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Critical impacts of global warming on land ecosystems

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Abstract

Globally increasing temperatures may have unmanageable impacts on terrestrial, aquatic and marine ecosystems. Quantifying impacts worldwide and systematically as a function of global warming is critical to substantiate the ongoing international negotiations on climate mitigation targets. Here we present a macro-scale analysis of climate change impacts on terrestrial ecosystems based on newly developed sets of climate scenarios featuring a step-wise sampling of global mean temperature increase between 1.5 and 5 K by 2100. These are processed by a biogeochemical model (LPJmL) to derive an aggregated metric of simultaneous biogeochemical and structural shifts in land surface properties which we interpret as a proxy for the risk of shifts and possibly disruptions in ecosystems.

Our results show a substantial risk of climate change to transform terrestrial ecosystems profoundly. Nearly no area of the world is free from such risk, unless strong mitigation limits warming to around 2 degrees above preindustrial level. Even then, most climate models agree that up to one fifth of the land surface may experience at least moderate change, primarily at high latitudes and high altitudes. If countries fulfill their current emissions pledges, resulting in roughly 3.5 K of warming, this area expands to cover half the land surface, including the majority of tropical forests and savannas and the boreal zone. Due to differences in regional patterns of climate change the area potentially at risk of severe ecosystem change considering all AOGCMs is up to 2.5 times as large as for a single AOGCM.

1 Introduction

One of the most critical consequences of globally increasing temperatures is the potentially unmanageable impact on terrestrial, aquatic and marine ecosystems, as climate is a prime determinant of ecosystem composition and functioning and explains much of their spatial variation (Woodward et al., 2004). In turn, through their material cycles, ecosystems and land surfaces are fundamental to the functioning of the Earth as a system of planetary chemical cycles, and they provide a multitude of ecological functions and services that human societies depend upon socially, culturally and economically (Millennium Ecosystem Assessment, 2005). Nonetheless, the potential of climate change to transform landscapes is less frequently mentioned as a principal element of "dangerous climate change" than more physical impacts such as sea level rise or direct damages from extreme weather events. This is partially due to the inherent complexity of ecosystems, rendering it difficult to systematically project their macroscopic response to multidimensional climate change. In fact, ecosystems are characterized by numerous internal feedbacks occurring in interlinked, multi-layered networks across various scales (both in space and time). While each layer is able to absorb some degree of change, reaching the limit of its adaptive capacity may trigger destructive cascades in successive hierarchical levels (Holling, 2001). Unfortunately, comprehensive theories and computer models of such complex systems and their dynamics up to the global scale are not available at present. Complicating the matter, there is considerable uncertainty in climate projections, due primarily to climate model-structural and emissions scenario uncertainty (Hawkins and Sutton, 2010).

Notwithstanding these methodological challenges, quantifying climate change impacts on ecosystems worldwide and systematically as a function of global warming is critical to substantiate the ongoing international negotiations on climate mitigation targets. While the negotiations focus on a target of a maximum warming of 2 K (cf. Cancun Agreements, UNFCCC, 2011), actual commitments by nation states to reduce greenhouse gas emissions currently add up to a warming well above 3 K (Rogelj et al., 2010, 3.3 K according to www.climateactiontracker.org, retrieved 28 February 2013). Given the inconclusive political debates on climate change in many industrialized countries, the robust economic growth in major developing countries, and a non-negligible possibility of high climate sensitivity of the Earth system (IPCC, 2007, ch. 8.6), an increase of global mean temperature (GMT) of 5 K above preindustrial by the end of this century is not out of the question (Rogelj et al., 2012). Therefore, assessing and illustrating the

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incremental impacts of a GMT rise of e.g. 2, 3.5 or 5 K and the associated uncertainties is of crucial importance.

Here we present a systematic macro-scale analysis of climate change impacts on terrestrial ecosystems and land surface properties as a function of GMT increase which addresses the methodological challenges raised above. Our quantitative assessment is based on a consistent modeling framework composed of (1) newly developed sets of climate scenarios that sample the space of GMT increase uniformly (between 1.5 and 5 K), which are processed by (2) a state-of-the-art global biogeochemical model simulating climate-dependent vegetation-soil dynamics to derive (3) an aggregated metric of simultaneous biogeochemical and structural shifts in land surface properties. We interpret this metric as a numerical proxy for the risk of shifts and possibly disruptions in fundamental ecosystem properties and underlying finer-scale processes in response to climate change. As there is no simple impact equivalent of ecosystem macro-variables as those characterizing the global climate (such as GMT increase or globally mixed atmospheric CO_2 concentration), the metric is designed to be spatially explicit.

2 Quantification of complex ecosystem change

On a fundamental level, ecosystems are characterized by their carbon exchange with the atmosphere and soil and by the water flowing through living tissues (Ripl, 2003). These properties, determined by the primary process of photosynthetic conversion of sunlight into biomass, constitute the base of the ecological food chain upon which trophic cascades and complex community structures depend (Mooney et al., 2009). At landscape level, ecosystems can be characterized by the prevailing broad types of vegetation in terms of their functional strategies, their carbon content, and their carbon and water exchange.

We argue that a climate-driven shift in these broad biogeochemical (water, carbon) and structural properties (vegetation type) implies corresponding impacts on the underlying, much more complex ecosystems (Heyder et al., 2011). In other words, changes

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in vegetation abundance and in magnitude or interrelation of exchange fluxes are taken to alter more detailed hierarchical structures, such as predator-prey and host-parasite relations (Parmesan, 2006), complementarity and competition regarding resource use (Hooper et al., 2005), or mutual interactions like pollination (Mooney et al., 2009). To quantify these shifts, we combine changes in the magnitude and relative size of biogeochemical fluxes and stocks of the terrestrial vegetation and changes in its functional structure – which, in contrast to the more detailed ecosystem structures, are captured by spatially explicit simulation models – into one macro-level indicator which we treat as a proxy for the risk of ecosystem and landscape change.

This approach has two advantages. (1) Well-developed models of the impacts of climate change on terrestrial carbon and water biogeochemistry and vegetation structure are available in the form of dynamic global vegetation models (DGVMs; Murray et al., 2012). (2) Using a macro-level proxy that can be simulated with a DGVM in conjunction with climate change scenarios circumvents having to describe in-depth climate change impacts on concrete local ecological networks, or synthesizing a large number of smaller-scale ecological studies into a coherent global picture, both of which are faced with nearly insurmountable methodological difficulties (Parmesan, 2006; Williams and Jackson, 2007).

2.1 Computation of the change metric

The generic change metric Γ developed by Heyder et al. (2011) is used to quantify overall biogeochemical and structural change and the implied risk of transitions in underlying ecosystem features, estimating the difference between an ecosystem state under climate change and the current state. Ecosystem states are characterized as vectors in a multi-dimensional state space. The distance between two state vectors represents the change an ecosystem is simulated to experience in terms of its biogeochemical properties. A larger distance implies a higher risk for underlying ecosystems to change, undergo restructuring, or collapse on short time scales. Ecosystem states for both the reference period (1980–2009) and the future (2086–2115) are characterized by the

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model variables specified in Table 1. Γ is formulated to evaluate five dimensions of change:

$$\Gamma = \left\{\Delta V + c\,S\,(c,\,\sigma_c) + g\,S\left(g,\,\sigma_g\right) + b\,S\,(b,\,\sigma_b)\right\}/4. \quad (1)$$

(1) Changes in vegetation composition in terms of major functional types representing different ecological strategies (woody vs. herbaceous, broadleaved vs. needleleaved, evergreen vs. deciduous), using a slightly modified version of the ΔV metric (Sykes et al., 1999) (see Supplement for details). (2) Changes in biogeochemical ecosystem state characteristics (all variables from Table 1 except vegetation structure) relative to previously prevailing conditions at each location to quantify the magnitude of local ecosystem alterations (local change c). (3) Changes in said parameters in absolute terms, i.e. their contribution to global-scale biogeochemistry; this global importance g takes into account that even moderate changes on the local scale may significantly feed back to larger scales (global carbon cycle, atmospheric circulation patterns, downstream water availability), possibly affecting ecosystems in other regions. (4) Changes in the magnitude of stores and fluxes relative to each other. Such shifts in balance b of biogeochemical properties indicate changes in the controlling dynamic processes and hence ecological functioning. (5) Changes in ecosystem state relative to present-day variability S, i.e. the range of previously encountered year-to-year variations to which ecosystems are adapted. All these dimensions are scaled between 0 (no change) and 1 (very severe change) and combined into the full metric Γ based on the assumption that simultaneous changes in several of them imply a higher risk of ecosystem destabilisation than changes in just one.

2.2 Interpretation of the change metric

To give a better understanding of what a certain Γ value means we calculated the metric for a hypothetical complete shift between present-day biomes, i.e. substituting space for time. For this, the modeled potential natural vegetation was categorized into 16 different biome classes (see Fig. S3a in the Supplement for the biome map and Fig. S4

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in the Supplement for the classification scheme) and Γ computed as the difference between each biome (rather than between a future and the present state). The difference between present biomes typically adopts values of $\Gamma > 0.3$, signaling fundamentally different underlying ecological systems (Fig. S2). For example, an average evergreen tropical rainforest differs from a tropical seasonal forest by a Γ value of 0.31; a shift to a savanna gives 0.51, and a shift to a C4 grassland 0.86. A shift from a boreal evergreen to a boreal deciduous forest amounts to 0.24, to a temperate coniferous forest 0.37 and to a tundra 0.66. Only shifts between similar but still distinct biome types, such as a temperate mixed forest transforming into a temperate broadleaved or temperate coniferous forest, have smaller Γ values. Overall, $\Gamma < 0.1$ implies that despite biogeochemical shifts possibly affecting community composition, biomes remain roughly the same in terms of their defining characteristics. Values of Γ between 0.1 and 0.3 signal a change that produces a different, but related biome. In this study, we consider such changes to reflect risk of "moderate" climate change impacts on ecosystems. Values of $\Gamma > 0.3$ are considered risk of "severe" change. Since biomes aggregate an often continuous spectrum of actual vegetation composition into discrete categories, ecosystems may change their biome at lower Γ values than those in Fig. S2 in the Supplement. Also, biomes can be rather broad categories. For example, the term savanna is used loosely in the literature to refer to very different ecological communities, covering a wide range of tree canopy cover anywhere between 5 and 80 % (Anderson et al., 1999). Owing to this high variability within biomes our definition of what constitutes severe change does not call for a change in biome class.

2.3 Vegetation model

We use the well-established LPJmL DGVM to calculate the biogeochemical and vegetation-structural process dynamics required to quantify the ecosystem change metric (described above). LPJmL simulates key physiological and ecological processes for 9 plant-functional types (PFTs) representing natural ecosystems at biome level (Sitch et al., 2003). Climate-dependent carbon and water cycles are directly coupled

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through photosynthesis based on a modified Farquhar approach (Farquhar et al., 1980; Collatz et al., 1992). Carbon taken up from the atmosphere is allocated to different vegetation carbon pools and subsequently converted to litter, forming soil carbon pools that decompose at various rates. PFTs coexisting within a grid cell compete for space, light and water, with establishment depending on climatic suitability and density of existing vegetation, mortality rates depending on growth efficiency, plant density and climatic stress, and fire disturbance depending on climate, fuel availability and PFT-specific fire resistance. The model is forced by monthly fields of temperature, precipitation and cloud cover, yearly values of atmospheric CO_2 concentration, and information on soil properties. All processes are calculated at a daily time step on a spatial grid of 0.5° longitude by 0.5° latitude resolution, with monthly climate data disaggregated as described in Gerten et al. (2004). Human land cover/land use changes and their potential effects are neglected here, but areas under cultivation are excluded when computing the absolute area affected (see *Model settings and simulation protocol* in the Supplement for more details).

3 Climate uncertainty

Previous studies encountered several problems hampering a systematic quantification of climate change impacts for different GMT levels. (1) Considerable differences are found in the magnitude and spatial pattern of projected climatic changes from different Atmosphere-Ocean General Circulation Models (AOGCMs) for a given future time period or GMT increase. This is particularly true for changes in precipitation patterns, with AOGCM differences not just in the magnitude, but even in the sign of change for a number of regions (IPCC, 2007, ch. 11). This necessitates the use of inputs from multiple AOGCMs in impact studies and to treat the differences as uncertainty. (2) Available climate scenarios do not sample the space of future GMT increase uniformly. For a given emission scenario the temperature reached by the end of this century differs between climate models due to differences in their climate sensitivity (IPCC, 2007, ch. 8.6).

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Combined with the limited number of emissions scenarios processed by AOGCMs and available in the CMIP3 archive[1] (Meehl et al., 2007), this introduces significant inconsistencies when attempting to compare multi-AOGCM impacts for different levels of GMT increase, because some future GMT ranges are reached by more (and different) climate models than others.

We address these challenges with a new dataset of temperature-stratified climate scenarios (Heinke et al., 2012), created from existing AOGCM runs available in the CMIP3 archive, but processed to reach specific GMT levels around the year 2100. These are created using a pattern-scaling approach (Huntingford and Cox, 2000) and are based on two pillars. (1) To cover emissions scenario uncertainty – ranging from ambitious mitigation over current commitment to continued emissions growth throughout the 21st century – temporal trajectories of emissions and resulting GMT increase over pre-industrial levels are computed by the fast, reduced-complexity climate model MAGICC6 (Meinshausen et al., 2011). From a large ensemble of artificial emissions trajectories we select those leading to global warming between 1.5 and 5 K in 0.5 K steps. These warming trajectories are physically and systemically plausible, with carbon cycle parameters adjusted to reproduce the Bern carbon cycle model and model parameters chosen to reproduce the median responses of the CMIP3 AOGCM ensemble, with a climate sensitivity of 3.0 K (Heinke et al., 2012). Target GMT levels are reached in the 30 yr mean around the year 2100. (2) To explicitly incorporate climate pattern uncertainty these 8 GMT trajectories are combined with the spatial characteristics from 19 AOGCMs. Existing runs from at least two emissions scenarios (SRES[2] A2 and 1 % yr^{-1} CO_2 increase to quadrupling for most models unless not available) are used to extract one scaling pattern per model and climate variable. These patterns describe AOGCM-specific local changes in temperature, precipitation and cloud cover as a function of GMT change.

[1]World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset

[2]Special Report on Emissions Scenarios (IPCC, 2000)

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The combination of scaling patterns for each AOGCM and climate variable with GMT trajectories for the 8 warming scenarios results in transient time-series of climate anomalies for the scenario period 2010 to 2115. Climate anomalies are then applied to a reference climate constructed from observed historical climate data (see below), which adds mean climatology and information on interannual variability. The process of anomaly application to the reference climate includes a bias correction. The resulting climate scenarios allow for a smooth transition from historical data to future projections and therefore transient impact model runs across the whole period.

For the historical simulation period the CRU TS 3.1[3] climatology (Mitchell and Jones, 2005) is used for temperature and cloud cover; and the GPCC[4] Full Data Reanalysis version 5 data for precipitation (Rudolf et al., 2010), extended to cover the full CRU grid. The number of wet days per month, used to distribute monthly sums, is created synthetically using the CRU approach (New et al., 2000) in order for the wet-day frequency to be consistent with GPCC precipitation. Historical climate data span from 1901 to 2009 and are followed seamlessly by climate scenario data. See Heinke et al. (2012) for an in-depth description of the climate scenario generation process. The resulting 152 climate scenarios (8 warming levels × 19 AOGCMs) allow a much more thorough and systematic sampling of the space of potential future GMT increase, retaining the key spatial properties of available AOGCMs while removing regionally distinct model-inherent biases. They provide a considerable step forward compared to up to 58 scenarios used in previous DGVM-based, multi-climate-model, global ecosystem impact assessments (Heyder et al., 2011; Scholze et al., 2006).

Γ values are computed for impact simulations under each of the 152 climate scenarios separately. A grid cell is considered "at risk" if at least one out of 19 AOGCMs demonstrates moderate or severe change at the respective GMT level. We determine

[3]Climate Research Unit's time-series data available from British Atmospheric Data Centre (BADC), http://badc.nerc.ac.uk/data/cru/

[4]Global Precipitation Climatology Centre operated by Deutscher Wetterdienst, http://gpcc.dwd.de

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the confidence in the projected severity of change based on the number of AOGCMs in agreement, using IPCC guidelines on uncertainty, i.e. about 2 out of 10 chance (4/19 AOGCMs), low confidence; about 5 out of 10 chance (10/19 AOGCMs), medium confidence, about 8 out of 10 chance (16/19 AOGCMs), high confidence (IPCC, 2007, ch. 1.6).

4 Results: severe and moderate ecosystem changes as a function of global warming

Our simulations show that the extent of global land area affected by either moderate or severe change is substantial and increases strongly with global warming. Assuming business-as-usual emissions leading to a GMT increase of 4–5 K above preindustrial by 2100, more than two thirds of the global, ice-free land surface not currently used for agriculture are at risk of severe ecosystem change (68 % at 4 K warming and up to 86 % at 5 K, left panel in Fig. 1). The uncertainty caused by differences in spatial patterns between climate models is large, however. For a global warming of 4 K, there is less than low confidence (less than 4 out of 19 AOGCMs in agreement) on 24 % of the land area, low to medium confidence on 23 % and high confidence (at least 16 of 19 models) on 20 % of the land area (dotted black and solid white line in Fig. 1). At 5 K, the affected areas are 17, 36 and 32 % of the land area with less than low, low to medium and high confidence, respectively.

Figure 2 shows the regions affected by either severe or moderate change, with colors indicating the degree of model agreement on both. Already for a warming of 2 K above preindustrial – the target agreed upon in the Cancun accords following the UNFCCC's objective to prevent dangerous interference with the climate system (UNFCCC, 1992) – severe ecosystem shifts are projected under a majority of the AOGCM simulations for the temperature-sensitive high northern latitudes and some high-altitude regions (Figs. 2a and 3a). These changes are associated primarily with migrations of the tree line and increased vegetation productivity, both of which have already been observed in

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recent decades (Lloyd, 2005; Walker et al., 2012). Significantly larger areas, equaling 23 % of the global land area with at least medium confidence (Fig. 1), would be affected by severe change at a global warming of 3.5 K – i.e. if countries restricted their greenhouse gas emissions according to their current pledges. In a 5 K world, vast areas on each continent and most biomes are likely to be severely affected (Figs. 2c and 3a). They expand into the Sahel region and eastern Africa, cover large portions of southern Africa, most of the Australian interior, the eastern flanks of the Andes and the Brazilian northeast, areas of the central United States, the temperate-to-boreal ecotone in North America, most of India and the northern part of Southeast Asia, the Tibetan Plateau and extensive areas of the boreal-steppe ecotone in the Asian continental interiors of Mongolia, Kazakhstan, southern Russia and northern China, as well as all of the circumpolar region presently covered by tundra. Many of these large-scale patterns are already partly realized at 3.5 K of warming, such as along the southern edge of the boreal zone, the forest transition zone in tropical Africa, East India, and the Chaco region in South America (Fig. 2b).

Adding to severely affected areas are regions for which our simulations project moderate ecosystem changes ($0.1 < \Gamma < 0.3$). Moderate change as defined here may still correspond e.g. to a tropical seasonal forest changing into a densely wooded savanna or may signal significant changes of tree composition in temperate forests (Fig. S2 in the Supplement). Taking these into account, the total area at risk more than doubles in the low emissions scenarios; for example, 45 % of the land area is at risk of at least moderate change compared to 19 % at risk of severe change in the 2 K scenarios (Fig. 1). The area for which we project only moderate ecosystem change is largest at 4 K and actually decreases in the higher warming scenarios as more and more regions go from moderate to severe change. As a result, the increment between GMT steps of the total area at risk – i.e. affected by either moderate or severe change under at least one AOGCM – tapers off beyond 3–3.5 K warming. On the other hand, confidence, based on AOGCM agreement, that ecosystems will be subjected to at least moderate change continues to grow (Fig. 1, right panel). The remaining model

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disagreement is located primarily in some deserts and grasslands – the only biomes that still have non-negligible parts where under no AOGCM either moderate or severe change is projected at 5 K global warming (16 % of deserts, 7 % of warm grasslands, 5 % of temperate grasslands, Fig. S5 in the Supplement).

Comparing changes in impact simulations under individual AOGCMs reveals the importance of using a large ensemble of climate models. Affected areas at a specific GMT level vary between AOGCM projections. In addition – because affected areas in different AOGCMs may lie in different regions (see Fig. S6 in the Supplement for maps of Γ values from individual model runs) – the total area at risk across all models is consistently higher than the model with the largest affected area (Fig. 4). For example, the total area where at least 1 AOGCM shows severe change is between 33 % (1.5 K warming) and 67 % (3.5 K) higher than the largest area simulated by any individual AOGCM (compare individual circles in Fig. 4 to solid black line). Even at 5 K, using the less strict criterion of $\Gamma > 0.1$ where AOGCM agreement is much higher, the total area taking into account the whole ensemble is at least 10 % higher than for any individual AOGCM. While the total area at risk represents a worst case that is extremely unlikely to come to pass, severe or at least moderate changes cannot be precluded in these regions based on the climate scenarios used.

5 Discussion and conclusions

This paper has shown that there is a substantial risk of climate change to transform the world's terrestrial ecosystems profoundly, as judged by shifts in basic biogeochemical functioning. Nearly no area of the world is free from such risk, unless strong mitigation limits warming to around 2 degrees above preindustrial level. Even then, most climate models agree that up to one fifth of the world's ice-free, non-agricultural land surface is under a risk of at least moderate change.

The results presented here are snapshots of the projected changes at the end of the 21st century. GMT is likely to continue to rise beyond the simulation period which

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means that pressure on ecosystems will continue into the 22nd century. Because of time-lags in their response ecosystems may also continue to change if GMT is stabilized by 2100. Adaptation can take place at the scale of years to decades in the case of vegetation decline, but time-lags may extend to centuries or even millennia where adaptation entails the migration and regrowth of forests (Leemans and Eickhout, 2004). The different rates of adaptation processes mean that ecosystem changes projected for the low warming scenarios cannot simply be taken to represent transitional states that happen at an earlier point in time of the higher warming scenarios.

Since Γ measures the amount of change regardless of the direction of change (increase or decrease) in the individual parameters describing ecosystem states, a high confidence in projected moderate or severe ecosystem change does not necessarily imply agreement on the type of change, only on the severity of it. For example, a tropical savanna may change into a seasonal forest following reduced water limitation or into a grassland if precipitation is reduced, both of which would be considered severe change in this analysis. This ability to capture many types of changes at once is important in the context of a risk assessment. The metric does not categorize changes as positive or negative, as such evaluations often depend on the perspective taken. For example, Leemans and Eickhout (2004) considered ecosystem changes resulting in an increase in net ecosystem production (NEP) as positive and changes resulting in a release of carbon into the atmosphere as negative, taking a human use perspective. However, they acknowledged that their assessment may have been different from a biodiversity or nature protection perspective. In contrast, Γ considers any significant change in the underlying biogeochemistry as an ecological adaptation challenge, putting pressure on species and communities to either adapt or migrate (Mooney et al., 2009).

While possibly the most comprehensive sampling of climate uncertainty with respect to projected changes in biogeochemical functioning to date, this study is based on one impact model only. Previous DGVM intercomparison studies found that model results matched quite well for contemporary, observed climatology, but diverged in their response to climate change (Cramer et al., 2001; Sitch et al., 2008). The recent

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Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, http://www.isi-mip.org) compiled impact simulations from more than 30 impact models within a consistent modeling framework covering the agricultural, biome, health and water sector. Comparing results from 7 global ecosystem models including LPJmL their analysis suggests that uncertainty from differences in impact models is larger than that caused by climate model differences. However, the study is based on climate scenarios from only three AOGCMs and directly relates ecosystem changes to changes in GMT regardless of emissions scenario and therefore timing, ignoring possible time-lag effects. While not directly comparable to our analysis (e.g. different reference conditions, lack of dynamic vegetation in several of the participating models), LPJmL results fall well within the range of the other biogeochemical models participating in ISI-MIP (Warszawski et al., 2013). Processes determining species composition in ecosystems are highly complex and in many cases poorly understood, especially in connection with novel climates (Williams and Jackson, 2007). While simulated dynamics in LPJmL constitute best current knowledge, further model development is required to improve the reliability of projected change in vegetation structure (see Supplement for further discussion).

In addition to the effects of climate change, land use change is a concurrent pressure acting upon ecosystems. This is expected to increase, as a rising global population and growing economic wealth will increase demand for food and feed, combined with a potentially substantial future demand for bio-energy production to achieve energy independence and climate mitigation targets (Lotze-Campen et al., 2010; van Vuuren et al., 2010). Ecosystem protection in the 21st century will therefore face both of these interacting pressures, global climate and land use change.

In view of the substantial risks of ecosystem change from global warming found in this study, advancing systematic, comprehensive numerical analysis of terrestrial climate change impacts should be a focus of scientific research in the next years with the aim of reducing the large present uncertainty in the quantification of impacts. This would provide a better foundation for policy processes considering tradeoffs with the political, social and economic transformations implied in managing global change.

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Despite the remaining uncertainties, our findings demonstrate that there is a large difference in the risk of global ecosystem change under business as usual, limited and effective mitigation.

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Table 1. LPJmL model outputs (aggregated to 30 yr averages) used to compute present and future ecosystem states and the Γ metric.

Carbon exchange fluxes	Net primary production (NPP), heterotrophic respiration (rH), fire carbon emissions
Carbon stocks	Carbon contained in vegetation and soils
Water exchange fluxes	Transpiration (representing productive water use), soil evaporation and interception from vegetation canopies (representing unproductive water use), runoff
Additional parameters describing system-internal processes	Fire frequency, soil water content
Vegetation structure	Composition of PFTs

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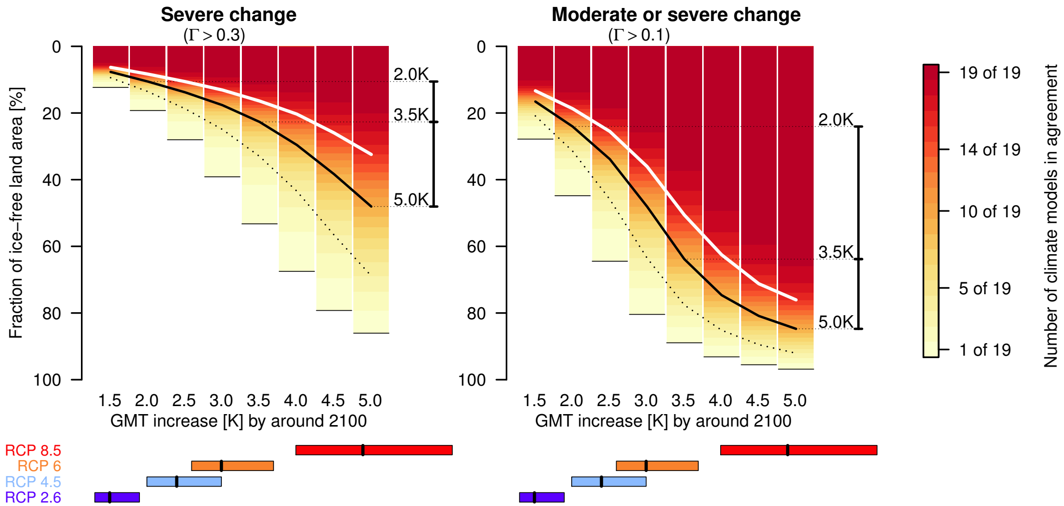

Fig. 1. Global land-surface area at risk of severe (Γ > 0.3, left panel) or at least moderate (Γ > 0.1, right panel) ecosystem change by around 2100. Black and white lines denote confidence based on AOGCM agreement: solid white, high; solid black, medium; dotted black, low confidence. Arrows to the right illustrate the difference in affected area (with medium confidence) between 2, 3.5 and 5 K of warming. Colored boxes below main figure compare results to the 66 % range of warming expected from four Representative Concentration Pathways (RCPs) after Table 2 in Rogelj et al. (2012).

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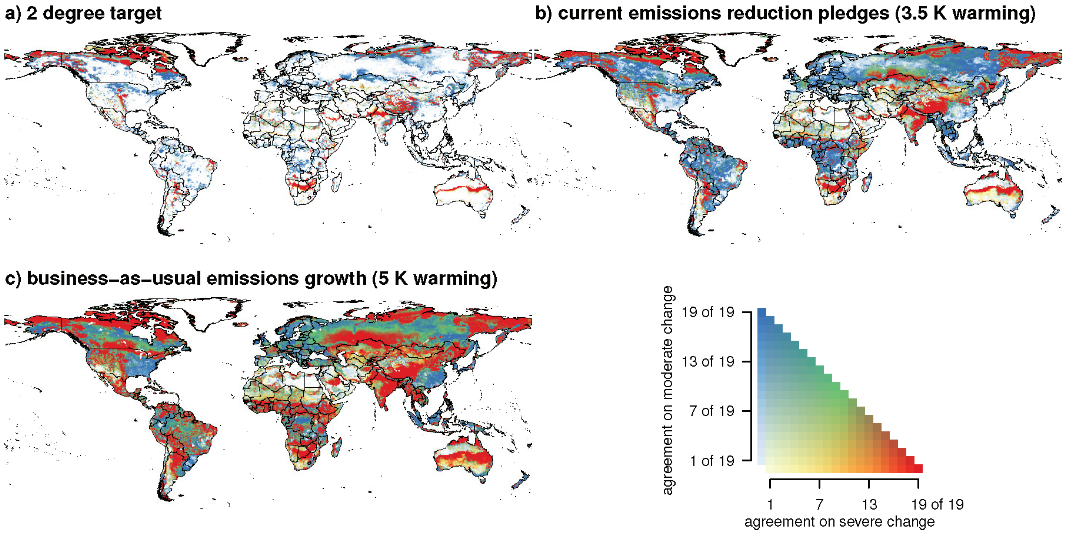

Fig. 2. Regional patterns of simulated ecosystem change by 2100 and their confidence, for different climate policies leading to a GMT increase of 2, 3.5 and 5 K above preindustrial, respectively. Colors indicate the number of simulations agreeing on either severe ($\Gamma > 0.3$) or moderate ecosystem change ($0.1 < \Gamma < 0.3$) in each grid cell.

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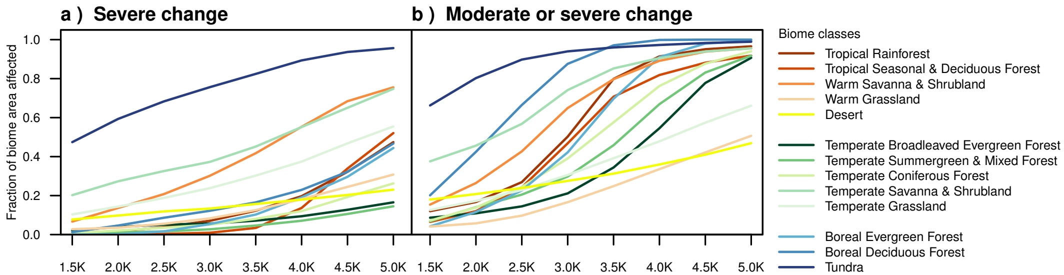

Fig. 3. Biome area affected by **(a)** severe ($\Gamma > 0.3$) or **(b)** at least moderate ($\Gamma > 0.1$) ecosystem change by around 2100 with at least medium confidence ($\geq$ 10/19 AOGCMs in agreement). For other levels of confidence see Fig. S5 in the Supplement.

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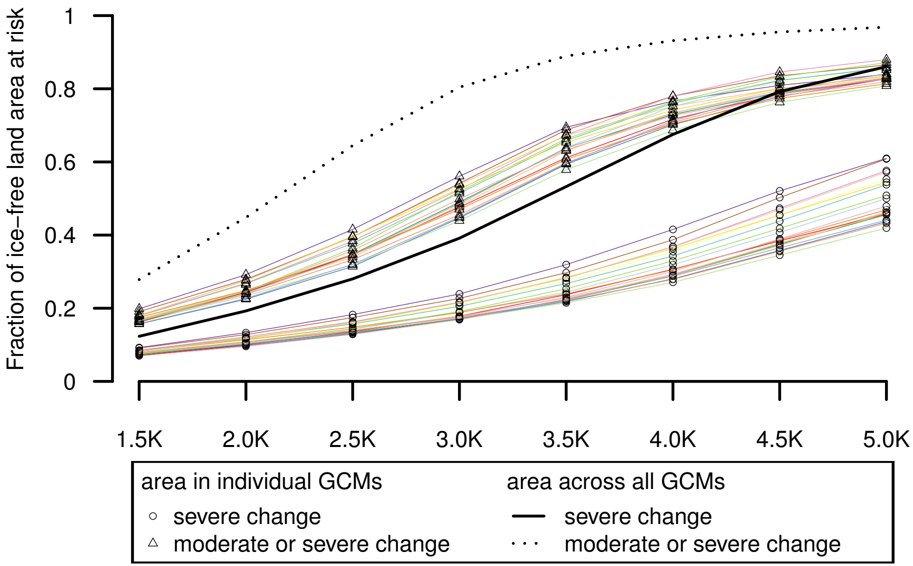

Fig. 4. Importance of climate ensemble analysis. Circles and triangles denote the area projected at risk of severe or at least moderate change, respectively, by individual AOGCMs. The black solid and dashed line mark the total area at risk across all AOGCMs. Higher total areas result from regional differences between AOGCMs.

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