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A Framework to Explore Regional Feedbacks under Changing Climate and Land-use Conditions

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Abstract

In this paper the main terrestrial ecosystem processes and related feedbacks with the climate system are reviewed and placed in a conceptual framework, used to explore the nature of potential bio geophysical feedbacks at the regional scale prior to executing complex and extensive numerical simulation of the coupled processes. We illustrate the framework for a limited number of regions where significant changes in climate and/or land use are expected. Where possible and appropriate, the quantitative effects of the feedbacks are presented, accompanied with a discussion of the drivers of these results. In Europe, under moisture-limited evapotranspiration conditions, heat waves are potentially amplified by a positive soil moisture-temperature feedback. Future warming and precipitation reduction in the Amazon can be amplified by forest dieback, pointing at a positive soil moisture-precipitation feedback. In India, irrigation may exert a positive soil moisture-precipitation feedback al local and regional scale, while a negative feedback occurs at larger spatial scales. The framework is designed to diagnose possible feedback loops that are worth exploring in further detail by dedicated (model) studies. Being a conceptual framework, complex Biogeophysical processes necessarily are simplified in straightforward process-response relationships. In some of the feedback loops explored, socio-economic dimensions need to be considered, particularly when these affect human decisions on land-use and land-cover change (LULCC). The framework can be used to design the necessary integration of Earth System (ES) and Integrated Assessment (IA) modeling systems.

Keywords: Feedbacks; Land-use change; Climate; Irrigation; Drought; Terrestrial ecosystems

Introduction

Terrestrial ecosystems are important global carbon sinks, and their functioning modulates the variability of the carbon exchange between the land surface and the atmosphere at annual to climate time scales. Vegetation cover also regulates the physical properties of land surface (e.g. albedo and roughness) and the surface energy partitioning of net radiation between sensible and latent heat, affecting water and energy exchange with the atmosphere. Anthropogenic Land-Use/Land-Cover Change (LULCC) modifies these land properties and the carbon cycle. The terrestrial response to this forcing can positively or negatively feedback to the climate system, and thus magnify or reduce the initial perturbation [1-4].

Model Intercomparison studies, such as the Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP) and the Land-Use and Climate, Identification of Robust Impacts (LUCID) [5-7]) systematically evaluate biogeochemical and Biogeophysical feedbacks. Within the C4MIP framework, Friedlingstein [8] projected a global net positive carbon-climate feedback on surface temperature and atmospheric carbon dioxide (CO_2)-levels; but large uncertainty persists due to the complex processes involved in this feedback [9-11]. An important control variable is the effect of increases in temperature on either ecosystem productivity or respiration, and the relative sensitivity of these processes to ambient temperature increases governs the sign of the terrestrial branch of the carbon-climate feedback.

Biogeophysical feedbacks between LULCC and climate have a generally slightly damping effect on the global temperature increase due to dominant increases in albedo in areas where forest is replaced by low vegetation, and snow shading plays a strong role [12]. However, these albedo changes and their associated feedback mechanisms have a strong spatial structure, leading to possibly large feedback responses at the regional scale [13]. But again models assessing regional Biogeophysical impacts of anthropogenic LULCC show large divergence between them [5].

The uncertainty associated with feedbacks between LULCC and the climate system has triggered considerable research, both at the global and at the regional-scale. While the global mean Biogeophysical response to LULCC is relatively small, it is potentially an important driver of climate change in regions with intensive LULCC [6]. In some regions (particularly in mid- and high- latitudes), the LULCC-induced cooling effect due to albedo changes is of similar magnitude but of opposite sign compared to the warming induced by the increasing CO_2. In other regions (i.e. the tropics) LULCC can amplify the CO_2 induced warming by promoting sensible heat release and reduce evaporative cooling [14].

The comprehensive modeling studies supporting the periodic assessments of the Intergovernmental Panel on Climate Change (IPCC) demonstrate that in various regions, future global warming is associated with increasing temperature variability and more frequent extreme events, such as heat waves and droughts [15]. Biogeophysical feedbacks, especially those related to soil moisture, play an important role in the duration and frequency of these events. Widespread vegetation responses to weather extremes can systematically modulate the carbon uptake by terrestrial ecosystems [16] that can be noticeable in the global carbon cycle. The short-term vegetation response to adverse extreme climatological conditions such as heat waves and droughts, and its interaction with the governing climate system, are thus worthwhile to explore.

The wide variety of processes, responses and feedbacks involved with land use change and the range of spatial and temporal scales at which these operate complicate systematic exploration of the relative importance of processes and effects. Processes can counteract, reinforce, or conditionally affect each other at different spatial and temporal scales. A careful examination of the net result of the balance of processes requires a modeling framework in which they are represented realistically, and where the mutual sensitivities are well imposed. Analysis of (multi-)model experiments in which these feedbacks are addressed such as [5-7] does not always lead to firm conclusions on the overall sign of the responses and feedbacks. In order to increase our understanding of these complex interactions even more system components in these modeling systems need to be considered, or additional detail to the processes already implemented needs to be added, which introduces a new set of dimensions and degrees of freedom to analyze. This process of deepening our understanding of the complex climate-vegetation system is aided by reflecting on a limited perspective of the whole system; a conceptual, simplified picture of it. Such a "conceptual framework" underlies many studies dealing with complex physical climate systems e.g. [16-18], and helps to identify the major feedbacks that are worth exploring further in advanced coupled modeling studies.

In this paper we discuss such a conceptual framework that depicts the major interactions between LULCC (i.e., deforestation and irrigation), vegetation and a changing climate at the regional scale. The framework by design simplifies existing relationships, and is limited in scope by not considering all external and internal processes and feedbacks that potentially affect the functioning of the regional vegetation-climate system. But this simplification serves the purpose of careful experimental design, and in teaching new experts in the field.

We shortly review the main feedbacks that play a role at the regional scale and introduce the conceptual framework in Terrestrial ecosystems – climate feedbacks in a conceptual framework. "Regional" is used here to denote the spatial scale at which systematic interactions between vegetation and climate conditions can be expected, and is loosely specified to be in the order of 250,000 km^2 (500 × 500 km) or more. We illustrate this framework for three regions where strong feedbacks take place in which LULCC plays a role (Applying the conceptual framework at the regional scale). Quantitative implications of the feedbacks based on literature are provided. The selection of these regions does not intend to be complete or formally justified; it rather serves the purpose of demonstrating the conceptual framework. We will discuss the necessary experimental model design needed to explore these regional scale feedbacks (Implications for experimental design), which entered a recent review of possible modeling strategies for feedback exploration by van Vuuren [19]. Finally, conclusions are given (Summary and conclusions).

Terrestrial Ecosystems – Climate Feedbacks in a Conceptual Framework

Overview of main feedbacks

Processes connecting LULCC and climate include interactions via the chemical pathways (involving for instance the carbon cycle and its impact on the climate system) and via physical mechanisms (such as hydrology and surface energy balance effects [20]. These are routinely labeled as "biogeochemical" and "Biogeophysical" processes and feedbacks, respectively.

Biogeochemical processes and feedbacks

Biogeochemical terrestrial carbon processes include sequestration of CO_2 from the atmosphere by living organisms, where Gross Primary Production (GPP; the CO_2 fixation via photosynthesis), the Net Primary Production (NPP; the net gain of carbon), production of CO_2 by plant growth and maintenance (R_A; autotrophic respiration), and heterotrophic respiration (R_H; through organic matter decomposition by soil biota) are the governing terms. The balance between these processes determines the net carbon uptake, known as Net Ecosystem Exchange (NEE). When also considering natural (e.g. fires) and anthropogenic (e.g. deforestation) disturbances, the net carbon uptake by the ecosystem is called Net Biome Productivity (NBP). Figure 1 summarizes these processes.

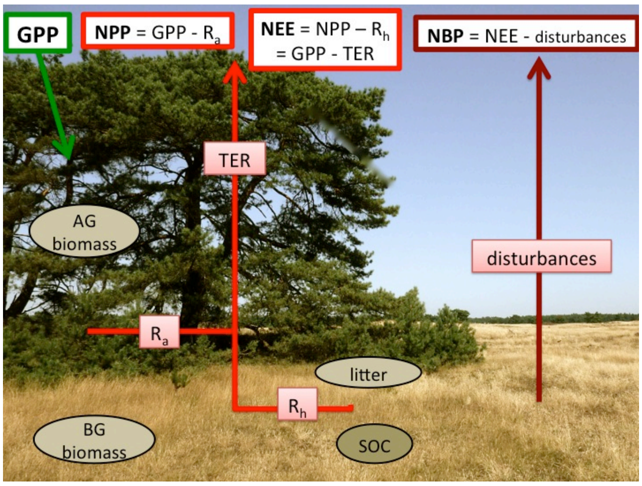

Figure 1: Schematic of the carbon balance for a given terrestrial ecosystem. Circles and squares represent carbon stocks and fluxes, respectively. AG: aboveground, BG: below ground, SOC: soil organic carbon, Ra: autotrophic respiration, Rh: heterotrophic respiration, TER: total ecosystem respiration, GPP: gross primary production, NPP: net primary production, NEE: net ecosystem exchange, and NBP: net biome production.

Of prime interest in the area of biogeochemical interactions and feedbacks is the degree to which ecosystems enhance photosynthesis (GPP) due to enriched atmospheric CO_2, which induces a negative (cooling) feedback associated with the reduction of atmospheric CO_2, in combination with the sensitivity of all relevant carbon fluxes to the changing temperature and moisture conditions. For unlimited water availability, the response of GPP to warming is non-linear and has an

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optimum: a positive response where mean temperature is lower than the optimal temperature (illustrated for instance by studies in the Yangtse river basin [21] and boreal forest [22]), and negative at higher temperatures (such as in many tropical regions [23]. The dependence of ecosystems on water availability has led to strong GPP reductions in the tropics, where there has been a drying trend during the past five decades [24]. Of importance as well is the possible restriction of enhanced carbon fixation by limited nutrient availability, such as nitrogen (N) [4,25,26] and phosphorous [27]. Rising temperatures can further enhance RH [28,29] which eventually leads to a positive (warming) feedback, while soil moisture can become a limiting factor when elevated temperatures also promote drying [30]. An uncertainty in the representation of soil moisture-R_H interactions in terrestrial models continues to be large, and dominates the determination of the net sign of the carbon-climate feedback [30-32].

Biogeophysical feedbacks

Reflection of incident solar radiation by the surface is governed by its albedo, which varies with land cover and ecosystem dynamics. Increases in atmospheric CO_2 levels and surface temperature can affect the timing of the vegetation growing season, and enhance forest expansion in areas where growth is energy limited (for instance in boreal regions [3]). The associated reduction of the surface albedo leads to an enhanced absorption of net radiation, which subsequently further promotes temperature increases (positive feedback). In contrast, extratropical deforestation exerts a negative radiative forcing (cooling) because of increased surface albedo, especially in boreal regions [33-35]. However, less cooling or even warming can occur when non-radiative processes (i.e. evapotranspiration efficiency, cloud formation, aerodynamic cooling) become dominant [12]. The decreased evapotranspiration and a warming effect of a resulting reduction in cloudiness can compensate the radiative-induced cooling by an increasing albedo [36, 16].

Soil moisture plays an important role at partitioning the surface energy into latent heat (cooling the surface) and sensible heat (raising the air temperature immediately above the surface). Positive soil moisture – temperature feedback takes place when limited soil moisture availability reduces evaporative surface cooling, and thus results in excess sensible heat exchange. The higher temperatures resulting from this promote evaporative drying and soil moisture depletion, which closes the feedback loop. The sign and strength of this soil moisture – temperature feedback varies with the climate regime [17].

Under special conditions evapotranspiration can affect precipitation in the region of interest, which can lead to a so-called soil moisture-precipitation feedback [37]. The sign of the interaction between evapotranspiration-precipitation and the resulting feedback varies widely with scale and conditions and is thus highly uncertain [17]. Soil moisture-precipitation feedback can be positive or negative depending on the atmospheric hydrological response to perturbations in the soil moisture-evapotranspiration system. A positive feedback leads to a reinforcement of a positive rainfall anomaly, resulting in higher soil moisture that enhances evapotranspiration and ultimately precipitation. Conversely, a negative feedback may exist, for instance, when precipitation is promoted through enhanced convection in dry conditions [38]. A strong soil moisture-precipitation feedback is generally found in transitional regions between dry (soil moisture controlled evaporation) and wet (net radiative energy controlled evaporation) climate regimes [39].

Vegetation can regulate both the hydrological and the carbon cycles via their stomatal control. Under enhanced CO_2 levels, a similar stomatal CO_2 transport can take place at a smaller stomatal opening condition, and the photosynthetic carbon assimilation rate can be maintained at reduced evapotranspiration levels. This physiological forcing exerted by the CO_2 level rise allows increasing water-use efficiency (WUE, ratio of carbon fixation to water loss), being as important as the CO_2 fertilization effect in water-limited ecosystems [40]. At the canopy scale, evapotranspiration is controlled by the canopy conductance, which depends on stomatal conductance and the leaf area index (LAI; total area of leaves per unit surface area). The relationship between soil moisture and (heterotrophic) respiration addressed before [30] plays a role in the regulation of carbon exchange between vegetation and the atmosphere by moisture conditions.

LULCC has a weak detectable direct impact on precipitation [41], but changes in the extent of irrigation area may systematically affect the regional hydrological cycle. Many regions with extensive irrigation show increases in evapotranspiration (and precipitation), the weak summer monsoon areas in India form an exception [42]. Although irrigation induces surface cooling at the regional scale, no detectable effect on global mean temperature has been reported [43].

The conceptual framework of responses and feedbacks

The selection of forcings, processes and interactions discussed above is grouped in a conceptual framework (Figure 2) that considers multiple processes and interactions acting on different temporal and spatial scales. It allows addressing global (such as the global carbon cycle) and regional/local (i.e., the hydrological cycle) feedbacks, at longer (e.g. those related to ecosystem respiration) and shorter (e.g. the effect of a heat wave event on soil moisture-precipitation feedback) time scales. Feedback loops in the framework are assumed to represent processes at a comparable spatial and temporal scale.

The role of vegetation in the feedback diagram exists on various time scales, including the seasonal climate variability, and extreme events at short (such as heat waves) and longer (droughts) time scales. In addition, persistent precipitation anomalies and warming can induce vegetation shifts at decadal to centennial time scales. Since the magnitude and the sign of vegetation-climate feedbacks are spatially and temporally dependent, selection of the appropriate scales is required for a useful evaluation of the vegetation-climate feedbacks.

As an illustration of this conceptual framework, Figure 3 shows a number of carbon cycle - climate feedbacks, where a positive relationship between atmospheric CO_2 concentration and global surface temperature is a key element. The net effect of the feedback depends on the dominant biogeochemical response to the elevated temperature. An acceleration of photosynthesis (GPP) by higher temperatures (T) under conditions of unlimited water supply, and for a limited response of changes in ecosystem respiration (TER), the overall feedback loop is negative (Figure 3a): the elevated GPP will reduce the atmospheric CO_2 concentration and dampen the initial perturbation. The feedback will be positive when higher temperature promotes TER, and thus more CO_2 is released to the atmosphere (Figure 3b). But this positive feedback can be reduced or disappear when the GPP declines by changes in temperature or moisture limitations, and less carbon is supplied to be respired or decomposed (Figure 3c). Processes involved in these feedbacks depend on soil moisture (θ), but also to nutrient availability such as nitrogen (not shown here).

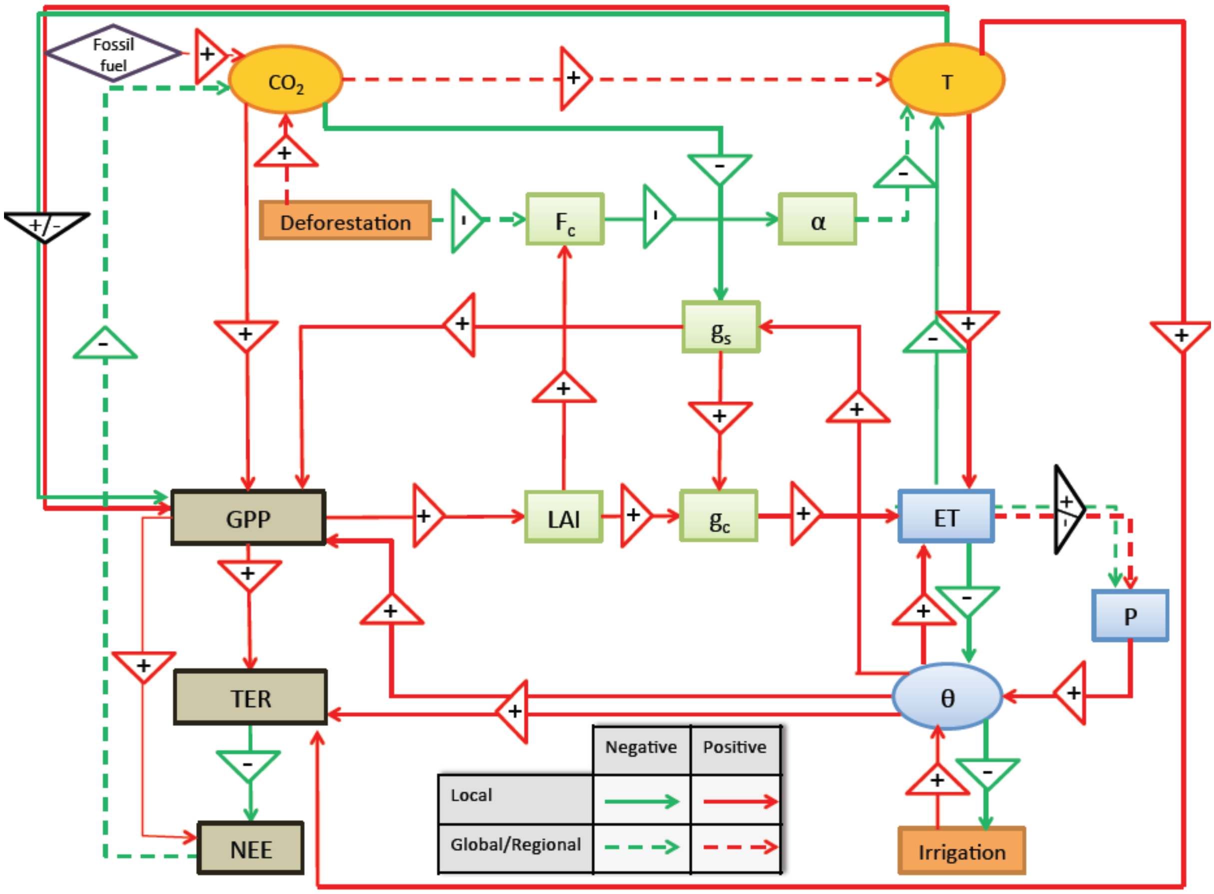

Figure 2: Conceptual framework of processes and interactions between terrestrial ecosystems and climate. Arrows connect system components. Red arrows indicate that an increase (decrease) of a process/state will increase (decrease) another process/state. Green arrows imply the reverse response. Arrows with solid lines refer to local interactions, and dashed arrows to larger scale (regional, global) interactions. Circles refer to states, squares to fluxes/processes, triangles to responses and diamonds to external drivers. Processes are assumed to act at a comparable spatial and temporal scale. T: temperature, GPP: gross primary production, NEE: net ecosystem exchange, TER: total ecosystem respiration, LAI: leaf area index, Fc: forest cover, α: albedo, gs: stomatal conductance, gc: canopy conductance, ET: evapotranspiration,P: precipitation, θ: soil moisture.

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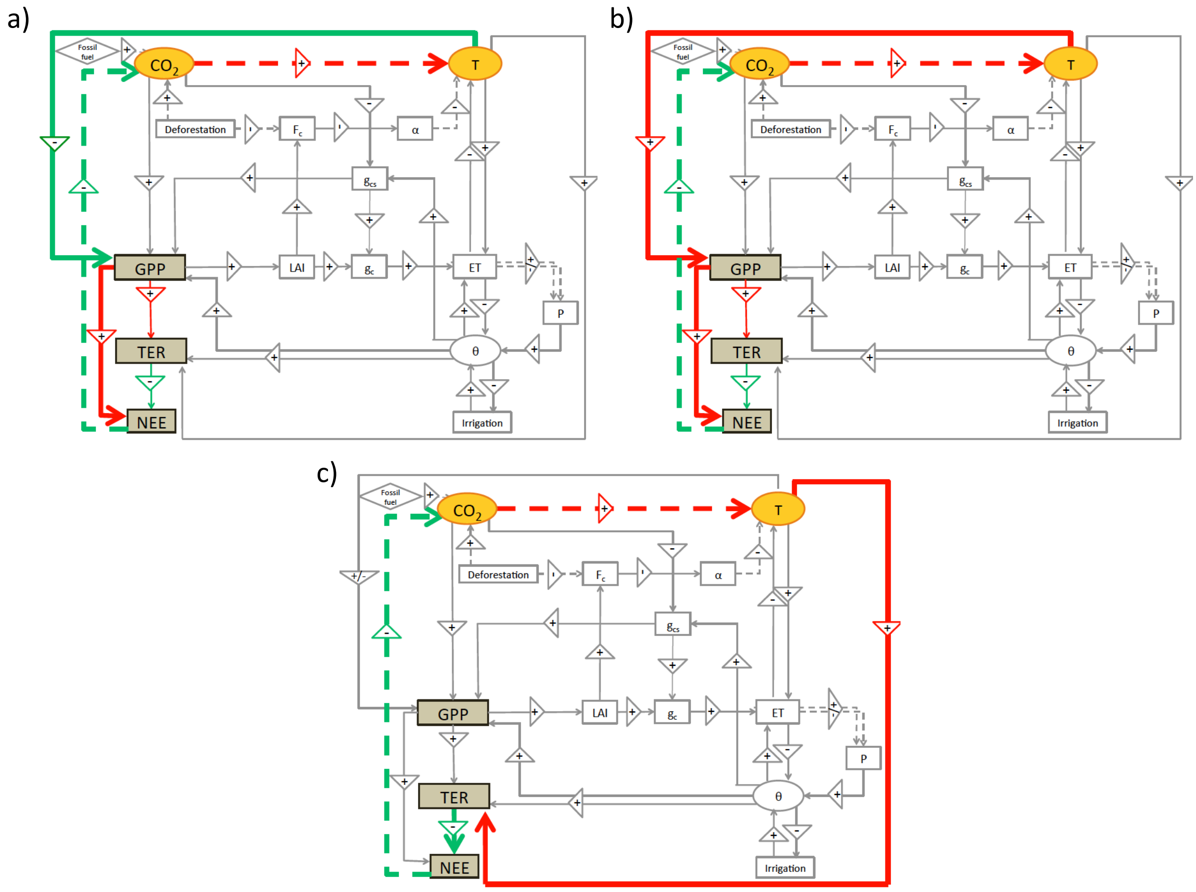

Figure 3: Schematic illustration of the carbon cycle-climate feedback loop using the conceptual framework (Figure 2). Closed loops (thicker arrows) between components represent feedbacks, and the product of all signed responses determines the overall sign of the feedback.

Applying the Conceptual Framework at the Regional Scale

Feedbacks of European ecosystems to warming and heat waves

Wramneby [44] detected a number of hotspots of Biogeophysical vegetation feedbacks in European forests by mapping the response to elevated greenhouse gas concentrations in regional climate model simulations with and without interactive vegetation. The advance of the boreal tree-line by CO_2 fertilization and warming in the Scandinavian Mountains exposed a positive albedo feedback in winter and spring (Figure 4a), leading to a seasonal mean albedo reduction of 0.15 to 0.20, and a temperature increase between 0.2 and 1°C. However, this warming can be offset by the evaporative surface cooling (0.2-0.5 °C) of the increased forest cover in summer and autumn (Figure 4b). In southern Europe, the negative evapotranspiration – temperature feedback in autumn and winter, caused by the modest forest expansion (Figure 4c), turns into a positive soil moisture – temperature feedback in summer due to soil moisture depletion (Figure 4d). Summer dryness reduces LAI of low vegetation (grass) significantly, amplifying the reduction in evapotranspiration and therefore increasing the surface temperature by 0.2 – 1°C.

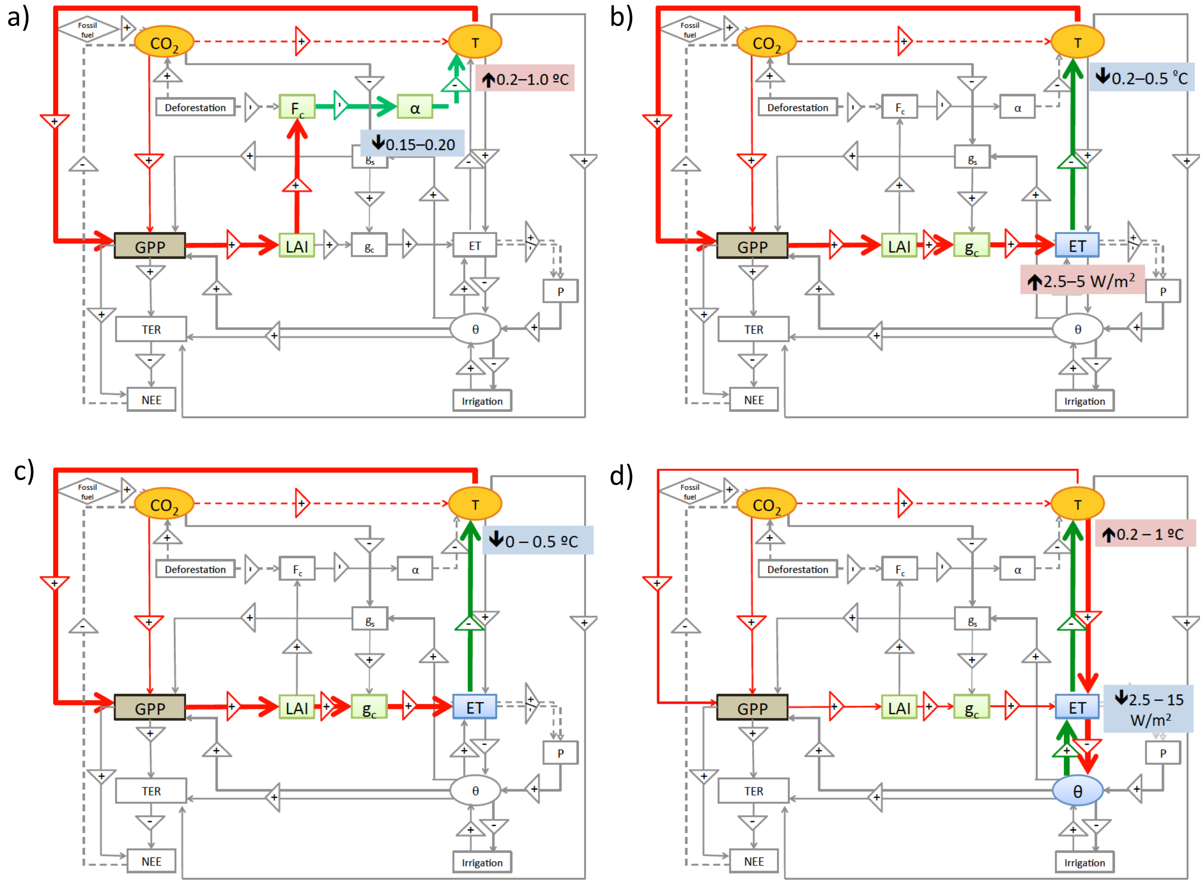

Figure 4: Terrestrial ecosystem-climate feedbacks for Europe: a) Positive albedo feedback during winter (DJF) and b) negative temperature feedback in summer (JJA) in Scandinavian Mountains. c) Negative temperature feedback in winter and d) positive feedback in summer in Southern Europe. Based on Wramneby [44].

At a shorter time scale, the surface response to heat waves depends on the type of land-cover [45]. Observations from flux towers in forest and grassland areas showed that during the 2003 heat wave forests reduced evapotranspiration, most probably due to stomatal closure. In contrast, grasslands showed a higher evapotranspiration early in the event, and thus generated a cooler ambient environment than the forest sites. However, when the dry conditions prolonged, the resulting depletion of soil moisture eventually led to a reduction of the latent heat flux and enhanced surface heating, thereby exceeding the heating response seen over forest areas, who tend to reduce water losses during a heat wave and prevent heat wave intensification on the long term.

Vegetation feedbacks to a drier Amazon

Net Primary Productivity in the Amazon can be strongly affected by changes in the hydro climate such as precipitation in the dry season [46], the interannual variability of the wet season onset, and frequency, extension and severity of droughts [47-49]. When these hydro climatic features are governed by global warming, a regional response such as a reduction in NPP may imply a positive feedback to the global climate system due to the large contribution of the Amazon to the global carbon balance [50]. Intense droughts can offset the net gains of an undisturbed Amazon forest [51]. Two major drought events (2005 and 2010, both with an estimated return time of once per more than a hundred years) had a strong impact on the NPP of the area [52, 53].

Also the projected shift of Amazon forests to different climate-vegetation equilibrium with tropical savannas [54] or seasonal and deciduous forests [55] in response to a changing climate may impose a positive feedback. The vegetation shifts enhance carbon release and may reduce regional water recycling, reinforcing the regional warming and vegetation change. In a climate model experiment, Betts [56] analyzed the impact of forcing and feedback mechanisms on the simulated decline of rainfall and forest dieback in a number of scenarios. Rainfall reduction was greater for runs with dynamic vegetation (2.4 mm day^{-1}) than in runs using prescribed fixed vegetation (1.9 mm day^{-1}). Stomatal closure and reduction of evaporation related to rising atmospheric CO_2 contributed 20% to the decreased precipitation. A positive Biogeophysical feedback through reducing local evaporative water recycling due to forest dieback further enhanced the rainfall reduction by 20% (Figure 5). However, rainfall projections and vegetation responses to altered climate conditions in the Amazon remain to be highly uncertain in current coupled climate-carbon cycle models [57].

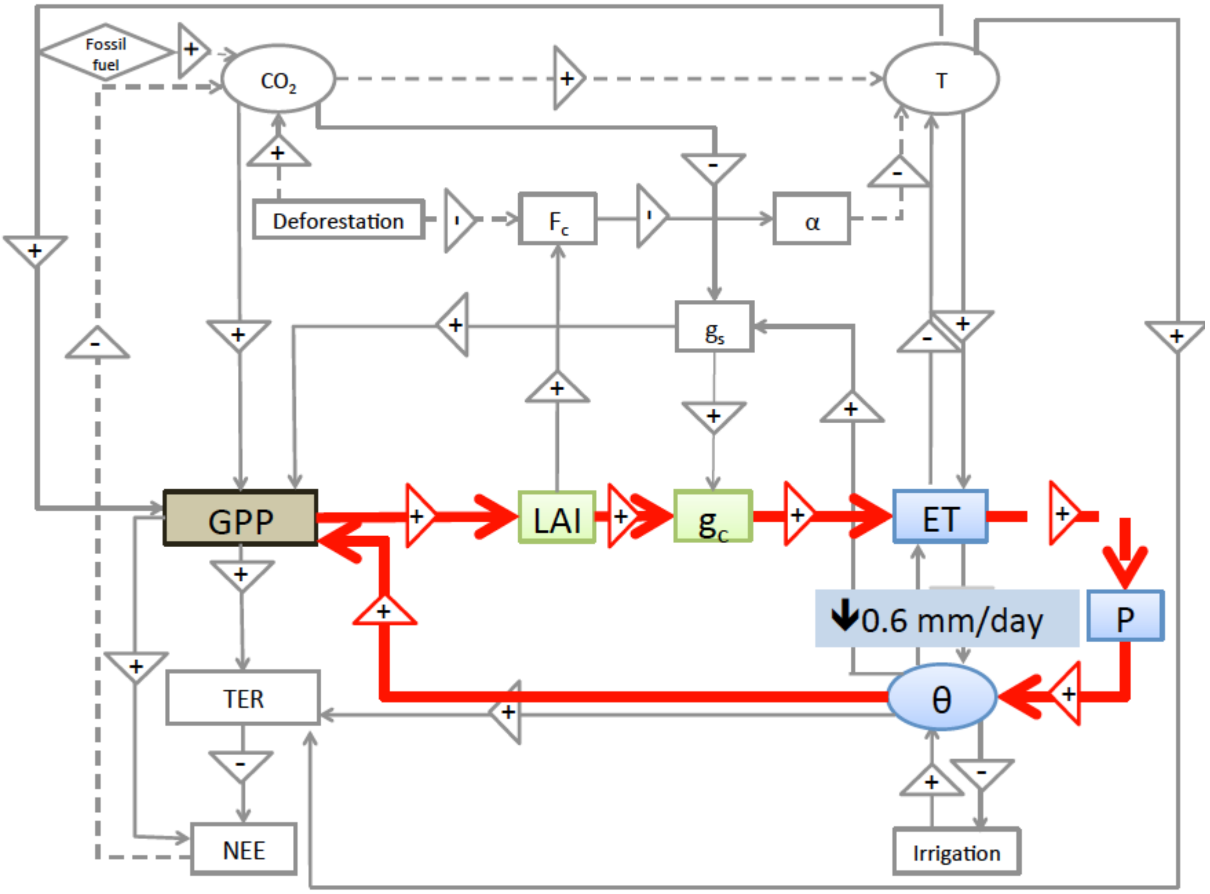

Figure 5: Positive soil moisture-precipitation feedback (further reduction of precipitation) by forest dieback in the Amazon. Based on Betts [55].

Irrigation impact on soil moisture – precipitation feedback in India

The monsoon climate in India induces a seasonal precipitation; little to no rainfall in winter (December-May), when dry continental air is adverted from the north, and monsoon precipitation in the wet season (June-August). The atmospheric transport of moist oceanic air is reversed in autumn (September-November) due to changes in the gradient between land-sea temperatures. Agricultural production heavily depends on monsoon rainfall, although technological innovation and irrigation expansion in the 1960s permitted to both reduce potential water deficits in the monsoon season, and to allow a second crop in agricultural systems during the dry season. More than 50% of the global irrigation is applied in India and Southeast Asia together [43].

The summer monsoon climate in India is considered a hot spot of soil moisture-precipitation coupling [37]. Excessive irrigation may play an important role in the hydrological cycle, for instance by increasing mean annual evapotranspiration especially in the dry season [58]. Large extractions of ground water for irrigation are confirmed by analyses of data from the GRACE satellite [59].

The effect of irrigation on the overlying atmosphere varies with temporal and spatial scales. At local scales boundary layer processes dominate, and the change of the surface energy balance due to irrigation modifies the ability of the atmosphere to trigger convection or produce convective precipitation. This change can either lead to positive or negative soil moisture – precipitation feedback. Moisture recycling plays a role at regional scales, and for large recycling rates the excess moisture supply due to irrigation may promote the subsequent formation of rain, a positive feedback. Moisture recycling in the Ganges basin is estimated to be 5% in winter and 60% during the monsoon season [60] (Figure 6). By changing the surface temperature gradient between land and ocean at large scale, irrigation can affect monsoon flow patterns, possibly weakening the summer monsoon [61,62]. This impact exceeds the effect of widespread deforestation in the area [63]. Changing wind patterns and consequently land-sea temperature gradients are shown to (slightly) shift precipitation from the Ganges basin towards the Indus basin and North-West India [64].

The signature of these feedback processes has a clear seasonal cycle. A dominant positive local precipitation – soil moisture feedback related to atmospheric boundary layer and convection processes only exists during the pre- and post-monsoon seasons between winter and summer. In summer and winter land surface does not exert a strong influence on precipitation; the atmosphere is too wet or too dry, respectively, to respond to local moisture anomalies [18].

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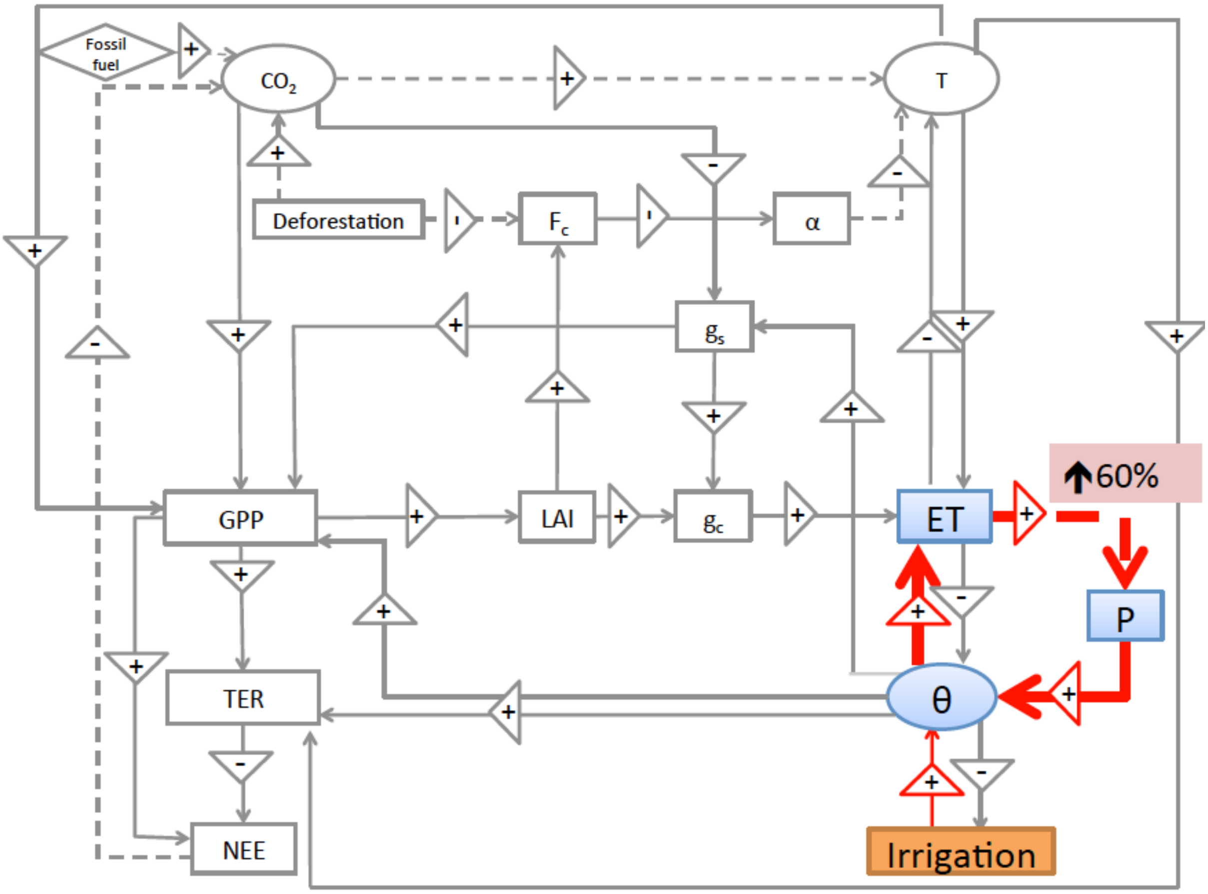

Figure 6: Positive soil moisture-precipitation feedback (further increasing precipitation) in irrigated areas of the Ganges basin in the monsoon season. Based on Tuinenburg [18].

Implications for Experimental Design

Climate models are useful and often applied tools to explore global carbon cycle-climate feedbacks. They allow inspection of processes and feedbacks by means of physically oriented picture of the important mechanisms driving climate variability and their spatially and temporally varying responses. However, inadequate representation of LULCC can lead to a biased representation of possibly relevant local feedbacks in regions with significant LULCC [65], for instance feedbacks related to the surface energy partitioning [6,14] and vegetation dynamics [66]. Rietkerk [67] pointed at the importance of the simultaneous representation of multiple relevant spatial and temporal scales, and proposed to apply model concepts that allow for cross-scale links between feedbacks at these various scales. Local ecosystem feedbacks need to be coupled to the regional and global scale by application of proper downscaling and up scaling procedures.

Changes in land use and crop production are based on human decisions, which depend on demographic, socio-economic and environmental factors [68]. So, potential feedbacks between the climate system and the socio-economic system may be important, for instance when human decisions have a (regional) climatic consequence that feed backs on the initial intervention. In spite of several attempts to integrate this socio-economic dimension in Earth System Models, the representation of these feedbacks remains a big challenge [2]. Given the importance of moving towards a better representation of the interaction between natural and human systems, improving levels of integration between Earth System (ES) and Integrated Assessment (IA) tools is needed [69]. In this respect, van Vuuren [19] discern four levels of interaction, ranging from a simple force-response model to a complex multi-way coupled system. In between the straightforward one-way information exchange and the most complex fully coupled modeling approaches, one can improve ES representation in IA models or vice versa. A priori, an assessment of the expected significance of the considered feedback loops is essential to select the most feasible model coupling strategy. Our feedback diagram is a useful conceptual framework to explore the degree to which a topic of interest needs to be addressed using highly integrated or loosely coupled modeling systems.

For the hotspots selected in this paper, different levels of model integration are suitable to study the issue in more detail. To explore whether policies like the promotion of reforestation mitigate the effects of heat waves in Europe, an intermediate integration level (improvement of socio-economic representation in ES models) is required. The Biogeophysical effects of the LULCC have a clear potential to change the regional heat wave climatology, but the feedback of this effect on the LULCC can be represent by offline coupling of a vegetation model and a climate model (Figure 4). The Amazon region is a complex case. Land-use changes are highly related to policy making and the (global) market for food and fuel. In addition, land-use changes in the Amazon have a large impact on the regional climate via the hydrological cycle, and they play an important role in the global carbon cycle and therefore in the global climate (Figure 5). Hence, in this case a fully coupled ES-IA approach is probably required. In the case of India, the problem can be strongly confined to the domain of the physical interactions and feedbacks. A relatively simple interaction level is sufficient to evaluate land requirements for future agricultural production, and treat LULCC as a boundary condition in the physical modeling framework. However, the feedbacks between irrigation and changes in the monsoon patterns do require a higher level of integration (Figure 6).

Summary and Conclusions

We briefly reviewed a number of major terrestrial ecosystems processes and feedbacks in the climate system, and outlined them in the form of a conceptual framework. This framework is used as a tool to explore and illustrate potential feedbacks at the regional scale. We selected Europe, the Amazon Basin and India as case studies, since noticeable changes in climate and land use are projected in these regions.

In Europe, land surface changes interact with the local climate leading to pronounced feedbacks both in winter (due to surface – albedo interactions) and summer (when positive soil moisture-temperature feedbacks can be triggered). In the Amazon Basin, positive soil moisture-precipitation feedback can play an important role in the length of the dry season and precipitation variability in the Amazon Basin. Forest dieback, induced by reduced precipitation in the future, can reinforce this positive feedback. In India, the effect of irrigation on the atmosphere is dependent on the season and on the spatial scale. While positive soil moisture-precipitation feedback is considered to be positive at the local-regional scale in transitional seasons, it can be slightly negative at larger scales.

This short list of findings reported in this paper illustrates the complexity that is needed to explore feedbacks systematically. Multiple feedbacks operate in parallel at multiple spatial and temporal scales, or can compensate responses that occurred during earlier episodes. Therefore, feedback analysis requires a clear conceptual picture of the process chain that is of interest, and a clear experimental design that is needed to establish the sign and size of the feedback under concern. Some of the feedbacks illustrated in this paper may turn out to be relatively weak or dominated by drivers not explicitly included in the analysis. Our feedback diagram may help to form this conceptual picture, and guide further experimental design in which the integration of modeling tools representing different realms of the complex climate – human dimension system needs to be optimized. It thus helps to guide an adequate model design where the applied level of complexity is justified by the process chain under consideration.

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