed to achieve specific outcomes: reduction of greenhouse-gas emissions and increase in sustainable development. Land use, land use change and forestry (LULUCF) is estimated to account for between 12% and 28% of the global emissions inventory, although there are considerable uncertainties in measurement [62]. The inclusion in the Kyoto Protocol of LULUCF in national emissions accounting has meant that agriculture, forestry and deforestation are integral components of carbon inventories, yet there has been little success in using the LULUCF sector to achieve the goals of the UNFCCC. Policy instruments have mainly engineered improved industrial processes, energy efficiency and investments in alternative energy generation technologies [52] because sustainability has been interpreted as technological and developmental progress. When sustainable development is interpreted in terms of poverty alleviation, ecological restoration, social equity and community development, international climate policy mechanisms are widely considered to have made minimal contributions [*53, 54, 55]. Land surface-atmosphere processes have been largely excluded from the financial accounting of climate policy processes, in much the same way as sustainability outcomes. The narrow definitions of climate policy instruments, and the market-based approaches employed as mitigation and adaptation strategies, are failing to achieve their larger goals [56]. Other mechanisms beyond the Protocol continue to be debated.

Clean Development Mechanism

The clean development mechanism, or CDM, is the principal source of carbon-emissions offsets for firms in developed countries, with more than 2600 registered projects at the end of June 2009, around 4000 more in the CDM “pipeline” [57], and more than US$6.5 billion in project-based transactions in 2008 [58]. However, the CDM has a questionable history in the Kyoto Protocol’s 2008-2012 First Commitment Period, with much of the credit granted having no real benefit for climate [*53, 59, 60]. The distribution of CDM project activities is also extremely uneven, with the overwhelming majority of projects occurring in China and India, and currently less than 2% in Africa [57].

CDM projects can be developed in any of 15 “sectoral scopes”, ranging from energy production (renewable and non-renewable) to agriculture. Forestry is one of these sectoral scopes, and CDM projects can generate carbon credits known as certified emission reductions (CERs) – which are tradeable commodities in the international carbon markets – through afforestation or reforestation of areas cleared prior to 1990 [61]. Notwithstanding efforts to encourage afforestation and reforestation project activities under the CDM, land use, land-use change and forestry currently play a negligible role in the global carbon market. Afforestation and reforestation projects currently represent less than 1% of all projects in the CDM pipeline, with only 16 registered as of June 2010. While there are numerous constraints that affect the development of forestry-related CDM projects, it is clear that the sector is under-represented. LUCC is also not addressed within the agriculture sectoral scope of the CDM. There were 127 projects registered using agricultural methodologies: these involved methane capture or recovery or animal waste management, with some biomass-based power generation [57]. The paucity of land use-based CDM methodologies, as well as the highly uneven distribution of project activities, ensures that the mechanism makes little if any contribution to the impact of LUCC on global climate.

REDD

Land cover change in the form of deforestation and forest degradation is recognised as a major contributor to global greenhouse gas emissions. Mechanisms that seek to reduce emissions from deforestation and forest degradation (REDD), particularly in tropical countries where forest carbon pools are large [63], are therefore attractive. REDD mechanisms offer a range of desirable ancillary benefits including the protection of habitat for biodiversity, production of food, regulation of local climate forcings and feedbacks, nutrient cycling and pollination. At the same time, REDD and other land use-based carbon management systems can contribute to building the adaptive capacities of communities affected by the impacts of climate change by securing ecosystem services into the future. These co-benefits benefits are recognised in the term “REDD-plus”.

Simply put, management of land use and land cover in the context of carbon markets represents a comprehensive response to climate change and an integrated approach to achieving sustainable development. Yet while these approaches have generally been considered as cost-effective methods of achieving emission reductions [64, *65], it is increasingly clear that the complexities inherent in such schemes render REDD and other forms of payment for environmental services extremely difficult to implement. In addition, there is growing recognition of a wider range of economic, social and political costs associated with REDD [**66], and a number of challenges remain to be addressed.

International discussions on REDD policy mechanisms have been ongoing since the Kyoto Protocol was signed in 1997. At the 11th Conference of Parties (COP11) in 2005, the UNFCCC began a program of work to develop policy mechanisms and incentives for REDD.

At COP13 in 2007, a number of countries advocated the inclusion of conservation activities in a REDD mechanism, but this was opposed by powerful players including the European Union and Brazil. The concern these countries expressed publicly was that such inclusions would create large amounts of "hot air" credits and effectively flood the carbon market, removing incentives for further conservation elsewhere. The uncertainty over the exact determination of eligible activities remains unresolved, although there was general agreement at COP15 in Copenhagen that REDD mechanisms need to be further developed to include the ancillary benefits mentioned previously under the rubric of REDD-plus [61, 67].

An issue that remains somewhat intractable is the question of funding for REDD, which derives either from public funds or market mechanisms [**68]. Different countries support different approaches, ranging from taxes and levies on joint implementation transactions to international-level financing through the World Bank and governments. Yet the funds that have been established has so far failed to secure major investment, with total commitments and contributions not more than US$1 billion to date [69, 70]. This suggests that regulated markets may be far more effective in funding REDD and REDD-plus mechanisms than voluntary systems. The key feature of market mechanisms is that they create incentives and drive innovation. In contrast, top-down regulatory approaches in the form of taxation or levies are difficult to manage and harder to enforce; no international authority capable of imposing such a fiscal regime currently exists.

The Copenhagen Accord recognises the critical role of reducing emissions from deforestation and forest degradation and the need to enhance the removal of greenhouse gases by forests. The Accord proposes to provide financial resources to facilitate REDD-plus, as well as adaptation, technology transfer and capacity building. Developed countries have collectively committed to financing close to US$30 billion for the period 2010 – 2012, with a further goal of mobilising US$100 billion a year by 2020 to support mitigation and adaptation in developing countries [61]. However, even if this funding is forthcoming, it is imperative to develop policy approaches that can overcome the technical and institutional constraints on REDD-plus, and market mechanisms are the most efficient tools to achieve these outcomes. Only regulated markets with strong and equitable governance will provide sufficient finance on a scale that delivers effective outcomes for forests and the people who depend on these forests [71]. Future climate negotiations need to strengthen REDD-plus to deal with this problem, as well as considering other ways to reduce the human influence on the climate such as minimizing conversion of all native ecosystems to human land uses.

The technical challenges of REDD are the same as those that confront forestry-based activities in the CDM. These include the determination of baselines (meaning decisions on how to calculate business-as-usual emissions and the additionality of reductions), the question of permanence, leakage (transferral of emissions from a project site to other areas beyond the project boundary), and importantly, the challenges of monitoring and verification (through satellite observation or sampling approaches). Proposals to address these constraints tend to involve one of two approaches: national regulation or project-level management. The essential differences between these approaches are ease of implementation and flexibility. National approaches are attractive because they are much simpler to mandate and finance, yet the challenge remains that countries where REDD programs are most likely to be implemented are also often those with least ability to conduct such programs, and poor records of governance and administrative capacity. Sub-national or project-based approaches require considerable flexibility depending on project locations and social conditions [72] and will benefit from the lessons of earlier conservation and development projects [73]. Yet top-down national policies have resulted in the disproportionate representation of some countries at the expense of others in the international market. A localised approach could result in better outcomes for a wider range of participants [74].

There are further institutional challenges to the development of integrated climate policies. Many countries lack the institutional and technical capacity to manage the administrative and transactional requirements of REDD and other mechanisms [75]. Implementation of REDD policies is further complicated by the presence of illegal activities and trade networks, corrupt governance and entrenched systems of vested interest, and questions of land tenure and property rights [76, 77]. The policies necessary to respond to these institutional challenges include reducing agricultural rents in forests, increasing and securing forest-derived incomes, directly regulating land use, forest protection and decentralisation of management [78]. Policy mechanisms should be structured to support communities and forest managers through direct delivery of extension programs and funding within the context of local cultural and governance systems, rather than operating only in collaboration with national governments and agencies. This approach is complex but more likely to achieve sustainable systems in the longer term.

The Way Forward

Expand Climate Change Paradigm

As the Earth's climate forms part of a complex adaptive system, the current global climate change agenda needs to recognise that tackling climate change is a complex issue with multiple drivers and feedbacks. However, except for their role as carbon sources and sinks, the international climate policy dimensions of the impacts of LUCC on the surface fluxes of water, heat and aerosols, and their resultant effects on weather, have received minimal attention. The omission of such local and regional-scale land-atmosphere forcings and feedbacks in climate change policies represents a major impediment to our ability to avoid critical transitions in the climate system at larger scales [79, 80].

The current premise is that reduction of industrial CO_2 emissions will diminish other environmental sustainability problems. The reality, however, is different. Human pressures on climate and land use are increasing the risk of abrupt environmental change. While Rockström *et al.* [81] claim that, globally, the pressures from change in land and freshwater use are within the "proposed safe operating space", in many regions the limits of sustainable land and water use have been reached [23, 82]. At a local and regional scale, unsustainable land use pressures are equally or even more important than larger scale climate change driven by CO_2. Many of these pressures relate to growing demand for commodities by developed and new consumer societies [83]. A recent report by the United Nations Environment Program [84] highlighted the need to change patterns of production and consumption, particularly through changing diets, in order to lessen the environmental impacts of population growth, and understand the linkages between different pressures on resources and the environment. It is critical, therefore, we proactively address climate change and environmental sustainability problems concurrently by adopting a complementary and precautionary assessment of the vulnerability of critical natural resources rather than wait until the CO_2 problem has been resolved [**5, 10, *44].

There are five broad areas for which vulnerability assessments are needed: water, food, energy, human health and ecosystem function. Each area has societally critical resources. The vulnerability concept requires the determination of the major threats to these resources from climate, but also from other social and environmental issues. After these threats are identified for each resource, then the relative risk from natural- and human-caused climate change (estimated from the GCM projections, but also the historical, paleo-records and worst case sequences of events) can be compared with other risks in order to adopt the appropriate mitigation/adaptation strategy.

Continuing degradation of the biosphere has adverse consequences for water resources, food security, energy, ecosystem health and human well-being [**5]. In addition, the ability of the biosphere to store carbon may be decreasing because of biogeochemical limitations on the capacity of vegetation to sequester carbon and also the overutilization of natural resources. Global cooperation on this matter is as pressing as reducing CO_2 emissions, otherwise degradation of many of the Earth's ecosystems will continue and this degradation will be further reinforced by its positive-feedback relationships with changes in temperature, precipitation and extreme weather events [1]. Confronting the detrimental effects of LUCC requires assessing and managing the inherent trade-offs between meeting immediate human needs and maintaining the capacity of ecosystems to provide goods and services in the long term [23].

Key Actions

We propose that a new policy paradigm is needed, in which land use, land use change, forestry, biodiversity and sustainable economic and social development are recognised as integral components of climate change mitigation and adaptation strategies (Table 1). The problem is that existing policy mechanisms (and those that are still being developed, such as REDD-plus) largely ignore the role of land surface-atmosphere forcings and feedbacks in regulating climate. This is an important policy failure, as deforestation and land use pressures can result in reduced ecological resilience and diminish the regenerative capacity of ecosystems. It is also important to consider as part of a vulnerability assessment: i) the sensitivity of environmentally and societally important water, food, energy, and human health issues to these climate variability and change on short (e.g. days); medium (e.g. seasons) and long (e.g. multi-decadal) time scales; and ii) what actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response).

[Insert Table 1 approx here]

Action 1: Stronger integration of inter-governmental policies and protocols

At the global or intergovernmental level, we need to take an integrated approach in policy responses to more effectively address the challenges of climate change and environmental sustainability (Table 1). Current inter-governmental policies and protocols require a broader consideration of climate processes including the effects on land-atmosphere forcings and feedbacks at multiple scales. At present, inter-governmental policies and protocols for addressing global problems (e.g., Montreal Protocol on Substances that Deplete the Ozone Layer, the Kyoto Protocol on climate change and the Millennium Development Goals) are not well integrated. The separation of Montreal and Kyoto protocols is a good example of where more integration is required as it has become apparent in recent years that replacements for chlorofluorocarbons (CFCs) resulted in a strong impact on the climate system via their role as greenhouse gases [85, 86]. The Millennium Development Goals aim to integrate the principles of sustainable development into national policies and programmes and reverse the loss of environmental resources and biodiversity, but have limited reference to climate change. Perhaps the best example of this lack of integration is provided by the Framework Convention on Climate Change (signed in 1992), the Convention on Biological

Diversity (1992) and the Convention on Desertification (1994): all three are targeted towards particular aspects of what is essentially a single complex problem. It is unclear whether any of these agreements will be successfully implemented resulting in tangible on-ground outcomes in reducing the vulnerability of terrestrial ecosystems resulting from land-use pressures and climate change.

Action 2: Strengthen carbon market mechanisms

Existing regulated carbon market mechanisms such as the CDM need to be strengthened to facilitate the greater engagement of forest-based activities and direct investment toward LULUCF activities. Encouraging regional governance and local management within international frameworks offers the most flexibility and greatest likelihood of achieving comprehensive and effective outcomes [**87]. Under the current system, national governments (through their Designated National Authority or DNA) approve CDM projects after these have been validated as meeting regulatory requirements by accredited independent entities. DNAs could operate as guides for project development and implementation, participating in existing networks of non-government organisations, the private sector, the research community, and people in many places. The CDM could evolve to become a vehicle to link both natural forests and planted forests with regulated carbon markets, but this would require a decentralisation of authority, with the CDM Executive Board acting as a facilitator rather than as an adjudicator, directly training DNAs in methodological applications [52]. This would expand the role of DNAs and encourage more direct national involvement in project development.

Policy makers and business in developed economies have the opportunity to benefit from similar adjustments in their own domestic carbon market regulations. Recognition of the broader ecosystem and social benefits that can be gained from various types of forest-based and land use activities within their own countries affords the possibility of engaging primary resource industries, the agriculture sector and communities in proactive climate policies. While the economics of carbon sequestration in vegetation and soils and the costs and benefits of environmental services remain challenging [88, 89], more comprehensive participation by land managers in integrated mitigation and adaptation schemes is likely to bring increased profitability and risk avoidance for producers and business while allowing policy reforms to reflect both broad consensus and precautionary scientific approaches [90, 91]. Arguably, delay in adapting to carbon-constrained business implies future disadvantage in international mechanisms and markets [92, 93].

Current national climate change mitigation policies should be revised to incorporate a new focus on LULUCF. This revision needs to occur in all countries, not just developing countries with tropical forests, as some developed countries (Australia, for instance) escape coverage by existing instruments such as the CDM and REDD. Greater inclusion of forest-based CDM offsets in the cap-and-trade schemes of developed economies could encourage forestry projects internationally and play a part in improving the popular understanding of offset mechanisms, especially through the use of preferential classification schemes [*53, 94, 95]. It may be that direct action is more relevant in developing country contexts whereas regulated markets (emission trading schemes) are appropriate in industrialised nations. Direct action allows for capacity building and extension work in conjunction with technology and funding transfers. Market-based mechanisms offer the consumer populations of industrialised democratic societies the opportunity to participate in voluntary markets and preferentially drive offset supply.

This is an opportune moment for climate policy reform. Political circumstances in many advanced economies are in many ways more balanced than in previous decades. In Australia, for instance, the balance of power in the national parliament is held by rural independents and the pro-environment party for the time being. The interests of primary producers and conservationists in many ways coincide, and there appear to be synergies in the policy approaches of disparate stakeholders. It may be that because traditional opponents are being required to collaborate this will result in more comprehensive, inclusive and successful policy reforms. Recognising the importance of land-atmosphere interactions in climate systems mandates the involvement of the agriculture and forestry sectors in climate strategy. Despite the challenges inherent in the political economy of mitigation, adaptation and regional resource management strategies, it is imperative that the most capable countries and institutions endeavour to formulate effective, integrated approaches [*53, 96, 97].

Action 3: Avoiding deforestation

Political will and institutional reform are required at a national level to substantially reduce current global rates of deforestation. At present there is no policy recourse if regulated carbon market mechanisms do not meet expectations due to failure to reach a global agreement, insufficient finance or poor governance [77]. Such policy reforms are critical, and need to be informed by the existing LUCC science incorporating the available knowledge about the specific proximate causes and underlying drivers of deforestation and forest regeneration in each region [98, 99, 100]. Complementary to this, Lambin and Meyfroidt [*101] argue that cost effective policy options should emphasise a slowing down of deforestation by accelerating land use transitions rather than halting deforestation. This would involve a set of interventions outside the forestry sector that have historically accounted for deforestation, such as diversifying income sources for local communities, institutional and technological reform, and changing global consumption patterns. The authors believe that this would lead to more sustainable land use practices in the long-term.

Protecting remaining intact native forests and woodlands (as well as other terrestrial ecosystems) within a regional land use planning framework is critical to maintaining their favourable feedbacks on the local and regional climate. Management-based repair of land-atmosphere feedbacks particularly needs to recognise the important function of forests and woodlands that are not carbon rich or are not a conservation priority. This requires implementation of policies to maintain and restore healthy ecosystem functioning of *all* forests and woodlands across *all* land ownerships. These policies, implemented through integrated landscape designs, can deliver multiple benefits for restoring hydrological functioning of ecosystems and increasing their resilience to the impacts of climate variability and change [36].

Action 4: Develop a coordinated global forest monitoring program

A critical aspect of halting global deforestation and forest degradation is a consistent multi-national monitoring program that ensures the timely tracking and credible accounting of the changes taking place. Currently, monitoring the terrestrial component of the biosphere and its role in climate change lags behind that of the atmosphere and ocean [102, 103]. Several issues related to the measurement of LUCC and greenhouse gas emissions were addressed in theory in the Good Practice Guide 2003 [104], but have not been implemented due to the lack of data to feed the information process. A comprehensive monitoring program needs to define robust spatial and temporal sampling schemes that provide the necessary precision, and ensure that data can be used for several ends, such as land cover, carbon stocks, biodiversity and modelling of future patterns of change. A global land cover/land use monitoring protocol is required to underpin the accounting of carbon, land–atmosphere interactions, hydrological flows and biodiversity. This should be capable of monitoring different degrees of forest loss, degradation and regrowth that can occur through time, underpinned by unifying definitions (e.g., of forests, "avoided deforestation"), land-cover classifications, input data and methods to adequately monitor such changes, including transparency and uncertainty assessments [105].

The need for credibility and accountability is a crucial aspect in this process, yet flexibility is also necessary to achieve consensus and incorporate the disparate social, economic and biophysical conditions of different countries. At the international level, it would be possible to establish a single credible scientific body which produces consolidated and verified reports from each country or region of national carbon stocks and land use accounts similar to the national greenhouse gas inventories required under Kyoto. A consistent and accountable monitoring system for LUCC will need to be able to separate direct human-induced impacts (e.g. land management) from dieback/degradation due to climate variability and natural disturbances (e.g. fires, drought).

Several remote-sensing resources are emerging as suitable for the global monitoring of LUCC. For example, a time-series of the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) is a suitable variable for monitoring and characterising the impacts of land use, climate variability and climate change on the biosphere [36]. FAPAR exhibits large-scale inter-annual variation and multi-year trends, with more than a decade of global observations already available. The LIDAR technology is another promising avenue for the needed 3D land cover mapping [106, 107]. The Global Forest Resources Assessment initiative (FRA2010) launched by FAO in October 2009 (http://geonetwork4.fao.org/geonetwork/srv/en/fra.home) also is an important and promising starting point in this direction. However, the methodological framework of the FRA2010 still shows various shortcomings according to the evaluation performed by Steininger et al. [108] who found that sampling errors could be in excess of 20%. Remote sensing is the undisputed basis for monitoring, but needs to be accompanied by field measurements. But, to ensure optimal and comparable results, improved transnational cooperation and training is required. Technically, approaches such as the one provided by Asner [109] may be ideal to help reach Tier II and III mapping levels, but will still take an unknown amount of time to be globally operational. Although the costs of satellite data are decreasing, the availability, image processing costs and temporal coverage are still an issue.

To establish a monitoring system that can effectively address the above cited requirements several questions remain: When will the needed data become accessible and free? When will the data and services become interoperable? What are the most cost-effective spatial and temporal resolutions? How often should the monitoring system update the land cover maps? How should sub-national monitoring strata be defined to accommodate the high variability of land cover and socioeconomic processes?

Conclusion

The role of terrestrial ecosystems, especially tropical and sub-tropical forests and woodlands, in the climate debate has predominantly focused on their potential for carbon sequestration. It is critical to adopt a broader perspective on the role of forests and other ecosystems in the climate debate and in climate policy mechanisms. This requires global and regional climate approaches which recognise the climate regulation function that forests and woodlands play through moderating regional climate variability, resisting abrupt change to existing climate regimes, as well as underpinning the hydrological cycle. This is especially important in the tropics and sub-tropics. Failure to acknowledge and adopt this broader perspective on dealing with the problem of climate change will result in sub-optimal solutions at the global scale and possible severe and irreversible damage at the regional scale.

References Cited

1. Fischlin A, Midgley GF, Price JT, Leemans R, Gopal B, Turely C, Rounsevell MDA, Dube OP, Tarazona J, Velichko AA: *Ecosystems, their properties, goods, and services* in *Climate Change 2007: Impacts, Adaptation and vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Parry, ML, Canzianai, OF, Palutikof, JP, van der Linden, PJ, and Hanson, CE, Editors Cambridge University Press. 2007: 211-272.

*2. Smith JB, Schnieder SH, Oppenheimer M, Yohe GW, Hare W, Mastrandrea MD, Patwardhan A, Burton I, Corfee-Morlot J, Magadza CHD, et al: **Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons for concern"**. Proceedings of the National Academy of Science, 2009. **106**: 4133-4137.

With the trajectory of emissions already tracking above the worst-case IPCC scenario, the authors reassess the sensitivity of 5 RFCs identified in the IPCC Third Assessment Report (including risk of extreme weather, risk to unique/threatened systems, and risk of large scale discontinuities) to increases in global mean temperature (GMT). For all 5, greater consequences than originally predicted will occur at lower GMTs.

3. Schneider SH, Semenov S, Patwardhan A, Burton I, Magadza CHD, Oppenheimer M, Pittock AB, Rahman A, Smith JB, Suarez A, et al: **Assessing key vulnerability and the risk from climate change.** In *Climate Change 2007: Impacts, Adaptation and vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Parry, ML, Canzianai, OF, Palutikof, JP, van der Linden, PJ, and Hanson, CE, Editors. Cambridge University Press. 2007: 779-810.

4. Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM: **The importance of land-cover change in simulating future climates**. Science, 2005. **310**: 1674-1678.

5. Piekle Sr. RA, Beven I, Brasseur G, Calvert J, Chahine M, Dickerson RR, Entekhabi D, Foufoula-Georgiou E, Gupta H, Gupta V, et al: **Climate change: The need to consider human forcings besides greenhouse gases. EOS, 2009. **90**: 413-414.

6. Pielke Sr. RA: **Land use and climate change**. Science, 2005. **310**: 1625-1626.

7. Chapin III FS, Randerson JT, McGuire AD, Foley JA, Field CB: **Changing feedbacks in the climate-biosphere system**. Frontiers in Ecology and Environment, 2008. **6**: 313-320.

8. National Research Council: *Radiative forcing of climate change: Expanding the concept and addressing uncertainties* Committee on Radiative Forcing Effects on Climate Change, Climate Research Committee, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies. 2005.

9. Piekle Sr. RA, de Guenni LB, *Conclusions. Vegetation, water, humans and the climate: A new perspective on an interactive system*. Springer; 2004.

10. Pielke Sr. RA, Adegoke JO, Chase TN, Marshall CH, Matsui T, Niyogi D: **A new paradigm for assessing the role of agriculture in the climate system and in climate change**. Agricultural and Forest Meteorology, 2007. **142**: 234-254.

11. Foley JA, Costa MH, Delire C, Ramankutty N, Snyder P: **Green surprise? How terrestrial ecosystems could affect earth's climate**. Frontiers in Ecology and the Environment, 2003. **1**: 38-44.

12. Levin SA: **Ecosystems and the biosphere as complex adaptive systems**. Ecosystems, 1998. **1**: 431-436.

13. Rial JA, Piekle Sr. RA, Beniston M, Claussen M, Canadell JG, Cox P, Held H, De Noblet-Ducoudré N, Prinn R, Reynolds JF, et al: **Nonlinearities, feedbacks and critical thresholds within the Earth's climate system**. Climatic Change, 2004. **65**: 11-38.

*14. Deo RC, Dkytus JI, McAlpine CA, Lawrence PJ, McGowan HA, Phinn SR: **Impact of historical land cover change on daily indices of climate extremes including droughts in eastern Australia**. Geophysical Research Letters, 2009. **36**: L08705.

Analysis of landscape change (loss of native forest) in eastern Australia since 1951 showed a significant link with increasing numbers of hot, dry days, decreasing daily rainfall intensity and increasing drought duration.

*15. Ellis EC, Goldewijk KK, Siebert S, Lightman D, Ramankutty N: **Anthropogenic transformation of the biomes, 1700 to 2000**. Global Ecology and Biogeography, 2010. **19**: 589-606.

Estimates areas and types of LUCC between over the past 3 centuries. Grid cells were classified according to population density and proportions of land uses in each century. 50% of the ice free land was used by humans to some extent in 1700, with this figure rising to 77% in 2000 mainly through conversion to pasture. Understanding the changing ecology of human managed lands will be critical to species survival in the future.

*16. Goldewijk KK, Beusen A, van Drecht G, de Vos M: **The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years**. Global Ecology and Biogeography, 2010. **in press 10 SEP 2010 DOI: 10.1111/j.1466-8238.2010.00587.x**.

Looks at land cover change over 12000 years, based on the HYDE 3.1 database. This uses human population, historical statistics and satellite maps to allocate land use to grid cells. Results show pulses in land use change, with population growth accelerating rapidly in the last century, accompanied by increases in cropland and pasture.

17. Liu Z, Wang Y, Gallimore R, Gasse F, Johnson T, deMenocal P, Adkins J, Notaro M, Prentice IC, Kutzbach J, et al: **Simulating the transient evolution and abrupt change of Northern Africa atmosphere-ocean-terrestrial ecosystem in the Holocene**. Quaternary Science Reviews, 2007. **26**: 1818-1837.

18. Marland G, Piekle Sr. RA, Apps M, Avissar R, Betts RA, Davis KJ, Frumhoff PC, Jackson St, Joyce LA, Kauppi P, et al: **The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy**. Climate Policy, 2003. **3**: 149-157.

19. McAlpine CA, Syktus J, Deo RC, Lawrence PJ, McGowan HA, Watterson IG, Phinn SR: **Modeling the impact of historical land cover change on Australia's regional climate. Geophysical Research Letters, 2007. **34**: Article No: L22711.

Analysis shows a strong relationship between land cover change and regional climate in southeast and southwest Australia, leading to increased temperatures and decreased rainfall, magnifiying the impacts of the ENSO cycle.

20. Nicholson SE, Webster PJ: **A physical basis for the interannual variability of rainfall in the Sahel**. Quarterly Journal of the Royal Meteorological Society, 2007. **133**: 2065-2084.

21. Webb TJ, Gaston KJ, Hannah L, Woodward FI: **Coincident scales of forest feedback on climate and conservation in a diversity hot spot**. Proceedings of the Royal Society. B - Biological Sciences, 2006. **273**: 757-765.

22. Jones C, Lowe J, Liddicoat S, Betts R: **Committed terrestrial ecosystem changes due to climate change**. Nature Geoscience, 2009. **2**: 484-487.

23. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, et al: **Global Consequences of Land Use**. Science, 2005. **309**: 570-574.

24. Hansen MC, Stehman SV, Potapov PV, Loveland TR, Townshend JRG, DeFries RS, Pittman KW, Arunarwati B, Stolle F, Steininger MK, et al: **Humid tropical forest clearing from 2000 to 2005 quantified by using multi-temporal and multi-resolution remotely sensed data**. Proceedings of the National Academy of Science, 2008. **105**: 9439-9444.

25. Leemans R, Eickhout B: **Another reason for concern: regional and global impacts on ecosystems for different levels of climate change**. Global Environmental Change Part A, 2004. **14**: 219-228.

26. Venter O, Laurance WF, Iwamura T, Wilson KA, Fuller RA, Possingham HP: **Harnessing carbon payments to protect biodiversity**. Science, 2009. **326**: 1368.

27. Wilson KA, McBride MF, Bode M, Possingham HP: **Prioritizing global conservation efforts**. Nature, 2006. **440**: 337-340.

28. World Bank Environment Department: *Convenient solutions to an inconvenient truth: ecosystem-based approaches to climate change* The World Bank. 2009.

29. World Resources Institute, *Global forest watch: Indonesia's forests in brief* 2009.

30. Ellis EC, Ramankutty N: **Putting people in the map: anthropogenic biomes of the world**. Frontiers in Ecology and Environment, 2008. **6**: 439-447.

31. Ramankutty N, Foley JA: **Estimating historical changes in global land cover: Croplands from 1700 to 1992**. Global Biogeochemical Cycles, 1999. **13**: 997-1027.

32. Gordon LJ, Steffen W, Jonsson BF, Folke C, Falkenmark M, Johannessen A: **Human modification of global water vapor flows from the land surface**. Proceedings of the National Academy of Science, 2005. **102**: 7612-7617.

33. Kravcik M, Pokorny J, Kohutiar J, Kovac M, Toth E, *Water for the recovery of the climate - a new water paradigm*. Krupa Print; 2007.

34. Bonan GB: **Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science, 2008. **320**: 1444-1449.

Reviews biosphere-atmosphere interactions in tropical, temperate and boreal forests and their differing impacts on global warming. Emphasises the need for integrated empirical research into climate forcings arising from these interactions and from changing land use.

35. Kabat P, Claussen M, Dirmeyer PA, Gash JHC, eds. *Vegetation, water, humans, and the climate : a new perspective on an interactive system*. 2004, Springer: New York.

36. Ryan JG, McAlpine CA, Ludwig JA: **Integrated vegetation designs for enhancing water retention and recycling in agroecosystems**. Landscape Ecology, 2010. **25**: 1277-1288.

37. Junkermann W, Hacker J, Lyons T, Nair U: **Land use change suppresses precipitation**. Atmospheric Chemistry and Physics, 2009. **9**: 6531-6539.

38. Mahfouf JF, Richard E, Mascart P: **The influence of soil and vegetation on the development of mesoscale circulations**. Journal of Climate and Applied Meteorology, 1987. **26**: 1483-1495.

39. Marshall CH, Piekle Sr. RA, Steyaert LT, Willard DA: **The impact of anthropogenic land-cover change on the Florida peninsula sea breezes and warm season sensible weather**. Monthly Weather Review, 2004. **132**: 28-52.

*40. Bala G, Caldiera K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A: **Combined climate and carbon-cycle effects of large-scale deforestation**. Proceedings of the National Academy of Science, 2007. **104**: 6550-6555.

Simulates the effects of deforestation on climate using a 3-D model incorporating phsical and biogeochemcial interactions in land, ocean and atmosphere. Tropical deforestation contributes to global warming, but in higher latitude boreal forest increases in land surface albedo from deforestation result in global cooling. Reafforestation should be targeted towards tropical areas for most benefit.

41. Silva Dias MAF, Rutledge S, Kabat P, Silva Dias PL, Nobre CA, Fisch G, Dolman AJ, Zipser E, Garstang M, Manzi AO, et al: **Cloud and rain processes in a biosphere-atmosphere interaction context in the Amazon Region**. Journal of Geophysical Research, 2002. **107**: D20.

*42. Cox PM, Harris PP, Huntingford C, Betts RA, Collins M, Jones CD, Jupp TE, Marengo JA, Nobre CA: **Increasing risk of Amazonian drought due to decreasing aerosol pollution**. Nature, 2008. **453**: 212-215.

Anomalies in sea surface temperature (SST) gradients will increase the number and severity of droughts in the Amazon. SST anomalies are associated with decreasing reflective aerosol pollution from the northern hemisphere, indicating that non-greenhouse gas forcing has maintained rainfall in South America.

43. Gordon LJ, Dunlop M, Foran B: **Land cover change and water vapour flows: learning from Australia**. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, 2003. **358**: 1973-1984.

*44. McAlpine CA, Syktus J, Ryan JG, Deo RC, McKeon GM, McGowan HA, Phinn SR: **A continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate**. Global Change Biology, 2009. **15**: 2206-2223.

Land use change across the Australian continent over the past 200 years has contributed to a hotter, drier climate, now exacerbated by global warming. Policy interventions based around strategic reforestation could buffer against climate variability, ameliorating some of the impacts of climate change on Australia's ecological and socio-economic systems.

45. McKeon GM, Stone GS, Syktus JI, Carter JO, Flood NR, Ahrens DG, Bruget DN, Chilcott CR, Cobon DH, Cowley RA, et al: **Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues**. The Rangeland Journal, 2009. **31**: 1-29.

46. Fearnside PM: **Global warming in Amazonia: Impacts and mitigation**. Acta Amazonica, 2009. **39**: 951-959.

47. Nobre CA, Borma LDS: **'Tipping points' for the Amazon forest**. Current Opinion in Environmental Sustainability, 2009. **1**: 28-36.

*48. Phillips OL, Aragao LEOC, Lewis SL, Fisher JB, Lloyd J, Lopez-Gonzalez G, Malhi Y, Monteagudo A, Peacock J, Quesada CA, et al: **Drought Sensitivity of the Amazon Rainforest**. Science, 2009. **323**: 1344-1347.

Measures the response of Amazon forest to severe 2005 drought, as analog for future events. Drought caused the forest to move from a carbon sink to a carbon source, with the potential for accelerating feedback on drying regional climates.

49. Fearnside PM, Laurence WF: **Tropical deforestation and greenhouse-gas emissions**. Ecological Applications, 2004. **14**: 982-986.

50. Lewis SL, Lopez-Gonzalez G, Sonké B, Affum-Baffoe K, Baker TR, Ojo LO, Phillips OL, Reitsma JM, White L, Comiskey JA, et al: **Increasing carbon storage in intact African tropical forests**. Nature, 2009. **457**: 1003-1006.

51. Cox PM, Betts RA, Collins M, Harris PP, Huntingford C, Jones CD: **Amazonian forest dieback under climate-carbon cycle projections for the 21st century**. Theoretical and Applied Climatology, 2004. **78**: 137-156.

52. Thomas S, Dargusch P, Harrison S, Herbohn J: **Why are there so few afforestation and reforestation Clean Development Mechanism projects?** Land Use Policy, 2010. **27**: 880-887.

*53. Boyd E, Hultman N, Timmons Roberts J, Corbera E, Cole J, Bozmoski A, Ebeling J, Tippman R, Mann P, Brown K, et al: **Reforming the CDM for sustainable development: lessons learned and policy futures**. Environmental Science & Policy, 2009. **12**: 820:831.

This review of CDM projects and their contribution to sustainable development (SD) shows that many projects contribute little in this regard. Alternative frameworks are discussed, all involving clear definition of and support for SD goals. Voluntary offsets and regional carbon markets offer potential opportunities for local benefits in developing countries.

54. Olsen KH: **The Clean Development Mechanism's contribution to sustainable development: a review of the literature**. Climatic Change, 2007. **84**: 59-73.

55. Wara M: **Is the global carbon market working?** Nature, 2007. **445**: 595-596.

56. Pielke (Jr) R, *The Climate Fix: What Sciencists and Politicians Won't Tell You About Global Warming*. Basic Books; 2010.

57. UNEP: *CDM/JI Pipeline Analysis and Database* www.cmdpipeline.org, accessed May 2010. 2010.

58. Capoor K, Ambrosi P: *State and rends of the carbon market 2009* World Bank. 2009.

59. Ellis J, Winkler H, Corfee-Morlot J, Gagnon-Lebrun F: **CDM: taking stock and looking forward**. Energy Policy, 2007. **35**: 15-28.

60. Pottinger L, *Climate change: The need to consider human forcings besides greenhouse gases*. International Rivers; 2008.

61. UNFCCC: *Reducing emissions from deforestation in developing countries: approaches to stimulate action FCCC/SBSTA/2009/L.19.* . 2009b.

62. IPCC: *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change* IPCC. 2007.

63. FAO: *FAO Global Forest Resource Assessment 2005* Food and Agriculture Organisation. 2006.

64. Stern N: *The Stern Review: the Economics of Climate Change* Cambridge University Press. 2006.

*65. Strassburg B, Turner RK, Fisher B, Schaeffer R, Lovett A: **Reducing emissions from deforestation the "combined incentives" mechanism and empirical simulations**. Global Environmental Change, 2009. **19**: 265-278.

Recent data were used to simulate REDD schemes, based on combined incentives framework (where historical and expected emissions from deforestation are used to reduce a country's emissions) operating either at a national or international level. Results indicate that while there are complexities in establishing REDD schemes, they can provide a cost-effective way to control deforestation.

*66. Ghazoul J, Butler RA, MateoVega J, Koh LP: **REDD: a reckoning of environment and development implications**. Trends in Ecology and Evolution, 2010. **25**: 396-402.

Emphasises the need to incorporate the full direct and indirect costs of REDD in terms of socio-political implications and lost-opportunity economic values of current land use, if REDD is to be a viable long-term forest conservation mechanism.

67. UNFCCC: *Copenhagen Accord* 2009a.

68. Skutsch M, McCall M: **Reassessing REDD: governance, markets and the hype cycle. Climatic Change, 2010. **100**: 395-402.

Assesses how practical and effective REDD/REDD+ policies will be, given that there are usually powerful socio-economic reasons for continuing deforestation and forest degradation together with other issues including financing, leakage, equitable access and governance. The suggestion is that small pilot projects will allow early problems with REDD to be ironed out.

69. Hamilton K, Chokkalingam U, Bendana M: *State of the forest carbon markets 2009: taking root and branching out* Ecosystem Marketplace. 2010.

70. World Bank: *Forest carbon partnership facility*. *FY2009 Annual Report.* World Bank. 2009.

71. IUCN: *Position paper: Reducing emissions from Deforestation and Forest Degradation (REDD) in developing countries*. 2009.

72. Corbera E, Estrada M, Brown K: **Reducing greenhouse gas emissions from deforestation and forest degradation in developing countries: revisiting the assumptions**. Climatic Change, 2010. **100**: 355:388.

73. Blom B, Sunderland T, Murdiyaso D: **Getting REDD to work locally: lessons learned from integrated conservation and development projects**. Environmental Science & Policy, 2010. **13**: 164-172.

74. Wertz-Kanounnikoff S, Angelsen A: **Global and national REDD+ architecture: Linking institutions and actions.** In *REDD+: National strategy and policy options*. Centre for International Forestry Research. 2009.

75. Jung M: **Host country attractiveness for CMD non-sink projects**. Energy Policy, 2006. **34**: 2173-2184.

76. Irland LC: **State failure, corruption and warfare: challenges for forest policy**. Journal of Sustainable Forestry, 2008. **27**: 189-223.

77. Peskett L, M. B: **When REDD+ goes national: a review of the realities, opportunities and challenges.** In *Realising REDD+: National strategy and policy options*, Eds Editor^Editors. Centre for International Forestry Research. 2009.

78. Anderson R, Candell J, Randerson J, Jackson R, Hungate B, Baldocch iD, Ban-Weiss G, Bonan G, Caldiera K, Cao L, et al: **Biophysical considerations in forestry for climate protection**. Frontiers in Ecology and Evolution, in press.

79. Lawrence PJ, Chase TN: **Investigating the climate impacts of global land cover change in the community climate system model doi: 10.1002/joc.2061**. International Journal of Climatology, 2010. **In press**.

80. Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, van Nes EH, Rietkerk M, Sugihara G: **Early-warning signals for critical transitions**. Nature, 2009. **461**: 53-59.

81. Rockström J, Steffen W, Noone K, Persson A, Chapin III FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, et al: **A safe operating space for humanity**. Nature, 2009. **461**: 472-475.

82. Woolley J, Cook SE, Molden D, Harrington L: **Water, food and development: the CGIAR Challenge Progam on Water and Food**. Water International, 2009. **34**: 4-12.

83. McAlpine CA, Etter A, Fearnside PM, Seabrook L, Laurance WF: **Increasing world consumption of beef as a driver of regional and global change: A call for policy action based on evidence from Queensland (Australia), Colombia and Brazil**. Global Environmental Change, 2009. **19**: 21-33.

84. UNEP: *Assessing the Environmental Impacts of Consumption and Production: Priority Products and Materials to the International Panel for Sustainable Resource Management* Hertwich E, van der Voet E, Suh S, Tukker A, Huijbregts M, Kazmierczyk P, Lenzen M, McNeely J, Moriguchi Y. 2010.

85. Schwarz W: *The rise and rise of fluorinated greenhouse gases as a share of global warming emissions* Öko-Recherche. 2004.

86. USEPA: *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020.* 2006.

87. Patt A: **Effective regional energy governance - not global environmental governance - is what we need right now for climate change. Global Environmental Change, 2010. **20**: 33-35.

Suggests that regional governance of energy may provide some of the building blocks to tackle climate change, if global governance is not possible in the short term because of national sovereignty, inequity and lack of trust.

88. Hunt C: **A science-driven market-based instrument for determining the cost of environmental services: A comparison of two catchments in Australia**. Ecological Economics, 2008. **66**: 309-318.

89. Lowell K, Drohan J, Hajek C, Beverley C, Lee M: **A science-driven market-based instrument for determining the cost of environmental services: A comparison of two catchments in Australia**. Ecological Economics, 2007. **64**: 61-69.

90. Ribaudo M, Greene C, Hansen L, Hellerstein D: **Ecosystem services from agriculture: Steps for expanding markets**. Ecological Economics, 2010. **69**: 2085-2092.

91. Ring I, Dreschler M, van Teeffelen AJA, Irawan S, Ventor O: **Biodiversity conservation and climate mitigation: what role can economic instruments play?** Current Opinion in Environmental Sustainability, 2010. **2**: 50-58.

92. Olmstead SM, Stavins RN: *Three Key Elements of Post-2012 Climate Policy Architecture*. Harvard Kennedy School. 2010.

93. Tandon S: *BHP boss calls for price on carbon* ABC News Online. Available at http://www.abc.net.au/news/stories/2010/09/15/3012724.htm. 15th September 2010.

94. MacKerron GJ, Egerton C, Gaskill C, Parpia A, Mourato S: **Willingness to pay for carbon offset certification and co-benefits among (high-)flying young adults in the UK**. Energy Policy, 2009. **37**: 1372-1381.

95. Thomas S, Dargusch P, Griffiths A, Hoegh-Guldberg O, Bruno J: **The colours of carbon**. Nature, 2010. **submitted**.

96. Brennan G: **Climate change: a rational choice politics view**. The Australian Journal of Agricultural and Resource Economics, 2009. **53**: 309-326.

97. Hajkowicz S: **Allocating scarce financial resources across regions for environmental management in Queensland, Australia**. Ecological Economics, 2007. **61**: 208-216.

98. DeFries RS, Rudel T, Uriarte M, Hansen M: **Deforestation driven by urban population growth and agricultural trade in the twenty-first century**. Nature Geoscience, 2010. **3**: 178-181.

99. Geist HJ, Lambin EF: **Proximate causes and underlying driving forces of tropical deforestation**. Bioscience, 2002. **52**: 143-150.

100. Rudel TK: **Changing agents of deforestation: From state-initiated to enterprise driven processes, 1970-2000**. Land Use Policy, 2007. **24**: 35-41.

*101. Lambin EF, Meyfroidt P: **Land use transitions: socio-ecological feedback versus socio-economic change**. Land Use Policy, 2010. **27**: 108-118.

Assesses pathways driving land use transition either by endogenous resource degradation (socio-ecological feedback) or by exogenous socio-economic change. The type of transition affects successful policy interventions, with socio-economic change better accounting for reafforestation, while socio-ecological change halts deforestation but only once new opportunities are in place. REDD schemes could provide these opportunities.

102. Gobron N, Belward A, Pinty B, Knorr W: **Monitoring biosphere vegetation 1997-2009**. Geophysical Research Letters, 2010. **37**: L15402.

103. Scholes RJ, Monteiro PMS, Sabine CL, Canadell JG: **Systematic long-term observations of the global carbon cycle**. Trends in Ecology and Evolution, 2009. **24**: 427-430.

104. Penman J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Pipatti R, Buendia L, Miwa K, Ngara T, Tanabe K, et al, eds. *Good Practice Guidance for Land-Use, Land-Use Change and Forestry*. 2003, Published by the Institute for Global Environmental Strategies (IGES) for the IPCC: Hayama, Kanagawa, Japan.

105. Olander LP, Gibbs HK, Steininger M, Swensen JJ, Murray BC: **Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods**. Environmental Research Letters, 2008. **3**: 025011.

106. Asner GP: **Tropical forest carbon assessment: integrating satellite and airborne mapping approaches**. Environmental Research Letters, 2009. **4**: 034009.

107. Asner GP, Powell GVN, Mascaro J, Knapp DE, Clark JK, Jacobson J, Kennedy-Bowdoin T, Balaji A, Paez-Acosta G, Victoria E, et al: **High-resolution forest**

carbon stocks and emissions in the Amazon. Proceedings of the National Academy of Sciences, 2010. **Early view, in press**.

108. Steininger MK, Godoy F, Harper G: **Effects of systematic sampling on satellite estimates of deforestation rates**. Environmental Research Letters, 2009. **4**: 034015.

109. Asner GP: **Tropical forest carbon assessment: integrating satellite and airborne mapping approaches**. Environmental Research Letters, 2009. **4**: 034009.

Figure captions.

Figure 1. Schematic of the multiple forcings and feedbacks impacting on the climate system in tropical and sub-tropical regions. Changes in land surface-atmosphere feedbacks are depicted for intact native ecosystems (left side) on moisture recycling and agricultural land use resulting from the conversion of intact native ecosystems (right side). The conversion of native forests and woodland ecosystems to crops and livestock pastures results in: reduced moisture recycling, net primary production, and carbon storage and sequestration; and increase in the sensible heat flux. These changes cumulatively impact on climate responses, with decreased cloud cover and precipitation over the modified land surface. Note: The width of the yellow lines is relative and does not represent absolute values.

Figure 2. Schematic showing the future of Earth's climate and ecosystems are strongly linked by land use and land cover change in addition to increasing atmospheric concentrations of CO_2. Note: The widths of the green and yellow lines are proportional to percentage forest cover and greenhouse gases and do not represent absolute values.

Figure 1

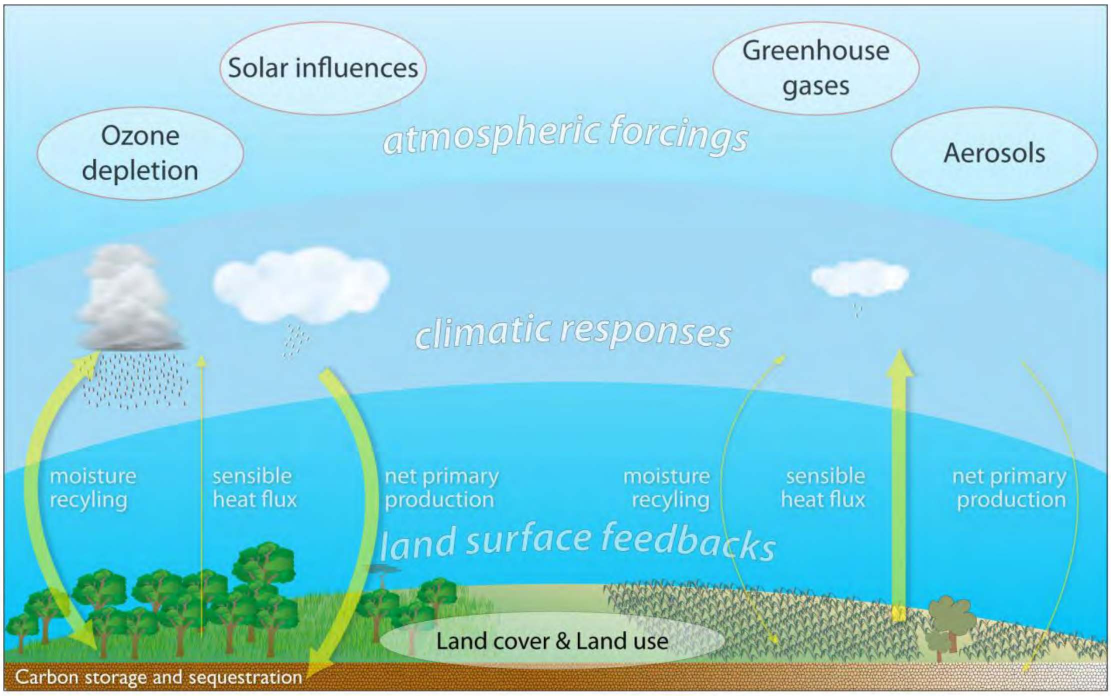

Figure 1.

Figure 2

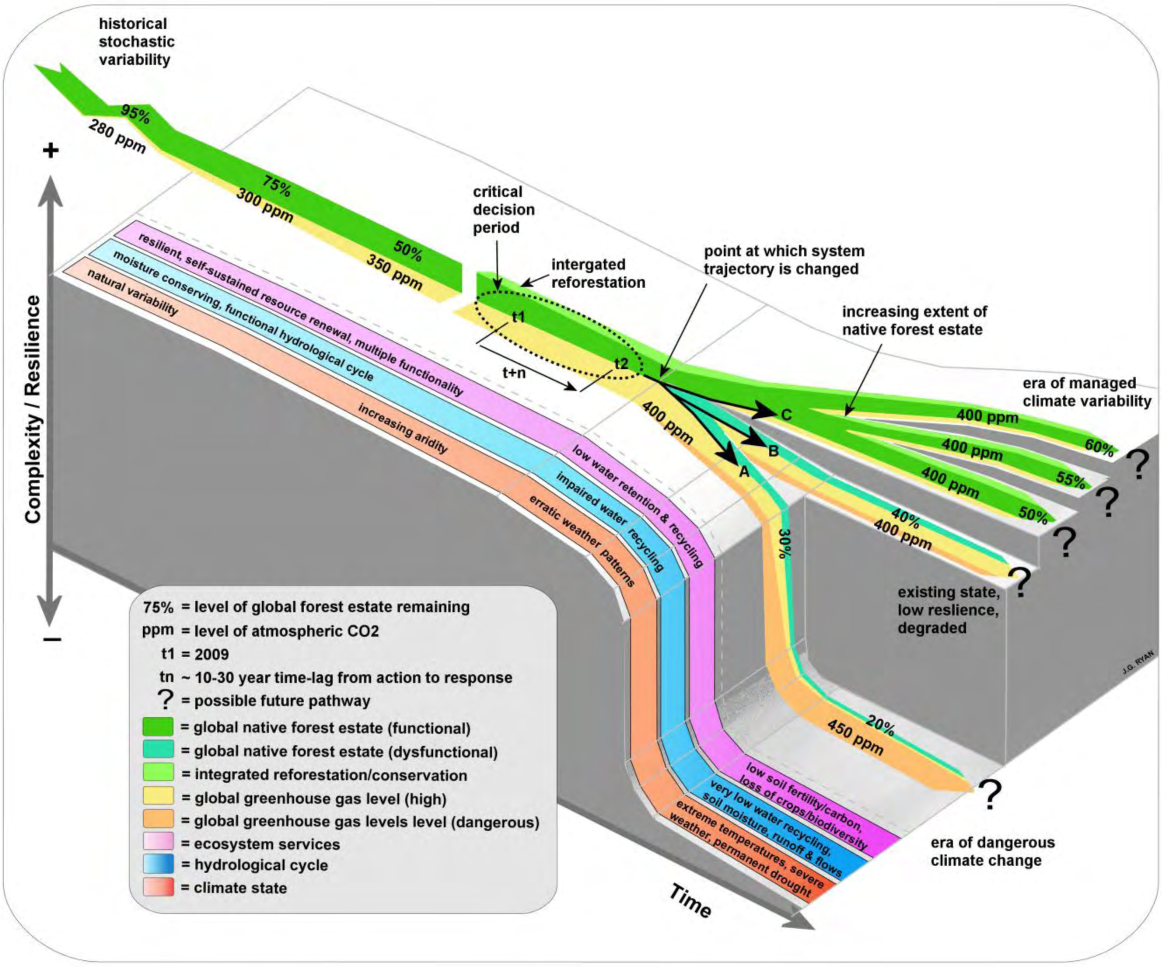

Figure 2.

Table

Table 1: Summary of key policy priorities and accompanying actions for broadening the perspective on dealing with the problem of climate change and variability.

Priorities	Purpose	Key Actions	Potential implementation	Actors	Scale
Integrate inter-governmental policies and protocols	More effectively address the challenges of climate variability and change and environmental sustainability	Assess existing policies and overlap. Develop stronger and more coordinated global agendas to reduce vulnerability of terrestrial ecosystems to land-use pressures and climate.	Need political will and cooperation to initiate and implement, but some precedents e.g .Montreal Protocol	National governments/global institutions	International, national
Strengthen carbon market mechanisms	Broaden the focus from controlling industrial CO_2 emissions to include LUCC	Strengthen CDM to link both native forests and planted forests with regulated carbon markets. Stronger focus of mitigation policies on LULUCF. Implement REDD+. Quantify the role of LUCC on changing surface fluxes of heat and water vapour and assess if this should be included as part of the market mechanisms.	Possible with appropriate funding and institutional support. Builds on existing mechanisms under COP process	National governments/global institutions. Non government organisations	International, national.
Avoid future deforestation	Ensure total forest cover increases with controlled deforestation and strategic reforestation	Address proximate and global drivers. Conduct vulnerability and risk assessments linked to climate models, and worst case historical and recent paleo-events. Develop regional land use and forest management plans. Strengthen institution capacity to ensure regulations are in place. Provide funding and policy guidance to developing countries. Societal and institutional change.	Difficult to enforce, but possibly with sufficient funding e.g. offsets and carbon markets Main problem lies in dealing with non-compliance or loss of forest through natural disturbances	National/local government, business, community	International, national, regional, local
Develop coordinated global forest monitoring program	Monitor forest loss and regeneration Policy effectiveness and compliance	Develop cost effective remote sensing methods. Establish land cover/land use baselines. Indentify most effective spatial and temporal resolution.	Technically achievable.	Research institutes, national/local government, business	International, national, regional