

This discussion paper is/has been under review for the journal Earth System Dynamics (ESD). Please refer to the corresponding final paper in ESD if available.

Regional feedbacks under changing climate and land-use conditions

L. Batlle Bayer¹, B. J. J. M. van den Hurk^{1,2}, B. J. Strengers³, and J. G. van Minnen³

¹IMAU – Institute for Marine and Atmospheric research Utrecht, Utrecht University, The Netherlands

²KNMI – Royal Netherlands Meteorological Institute, De Bilt, The Netherlands

³PBL – Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands

Received: 29 February 2012 – Accepted: 8 March 2012 – Published: 2 April 2012

Correspondence to: L. Batlle Bayer (l.batllebayer@uu.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

201

Abstract

Ecosystem responses to a changing climate and human-induced climate forcings (e.g. deforestation) might amplify (positive feedback) or dampen (negative feedback) the initial climate response. Feedbacks may include the biogeochemical (e.g. carbon cycle) and biogeophysical feedbacks (e.g. albedo and hydrological cycle). Here, we first review the most important feedbacks and put them into the context of a conceptual framework, including the major processes and interactions between terrestrial ecosystems and climate. We explore potential regional feedbacks in four hot spots with pronounced potential changes in land-use/management and local climate: sub-Saharan Africa (SSA), Europe, the Amazon Basin and South and Southeast Asia. For each region, the relevant human-induced climate forcings and feedbacks were identified based on published literature.

When evapotranspiration is limited by a soil water deficit, heat waves in Europe are amplified (positive soil moisture-temperature feedback). Drought events in the Amazon lead to further rainfall reduction when water recycling processes are affected (positive soil moisture-precipitation feedback). In SSA, the adoption of irrigation in the commonly rainfed systems can modulate the negative soil moisture-temperature feedback. In contrast, future water shortage in South and Southeast Asia can turn the negative soil moisture-temperature feedback into a positive one.

Further research including advanced modeling strategies is needed to isolate the dominant processes affecting the strength and sign of the feedbacks. In addition, the socio-economic dimension needs to be considered in the ecosystems-climate system to include the essential role of human decisions on land-use and land-cover change (LULCC). In this context, enhanced integration between Earth System (ES) and Integrated Assessment (IA) modeling communities is strongly recommended.

202

1 Introduction

Terrestrial ecosystems account for large carbon stocks and explain large fractions of the variance of carbon exchange between the atmosphere and land surface. In addition, vegetation governs physical properties of the land surface (e.g. albedo, rooting depth and roughness) that affect water and energy exchange with the atmosphere. Vegetation controls the surface energy partitioning, distributing net radiation over sensible and latent heat, which affects surface temperature and evapotranspiration. Human-induced land-use/land-cover change (LULCC) has the effect of a (regional) climate forcing by modifying land properties and the carbon cycle (de Noblet-Decoudré et al., 2012).

The response of terrestrial ecosystems to these anthropogenically-induced climate forcings can positively or negatively feed back to the climate system, and thus magnify or reduce the initial perturbation (Field et al., 2007; Chapin et al., 2008; Arneeth et al., 2010). Global modeling studies show a net positive carbon-climate feedback on surface temperature and atmospheric CO₂-levels (Cox et al., 2000; Dufresne et al., 2002; Friedlingstein et al., 2006). However, these projections are still uncertain due to the complexity of the involved processes in the carbon-climate feedback loops (Meir et al., 2006; Heimann and Reichstein, 2008; Luo et al., 2009; Friedlingstein and Prentice, 2010). While biogeophysical feedbacks (albedo and water cycle) show a global negative feedback (cooling effect), they are relatively more significant at the regional scale. Their sign varies among regions (Bonan, 2008; Davin and de Noblet-Ducoudré, 2010), with a usually cooling effect at high latitudes and warming in the tropics, partly related to cloud feedbacks (van der Molen et al., 2011a). However, mutual agreement among models to evaluate biogeophysical impacts of human-induced land-cover change is small (Pitman et al., 2009).

In this paper we explore potential feedback mechanisms at the regional scale as a result of land-use change and a changing climate. After a brief review of the main feedbacks (Sect. 2.1), a conceptual framework is presented (Sect. 2.2). This is used to

203

illustrate and discuss the potential feedbacks in four regional hotspots (Sect. 3). Finally, conclusions are given (Sect. 4), as well as recommendations for further research.

2 Terrestrial ecosystems – climate feedbacks in a conceptual framework

2.1 Overview of the main feedbacks

2.1.1 Global carbon cycle – climate feedbacks

Vegetation sequesters atmospheric carbon dioxide (CO₂) via photosynthesis, known as Gross Primary Production (GPP) at the ecosystem level (Fig. 1). Part of the sequestered carbon is released through respiration for plant growth and maintenance (autotrophic respiration, R_A). The difference between GPP and R_A is the net gain of carbon by plants, the Net Primary Production (NPP). Part of this sequestered carbon is released back to the atmosphere through organic matter decomposition by soil biota (heterotrophic respiration, R_H). The net carbon uptake by an ecosystem, being the balance between NPP and R_H , is known as the Net Ecosystem Exchange (NEE). Furthermore, disturbances from both natural (e.g. fires) and anthropogenic (e.g. deforestation) sources imply a CO₂ source to the atmosphere. When also accounting for these disturbances, the total carbon flux is called Net Biome Productivity (NBP). When NPP exceeds the sum of disturbances and R_H , NBP is positive, implying a net carbon uptake by an ecosystem.

Current research on interactions between the carbon balance of terrestrial ecosystems and climate focuses on the capability of plants to enhance photosynthesis due to enriched atmospheric CO₂, and the sensitivity of all relevant carbon fluxes to the increasing temperature and changing moisture conditions. Enhancing photosynthesis – and thus plant growth – in response to elevated atmospheric CO₂-levels implies a negative feedback on CO₂-perturbations. This photosynthesis response to increasing CO₂-levels varies across plant types, such as between C₃ and C₄ (greater for C₃ grasses than for C₄ under a doubled CO₂ enrichment; Wand et al., 1999). Furthermore,

204

water-use efficiency (WUE; ratio of carbon fixation to water loss) is also enhanced under enhanced CO₂-levels since it tends to reduce the stomatal opening to reduce water losses. In water-limited systems, this indirect stomatal effect can be as important as the direct effect of CO₂ fertilization (Campbell et al., 2000). However, enhancement of carbon fixation by terrestrial ecosystems might be restricted by Nitrogen (N) availability (Norby et al., 2005, 2010; Arneeth et al., 2010).

The response of GPP to warming is usually positive at low temperatures and reduces at higher temperatures. The rising projected temperatures may also enhance soil respiration, the second-largest carbon flux from the surface to the atmosphere. However, this response is highly uncertain since the dynamics and processes of this carbon flux are still not fully understood (Bond-Lamberty et al., 2004; Davidson and Janssen, 2006; Friedlingstein et al., 2006). Nevertheless, recent studies at the global scale showed a positive correlation between soil respiration and temperature anomalies (Bond-Lamberty and Thomson, 2010), and a global increase of soil respiration (a positive feedback) with rising temperature (Wei et al., 2010).

At the global scale, NPP is about 60 PgC yr⁻¹, and an annual increase of about 0.15–0.40 % yr⁻¹ is estimated over the past 3 decades (Ito and Sasai, 2006; Piao et al., 2009; Pan et al., 2011). CO₂ fertilization, N deposition, forest regrowth and warming are considered to be related to the increased NPP at high latitudes, while the CO₂ fertilization component dominates the enhanced NPP in the tropics. Higher solar radiation due to reduced cloud cover are found to enhance NPP in the Amazon (Nemani et al., 2003). Although global warming might enhance primary productivity in temperate regions, the anticipated increase in the frequency of droughts and heat waves is expected to negatively affect the terrestrial carbon cycle (van der Molen et al., 2011b), which can lead to a positive feedback. For example, the August 2003 heat wave in Europe was recorded as the lowest productivity level in the last century (Ciais et al., 2005). In the tropics, warm and dry periods during El Niño/Southern Oscillation (ENSO) years also showed a net release of carbon to the atmosphere. In addition, a major concern is the vulnerability of tropical forests to more frequent droughts and land-use changes.

2.1.2 Hydrological cycle feedbacks

Energy absorbed by ecosystems is partitioned into latent heat (cooling the surface) and sensible heat rising the air temperature immediately above the surface. The exchange of energy and water between the land surface and the atmosphere is affected by the ecosystem type, as shown by da Rocha et al. (2009) along a biome gradient from savannas to tropical forest in Brazil. Comparing forest, transition forest and savannas, a clear difference in evaporation rates (4, 2.5 and 1 mm d⁻¹, respectively), annual rainfall (higher in forested areas) and the length of the dry season (longer in savanna regions) were reported.

Soil moisture plays an important role. In soil moisture controlled evaporation regimes, reduction of soil moisture decreases evapotranspiration and increases sensible heat, which further increases evapotranspiration and thus reduces soil moisture via a positive soil moisture – temperature feedback loop (Seneviratne et al., 2010). The relationship between soil moisture and evapotranspiration depends on the climate regime (Koster et al., 2004; Seneviratne et al., 2006). In dry regions, evapotranspiration is highly sensitive to soil moisture, while in wetter regions it depends on the net radiative energy. In this context, da Rocha et al. (2009) highlighted that seasonal evaporation patterns in forests are controlled by the atmospheric evaporative demand, while evaporation rates in savannas are restricted by soil moisture availability. Seneviratne et al. (2010) argue that a positive correlation between soil moisture and evaporation (pointing at soil water controlled evaporation) is particularly significant in transitional regions between dry and wet climate regimes. Under conditions where evapotranspiration also affects precipitation, a so-called soil moisture-precipitation feedback can be established. For instance, model studies in which moist tropical savannas were converted into grasslands, a decrease of annual precipitation and a longer dry season by declining frequencies of rainfall at the beginning and end of the wet season were simulated (Hoffmann and Jackson, 2000). However, the sign of the interaction between evapotranspiration-precipitation and the resulting feedback are still uncertain and vary widely (Seneviratne et al., 2010).

Land-use such as agriculture plays a significant role in land-atmosphere interactions, particularly in hydrological systems with extensive irrigation. Puma and Cook (2010) evaluated the global impact of observed irrigation changes in the 20th century. Evapotranspiration was strongly increased with irrigation, especially in the Indian region, while evaporation change in China's irrigation area was small due to energy limitation. Regions with high irrigation had a cooling of about 1–2 K, with the largest cooling (~ 3 K) in the northwest of the Indian subcontinent. However, a warming effect was shown in eastern India due to a weakening monsoon, which caused a decrease of soil moisture and enhanced sensible heat flux. The increasing irrigation in the Sahel region also showed a rise of cloud cover and precipitation. Although a cooling effect due to irrigation has been found at the regional scale, no detectable effect on global mean temperature has been reported (Sacks et al., 2009).

2.1.3 Vegetation cover-albedo feedback

Surface albedo (the fraction of incident solar radiation reflected by the surface) is a function of the vegetation coverage, and thus related to ecosystem dynamics and processes, which in turn are affected by global warming or enriched CO_2 levels. Changes in surface albedo alter the energy and water balances through changes in net surface radiation. For instance, the increase of vegetation cover in the boreal region decreases surface albedo and therefore increases available surface energy. This enhances transpiration, which may lead to greater precipitation in summer and lower snow cover in late spring/early summer. Subtropical regions might also show a positive vegetation cover-albedo feedback as a result of climate change. With a fully coupled model, Zeng and Yoon (2009) explored the effect of this feedback to world's increasing desert in 2100. The expansion of desert increased from 10 % to 34 % when the vegetation cover-albedo feedback was considered.

Surface albedo change is the most significant driver of deforestation-induced climate change (Berbet and Costa, 2003). Simulation experiments of deforestation in boreal regions with global circulation models (GCM) coupled to a dynamic global vegetation

207

model (DGVM) have reported a cooling effect due to increased albedo, reduced sensible heating and a longer snow season (Bonan et al., 1992; Snyder et al., 2004; Cook et al., 2008; Notaro and Liu, 2008). Conversely, deforestation in tropical regions shows less cooling, or even warming. The warming effect of reduced cloudiness, resulting from decreased evapotranspiration, might nearly offset the cooling of increasing albedo due to deforestation (Bala et al., 2007; van der Molen et al., 2011a).

2.2 The conceptual framework of responses and feedbacks

Forcings, interactions and processes that control terrestrial ecosystems-climate feedbacks are summarized in a conceptual framework (Fig. 2). Arrows connect system components, and closed loops between components represent feedbacks. Red arrows with a (+) sign imply that an increase of A will increase B or vice versa; green arrows with a (–) sign imply the reverse response; and double colored arrows with a (\pm) sign imply a response that can be either positive or negative. The product of all processes in a closed loop determines the overall sign of the feedback. Feedback loops are assumed to represent processes at a comparable spatial and temporal scale. Some feedbacks reflect regional processes during specific episodes (such as droughts), while others reflect the entire global carbon-climate system.

In the diagram shown in Fig. 2, changes in atmospheric CO_2 are induced by fossil fuel combustion, deforestation and net carbon uptake from terrestrial ecosystems. Higher atmospheric CO_2 increases carbon sequestration via photosynthesis (GPP), which in turn reduces atmospheric CO_2 . In addition, CO_2 enrichment reduces stomatal conductance, which reduces water losses via evapotranspiration (ET) while maintaining carbon sequestration. This combination implies an increasing WUE (= GPP/ET).

Temperature affects both GPP and ecosystem respiration (R_A and R_H). The response of GPP to temperature can be either positive or negative, since it increases at low temperatures and it usually decreases at high temperatures. Ecosystem respiration is positively stimulated by higher temperature and is also highly related to GPP. The net effect of the feedback depends on which temperature response will be dominant. If

208

term (Fig. 4a) and the long run (Fig. 4b) are enhanced and a positive feedback to the initial greenhouse forcing may take place. However, the sign of this feedback will depend on the adoption of agro-technologies and crop selection, the responses of crops to increasing temperature, the food demand and the relative role of the local carbon balance in the global carbon cycle.

Soil moisture is a major limiting factor for crop production in SSA. Crop failures are in this region highly correlated to drought events (Rojas et al., 2011), which are projected to become more frequent. Figure 4c shows the positive soil moisture-temperature feedback during a drought event. Soil water deficit reduces evapotranspiration, which positively feeds back to the increasing surface temperature. Crop productivity will depend on agricultural management, and irrigation is an important factor for increasing crop yields. If policies promote agricultural management such as irrigation, these will feed back negatively by reducing surface temperature due to increased evapotranspiration. However, limited availability of water resources can provide a serious constraint. Crop selection is an important means for adapting to a changing climate, which may be regulated by policy measures for specific regions and adequate crop and soil management.

3.2 Heat waves and vegetation feedbacks in European ecosystems

Increasing interannual variability of summer climate in Europe (Seneviratne et al., 2006) is expected to increase the frequency of heat waves, usually linked to prolonged anticyclonic circulation anomalies. Land – atmosphere interactions played an important role in the 2003 heat wave (Fischer et al., 2007b). A low precipitation anomaly in winter and spring is shown to be related to warm summers during various years in Europe (Vautard et al., 2007). Fischer et al. (2007a) illustrated the importance of land-atmosphere interactions by comparing coupled and uncoupled (prescribed soil moisture) land surface representations in a regional climate model. For a selection of heat waves (1976, 2003 and 2005), land-atmosphere interactions amplified precipitation anomalies four months before the particular event and increased evaporation during

211

spring, which increased daily temperature extremes for the hottest days in summer and augmented heat wave duration. The surface response to heat waves, is sensitive to the type of land-cover (Teuling et al., 2010). 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 a cooler environment than forests. For prolonged dry conditions, the resulting depletion of soil moisture eventually led to a reduction of latent heat flux and enhanced surface heating compared to forests. Forest areas tend to reduce water losses during a heat wave and prevent heat wave intensification in the long term. Figure 5a depicts the positive soil moisture – temperature feedback in ecosystems during a heat wave.

Future hot spots of biophysical vegetation feedbacks in European forest areas were analyzed with the DGVM LPJ-GUESS by Wramneby et al. (2010). These hot spots were diagnosed by mapping the different greenhouse scenario response between regional climate model simulations with and without interactive vegetation responses. A negative cooling feedback was found in central Europe, where CO₂ fertilization promoted plant growth and thus increased evapotranspiration. Scandinavian Mountains exposed a positive warming feedback due to the increased forest area extent and the reduced snow cover leading to a decrease of surface albedo (Fig. 5b). Drier summers in southern Europe showed a positive feedback by reduction of evapotranspiration due to decreased plant growth.

3.3 Droughts and deforestation in the Amazon basin

The Amazon has been warming at a rate of 0.25 °C per decade in the past decades and a mean increase of 3.3 °C is projected for the 21st century (Malhi et al., 2008). A decline of precipitation by 0.32 % yr⁻¹ between 1970 and 1999 has been reported in the southern Amazon (Li et al., 2008). Rainfall anomalies and the length of dry seasons in the Amazon are causally related to the local evapotranspiration, and to the sea surface

212

temperature (SST) of the Pacific and Atlantic Oceans. SST variability explains about half of the rainfall variability in the Amazon (Zeng et al., 2008), while about 50 % of the rainfall in the Amazon is provided by water vapor originating from local sources (Li et al., 2006). Surface evaporation is the main source of moisture in the dry and early transition period (between dry and wet seasons) in the Amazon (Li et al., 2006; Li and Fu, 2004).

Land surface characteristics can contribute significantly to the interannual variability of the wet season onset (Fu and Li, 2004). Deforestation may reduce soil moisture, delay the transition period and therefore prolong the dry season. Costa et al. (2007) highlighted the effect of deforestation on increasing surface albedo and consequent reduction of evapotranspiration, which was well correlated to declined precipitation. This feedback loop was also confirmed by Sampaio et al. (2007), who projected an increase of surface temperature, and a decrease of evapotranspiration and precipitation in eastern Amazonia, especially during the dry season. Moreover, Amazon deforestation might enhance ENSO over the Pacific and thus induce greater reductions of rainfall (positive feedback) as reported by Nobre et al. (2009).

More frequent, extended and severe droughts are projected in the Amazon Basin for this century (Li et al., 2006). The ENSO-related droughts (e.g. 1982/1983 and 1997/1998) particularly concern the northern and northeastern regions. However, the intense drought in 2005, associated to anomalously warm tropical North Atlantic SSTs, highly affected the southern and southwestern regions, especially in the dry season. The 2005 drought was reported as a one-in-a hundred year event (Marengo et al., 2008). However, a more severe drought during the dry season in 2010 occurred (Lewis et al., 2011), which could be related again to the high Atlantic SST. Biomass and NPP might be reduced by increasing drought event frequency in the Amazon (Samanta et al., 2010; Xu et al., 2011). The large contribution of the Amazon to the global NPP (4–6 PgC yr⁻¹; Poulter et al., 2010) may imply a positive feedback to the global climate system. During the 2005 drought, aboveground biomass of the Amazon forests was reduced by 1.2–1.6 PgC (Phillips et al., 2009), showing the significant vulnerability of

213

the Amazon forests to droughts. Two intense droughts in a decade might offset the net gains of an undisturbed Amazon forest (Lewis et al., 2011) and an increased frequency of these events could lead to forest dieback (negative NPP) or savannization (Nobre and Borma, 2009; Sampaio et al., 2007), especially over eastern and southeastern Amazonia (Salazar et al., 2007).

Several studies have evaluated the dynamics of the Amazon forests and biome shifts under a changing climate, which might feed back to the climate system. Oyama and Nobre (2003) reported a second climate-vegetation equilibrium in the Brazilian Amazon with tropical savannas replacing forests in a large area of the Amazon Basin. Malhi et al. (2009) suggested that seasonal and deciduous forests in the eastern Amazon could replace current vegetation. Nobre and Borma (2009) discussed thresholds that could cause the Amazon forest to switch to a stable savanna equilibrium, and concluded two main tipping points for the Amazon forest: 40 % of cleared Amazon forest and a temperature increase greater than 3–4 K.

The feedbacks related to deforestation in the Amazon are depicted in Fig. 6a. The increase of albedo and associated reduction of precipitation and evapotranspiration increases drying. This possibly reduces vegetation cover, implying a positive feedback to the initial forcing (forest reduction). Lapola et al. (2009) evaluated negative feedbacks of CO₂ fertilization in several future climate and CO₂ fertilization scenarios with a potential vegetation model. They reported a drier climate and a biome shift in response to elevated CO₂-concentrations when no CO₂ fertilization effect was considered. Conversely, a wetter climate and no changes in forest dynamics were simulated when including the CO₂ fertilization. Nevertheless, a biome shift towards tropical savanna was projected if the dry season would systematically be longer than 4 months.

Betts et al. (2004) evaluated the influence of forcing and feedback mechanisms leading to reduced rainfall (from 5 mm day⁻¹ in 2000 to 2 mm day⁻¹ in 2100) and forest dieback (mean broadleaf tree coverage from 80 % in 2000 to less than 10 % in 2100) in their scenario calculations with a coupled ocean-atmospheric GCM. Stomatal closure contributed 20 % to the decreased precipitation. Moreover, forest dieback reduced

214

evaporation (positive biogeophysical feedback) and carbon sequestration (positive biogeochemical feedback), which caused 20 % and 5 % reduction of precipitation, respectively. Both feedback mechanisms are represented in Fig. 6b: (a) the effect of stomatal conductance to the soil moisture feedback, and (b) the reduction of evaporative water recycling due to forest cover decline.

3.4 Irrigation in South and Southeast Asia

South and Southeast Asia, together with East Asia, are known as the monsoon Asia, where half of the world's population lives. Agricultural production depends on monsoon rainfall during the summer season (June–August). However, technological innovation and irrigation expansion in the 1960s permitted to both reduce potential water deficit in the monsoon season, and to allow a second crop in agricultural systems during the dry season. India and Southeast Asia together use more than half of the global irrigation (Sacks et al., 2009). Pakistan and Bangladesh have the highest percentage of irrigation in arable land (83 % and 56 %, respectively), and 35.4 % of the arable land in India (about 1.6 million km², the greatest in South Asia) is under irrigation (Alauddin and Quiggin, 2008). Furthermore, Bangladesh has the highest level of irrigation intensity due to irrigation in the dry season. However, Southeast Asia already faces water supply shortage and Sri Lanka is the only country in South Asia with little or no scarcity (Chuan, 2003). Water shortage might induce a positive feedback as shown in Fig. 7a. Less water availability reduces soil moisture, which affects crop productivity. This will reduce evapotranspiration and thus increase surface temperature, which would intensify evapotranspiration and further reduce soil moisture. More irrigation is needed to keep crop production at a sufficient level.

Human-induced deforestation for agricultural expansion might affect monsoon patterns, as shown by Fu (2003) who reported an increase of winter monsoon and a weaker summer monsoon in East Asia due to LULCC. By using an atmospheric GCM, Takata et al. (2009) also found decreases of monsoon precipitation and the related

215

weakening of Asian summer monsoon circulation between 1700 and 1850, especially over South and Southeast Asia. However, the impact of irrigation on rain patterns in the Indian monsoon region might be greater than LULCC, as stated by Douglas et al. (2009). Irrigation increases soil moisture and thus latent heat flux, which in turn reduces surface temperature and changes regional circulation patterns and precipitation. Douglas et al. (2006) reported a mean annual increase of 17 % of evapotranspiration from pre-agricultural to current land-cover, particularly in the dry season (January–May). About 65 % of this enhancement was explained by irrigation. The greatest increases in India were found in irrigated areas, especially in the dry northern and central-northern regions. Lee et al. (2009) also reported that the increase of latent heat flux in the pre-monsoon season between 1982 and 2003 – related to irrigation and LULCC – reduced surface temperature in July. This decreased land-sea temperature gradient weakened the early monsoon strength.

4 Summary and conclusions

In this review study, the strength of terrestrial ecosystem-climate feedbacks at the regional and global level was explored. We identified four hot spots with ongoing or projected changes in land-use or management and in climate: sub-Saharan Africa (SSA), Europe, the Amazon Basin and South and Southeast Asia. We applied a conceptual framework (Fig. 2) as a tool to explore potential regional feedbacks. The diverse climatic, ecologic and socio-economic conditions led to different feedbacks among the hot spots.

In Europe, the high surface temperatures during a heat wave causes a soil water deficit, which reduces evapotranspiration and consequently further raises surface temperatures (positive soil moisture-temperature feedback). Conversely, during drought events in the Amazon, soil moisture-precipitation feedback dominates; soil moisture further declines due to reduced water recycling. Additionally, this feedback may result

216

in forest dieback and carbon emissions, which also have an impact on the global climate. Human-induced land-use changes (deforestation) in the Amazon also influence ecosystem dynamics and initiate a positive vegetation albedo feedback through further declining vegetation cover due to its impact on the water balance.

5 Irrigation is essential for agriculture to adapt to changes in rainfall patterns and drought events, and it plays an important role in different feedbacks. In SSA, where agriculture is almost exclusively rainfed, investment in irrigation has high potential (de Fraiture and Wichelns, 2010). More frequent use of irrigation can have a local cooling effect due to enhanced evapotranspiration, leading to a negative soil moisture-
10 temperature feedback. In contrast, South and Southeast Asian agriculture is largely irrigation based, and more frequent water shortage, due to further water use, will lead to a positive soil moisture-temperature feedback. Deforestation and irrigation can also enhance changes in the Asian monsoon patterns. Irrigation increases latent heat flux in the pre-monsoon season. The subsequent surface temperature reduction, and thus
15 the decrease in land-sea temperature gradient, changes regional circulation patterns and consequently the early monsoon becomes weaker (Lee et al., 2009). Furthermore, Gordon et al. (2005) reported that projected extended deforestation in SSA changed the hydrological cycle, including enhanced changes in the Asian monsoon patterns. Thus enhanced food production in one region potentially leads to changes in the production in other areas.

20 Also global feedbacks, such as the carbon cycle-climate feedback, can be explored with the conceptual framework. Furthermore, if the local or regional cooling effect of irrigation has a signal on the global mean temperature, the feedback attains a global scope. For each hotspot, the ultimate sign of a feedback relies on the individual processes in the feedback chain. Further research is needed to gain confidence in the
25 way the balance between processes may affect the ultimate feedback sign.

The framework also gives a conceptual representation of the effect of human activities (e.g. irrigation and land-use change) in the ecosystems-climate system. Changes in land-use and crop production are based on human decisions, which depend on

demographic, socio-economic and environmental factors. Although several attempts to integrate this socio-economic dimension in Earth System Models, the representation of these feedbacks remains a big challenge (Chapin et al., 2008).

5 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 (Hibbard et al., 2010). In this respect, van Vuuren et al. (2012) discern four levels of interaction, ranging from a simple force-response to a complex coupled system. These interactions can be examined in collaboration studies involving coupled ES and IA models, where the degree of required coupling depends on the type of interaction considered. In between
10 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 feedback strength is essential to select the most feasible model coupling strategy.

15 Based on these four levels of interactions, different approaches are suggested for the hotspots selected in this paper. For SSA, an intermediate approach is sufficient by improving the representation of the climate system in an IA model. The system dynamics are dominated by socio-economical developments (such as food demand and agro-technology) and a fairly crude representation of the interaction with the climate system is appropriate. However, if due to for instance unexpected non-linear responses the local feedback turns out to be strong, a fully coupled system must be considered. For the European heat wave case, if policies like the promotion of reforestation are added, an intermediate integration level (improvement of socio-economic representation in ES model) is required. The Amazon region is a complex case. Land-use changes are highly related to policymaking and global food trade. In addition,
20 Amazon land-use changes 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. Hence, a fully coupled ES-IA approach is needed. In the case of South and South East Asia, the simplest interaction level is adequate to evaluate

land requirements for future agricultural production. However, the feedbacks between irrigation and changes in the monsoon patterns do require a high level of integration.

Acknowledgements. The research was funded by the Netherlands Organisation for Scientific Research (NWO). The project is coordinated by Wilco Hazeleger (KNMI).

5 References

- Alauddin, M. and Quiggin, J.: Agricultural intensification, irrigation and the environment in South Asia: Issues and policy options, *Ecol. Econ.*, 65, 111–124, doi:10.1016/j.ecolecon.2007.06.004, 2008.
- Arneth, A., Harrison, S. P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P. J., Feichter, J., Korhola, A., Kulmala, M., O'donnell, D., Schurgers, G., Sorvari, S., and Vesala, T.: Terrestrial biogeochemical feedbacks in the climate system, *Nat. Geosci.*, 3, 525–532, doi:10.1038/NGEO905, 2010.
- Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., and Mirin, A.: Combined climate and carbon-cycle effects of large-scale deforestation, *Proc. Natl. Acad. Sci.*, 104, 6550–6555, doi:10.1073/pnas.0608998104, 2007.
- Berbet, M. and Costa, H.: Climate Change after Tropical Deforestation?: Seasonal Variability of Surface Albedo and Its Effects on Precipitation Change, *J. Climate*, 16, 2099–2104, doi:10.1175/1520-0442(2003)016<2099:CCATDS>2.0.CO;2, 2003.
- Betts, R. A., Cox, P. M., Collins, M., Harris, P. P., Huntingford, C., and Jones, C. D.: The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming, *Theor. Appl. Climatol.*, 78, 157–175, doi:10.1007/s00704-004-0050-y, 2004.
- Bonan, G. B.: Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests, *Science*, 320, 1444–1449, doi:10.1126/science.1155121, 2008.
- Bonan, G. B., Pollard, D., and Thompson, S. L.: Effects of boreal forest vegetation on global climate, *Nature*, 359, 716–718, doi:10.1038/359716a0, 1992.
- Bond-Lamberty, B. and Thomson, A.: A global database of soil respiration data, *Biogeosciences*, 7, 1915–1926, doi:10.5194/bg-7-1915-2010, 2010.
- Bond-Lamberty, B., Wang, C., and Gower, S. T.: A global relationship between the heterotrophic and autotrophic components of soil respiration?, *Global Change Biol.*, 10, 1756–1766, doi:10.1111/j.1365-2486.2004.00816.x, 2004.
- Campbell, B. and Stafford Smith, D.: A synthesis of recent global change research on pasture and rangeland production: reduced uncertainties and their management implications, *Agr. ecosyst. environ.*, 82, 39–55, doi:10.1016/S0167-8809(00)00215-2, 2000.
- Chapin, F. S., Randerson, J. T., McGuire, A. D., Foley, J. A., and Field, C. B.: Changing feedbacks in the climate–biosphere system, *Front. Ecol. Environ.*, 6, 313–320, doi:10.1890/080005, 2008.
- Chuan, G. K.: Hydrological studies and water resource concerns in Southeast Asia, Singapore *J. Trop. Geo.*, 24, 86–110, doi:10.1111/1467-9493.00145, 2003.
- Ciais, Ph, Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, Chr., Carrara, F., Chevallier A., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T., and Valentini, R.: Europe-wide reduction in primary productivity caused by the heat and drought in 2003, *Nature*, 437, 529–533, doi:10.1038/nature03972, 2005.
- Cook, B. I., Bonan, G. B., Levis, S., and Epstein, H. E.: Rapid vegetation responses and feedbacks amplify climate model response to snow cover changes, *Clim. Dynam.*, 30, 391–406, doi:10.1007/s00382-007-0296-z, 2008.
- Costa, M. H., Yanagi, S. N. M., Souza, P. J. O. P., Ribeiro, A., and Rocha, E. J. P.: Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophys. Res. Lett.*, 34, L07706, doi:10.1029/2007GL029271, 2007.
- Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature*, 408, 184–187, doi:10.1038/35041539, 2000.
- da Rocha, H. R., Manzi, A. O., Cabral, O. M., Miller, S. D., Goulden, M. L., Saleska, S. R., R.-Coupe, N., Wofsy, S.C., Borma, L. S., Artaxo, P., Vourlitis, G., Nogueira, J. S., Cardoso, F. L., Nobre, A. D., Kruijt, B., Freitas, H. C., von Randow, C., Aguiar, R. G., and Maia, J. F.: Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil, *J. Geophys. Res.*, 114, 1–8, doi:10.1029/2007JG000640, 2007.
- Davidson, E. A. and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, *Nature*, 440, 165–173, doi:10.1038/nature04514, 2006.

- Davin, E. L. and de Noblet-Ducoudré, N.: Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes, *J. Climate*, 23, 97–112, doi:10.1175/2009JCLI3102.1, 2010.
- de Fraiture, C. and Wichelns, D.: Satisfying future water demands for agriculture, *Agr. Water Manage.*, 97, 502–511, doi:10.1016/j.agwat.2009.08.008, 2010.
- de Noblet-Decoudré, N., Boisier, J.-P., Pitman, A. J., Bonan, G. B., Browkin, V., Cruz, F., Delire, C., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P. J., van der Molen, M. K., Müller, C., Reick, C. H., Strengers, B. J., and Voldoire, A.: Determining robust impacts of land-use induced land-cover changes on surface climate over North America and Eurasia; results from the first set of LUCID experiments, *J. Climate*, in press, doi:10.1175/JCLI-D-11-00338.1, 2012.
- Douglas, E. M., Beltrán-Przekurat, A., Niyogi, D., Pielke, R. A., and Vörösmarty, C. J.: The impact of agricultural intensification and irrigation on land-atmosphere interactions and Indian monsoon precipitation – A mesoscale modeling perspective, *Global Planet. Change*, 67, 117–128, doi:10.1016/j.gloplacha.2008.12.007, 2009.
- Douglas, E. M., Niyogi, D., Frolking, S., Yeluripati, J. B., Pielke, R. A., Niyogi, N., Vörösmarty, C. J., and Mohanty, U. C.: Changes in moisture and energy fluxes due to agricultural land-use and irrigation in the Indian Monsoon Belt, *Geophys. Res. Lett.*, 33, 1–5, doi:10.1029/2006GL026550, 2006.
- Dufresne, J., Friedlingstein, P., Berthelot, M., Bopp, L., Ciais, P., Fairhead, L., Le Treut, H., and Monfray, P.: On the magnitude of positive feedback between future climate change and the carbon cycle, *Geophys. Res. Lett.*, 29, 1405, doi:10.1029/2001GL013777, 2002.
- Field, C. B., Lobell, D. B., Peters, H.A., and Chiariello, N. R.: Feedbacks of Terrestrial Ecosystems to Climate Change, *Annu. Rev. Env. Resour.*, 32, 1–29, doi:10.1146/annurev.energy.32.053006.141119, 2007.
- Fischer, E. M., Seneviratne, S. I., Lüthi, D., and Schär, C.: Contribution of land-atmosphere coupling to recent European summer heat waves, *Geophys. Res. Lett.*, 34, 1–6, doi:10.1029/2006GL029068, 2007a.
- Fischer, E. M., Seneviratne, S. I., Vidale, P. L., Lüthi, D., and Schär, C.: Soil Moisture–Atmosphere Interactions during the 2003 European Summer Heat Wave, *J. Climate*, 20, 5081–5099, doi:10.1175/JCLI4288.1, 2007b.
- Friedlingstein, P. and Prentice, I. C.: Carbon – climate feedbacks: a review of model and observation based estimates, *Current Opinion in Environmental Sustainability*, 2, 1–7, doi:10.1016/j.cosust.2010.06.002, 2010.

- Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison, *J. Climate*, 19, 3337–3353, doi:http://dx.doi.org/10.1175/JCLI3800.1, 2006.
- Fu, C.: Potential impacts of human-induced land-cover change on East Asia monsoon, *Global Planet. Change*, 37, 219–229, doi:10.1016/S0921-8181(02)00207-2, 2003.
- Fu, R., and Li, W.: The influence of the land surface on the transition from dry to wet season in Amazonia, *Theor. Appl. Climatol.*, 78, 97–110, doi:10.1007/s00704-004-0046-7, 2004.
- Gordon, L. J., Steffen, W., Jönsson, B. F., Folke, C., Falkenmark, M., and Johannessen, Å.: Human modification of global water vapor flows from the land surface, *Proc. Natl. Acad. Sci.*, 102, 7612, doi:10.1073/pnas.0500208102, 2005.
- Heimann, M. and Reichstein, M.: Terrestrial ecosystem carbon dynamics and climate feedbacks, *Nature*, 451, 289–292, doi:10.1038/nature06591, 2008.
- Hoffmann, W. A. and Jackson, R. B.: Vegetation–climate feedbacks in the conversion of tropical savanna to grassland, *J. Climate*, 13, 1593–1602, doi:http://dx.doi.org/10.1175/1520-0442(2000)013<1593:VCFITC>2.0.CO;2, 2000.
- Ito, A. and Sasai, T.: A comparison of simulation results from two terrestrial carbon cycle models using three climate data sets, *Tellus B*, 58, 513–522, doi:10.1111/j.1600-0889.2006.00208.x, 2006.
- Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C.-H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y. and Yamada, T.: Regions of strong coupling between soil moisture and precipitation, *Science (New York, N.Y.)*, 305, 1138–1140, doi:10.1126/science.1100217, 2004.
- Lapola, D. M., Oyama, M. D., and Nobre, C. A.: Exploring the range of climate biome projections for tropical South America: The role of CO₂ fertilization and seasonality, *Global Biogeochem. Cy.*, 23, 1–16, doi:10.1029/2008GB003357, 2009.
- Lee, E., Chase, T. N., Rajagopalan, B., Barry, R. G., Biggs, T. W., and Lawrence, P. J.: Effects of irrigation and vegetation activity on early Indian summer monsoon variability, *Int. J. Climatol.*, 29, 573–581, doi:10.1002/joc.1721, 2009.
- Lewis, S. L., Brando, P. M., Phillips, O. L., van der Heijden, G. M. F., and Nepstad, D.: The 2010

- Amazon drought, *Science*, 331, 554, doi:10.1126/science.1200807, 2011.
- Li, W. and Fu, R.: Transition of the large-scale atmospheric and land surface conditions from the dry to the wet season over Amazonia as diagnosed by the ECMWF re-analysis, *J. Climate*, 17, 2637–2651, doi:10.1175/1520-0442(2004)017<2637:TOTLAA>2.0.CO;2, 2004.
- 5 Li, W., Fu, R., and Dickinson, R. E.: Rainfall and its seasonality over the Amazon in the 21st century as assessed by the coupled models for the IPCC AR4, *J. Geophys. Res.*, 111, 1–14, doi:10.1029/2005JD006355, 2006.
- Li, W., Fu, R., Juárez, R. I. N., and Fernandes, K.: Observed change of the standardized precipitation index, its potential cause and implications to future climate change in the Amazon region, *Phil. Trans. R. Soc.*, 363, 1767–1772, doi:10.1098/rstb.2007.0022, 2008.
- 10 Liu, J., Fritz, S., Vanwesenbeeck, C., Fuchs, M., You, L., Obersteiner, M., and Yang, H.: A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change, *Global Planet. Change*, 64, 222–235, doi:10.1016/j.gloplacha.2008.09.007, 2008.
- 15 Lobell, D. B., Bänziger, M., Magorokosho, C., and Vivek, B.: Nonlinear heat effects on African maize as evidenced by historical yield trials, *Nature Climate Change*, 1, 42–45, doi:10.1038/nclimate1043, 2011.
- Luo, Y., Sherry, R., Zhou, X., and Wan, S.: Terrestrial carbon-cycle feedback to climate warming: experimental evidence on plant regulation and impacts of biofuel feedstock harvest, *GCB Bioenergy*, 1, 62–74, doi:10.1111/j.1757-1707.2008.01005.x, 2009.
- 20 Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., and Nobre, C. A.: Climate change, deforestation, and the fate of the Amazon, *Science (New York, N.Y.)*, 319, 169–72, doi:10.1126/science.1146961, 2008.
- Malhi, Y., Aragão, L. E. O. C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C., and Meir, P.: Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest, *Proc. Natl. Acad. Sci.*, 106, 20610–20615, doi:10.1073/pnas.0804619106, 2009.
- 25 Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., de Oliveira, G. S., de Oliveira, R., Camargo, H., Alves, L. M., and Brown, I. F.: The drought of Amazonia in 2005, *J. Climate*, 21, 495–516, doi:http://dx.doi.org/10.1175/2007JCLI1600.1, 2008.
- 30 Meir, P., Cox, P., and Grace, J.: The influence of terrestrial ecosystems on climate, *Trends Ecol. Evol.*, 21, 254–260, doi:10.1016/j.tree.2006.03.005, 2006.
- Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myeni, R.

- B., and Running, S. W.: Climate-driven increases in global terrestrial net primary production from 1982 to 1999, *Science*, 300, 1560–1563, doi:10.1126/science.1082750, 2003.
- Nobre, C. A. and Borma, L. D. S.: “Tipping points” for the Amazon forest, *Current Opinion in Environmental Sustainability*, 1, 28–36, doi:10.1016/j.cosust.2009.07.003, 2009.
- 5 Nobre, P., Malagutti, M., Urbano, D. F., de Almeida, R. A. F., and Giarolla, E.: Amazon Deforestation and Climate Change in a Coupled Model Simulation, *J. Climate*, 22, 5686–5697, doi:10.1175/2009JCLI2757.1, 2009.
- Norby, R. J., Delucia, E. H., Gielen, B., Calfapietra, C., Giardina, C. P., King, J. S., Ledford, J., McCarthy, H. R., Moore, D. J. P., Ceulemans, R., De Angelis, P., Finzi, A. Z., Karnosky, D. F., Kubiske, M. E., Lukac, M., Pregitzer, K. S., Scarascia-Mugnozza, G. E., Schlesinger, W. H., and Oren, R.: Forest response to elevated CO₂ is conserved across a broad range of productivity, *Proc. Natl. Acad. Sci.*, 102, 18052–18056, doi:10.1073/pnas.0509478102, 2005.
- 10 Norby, R. J., Warren, J. M., Iversen, C. M., Medlyn, B. E., and Mcmurtrie, R. E.: CO₂ enhancement of forest productivity constrained by limited nitrogen availability, *Proc. Natl. Acad. Sci.*, 107, 19368–19373, doi:10.1073/pnas.1006463107, 2010.
- 15 Notaro, M. and Liu, Z.: Statistical and dynamical assessment of vegetation feedbacks on climate over the boreal forest, *Clim. Dynam.*, 31, 691–712, doi:10.1007/s00382-008-0368-8, 2008.
- 20 Oyama, M. D. and Nobre, C. A.: A new climate-vegetation equilibrium state for Tropical South America, *Geophys. Res. Lett.*, 30, 4, doi:10.1029/2003GL018600, 2003.
- Paeth, H., Born, K., Girmes, R., Podzun, R., and Jacob, D.: Regional Climate Change in Tropical and Northern Africa due to Greenhouse Forcing and Land-use Changes, *J. Climate*, 22, 114–132, doi:10.1175/2008JCLI2390.1, 2009.
- 25 Pan, Y., Birdsey, R., Fang, J., Houghton, R., Kauppi, P., Kurz, W., Phillips, O., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., and Hayes, D.: A Large and Persistent Carbon Sink in the World's Forests, *Science*, 333, 988–993, doi:10.1126/science.1201609, 2011.
- 30 Phillips, O. L., Aragão, L. E. O. C., Lewis, S. L., Fisher, J. B., Lloyd, J., López-González, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C. A., van der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T. R., Bánki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., de Oliveira, A. C. A., Cardozo, N. D., Czimczik, C. I., Feldpausch, T. R., Freitas, M. A., Gloor, E., Higuchi, N., Jiménez, E., Lloyd, G., Meir, P., Mendoza, C., Morel, A., Neill, D. A.,

- Nepstad, D., Patiño, S., Peñuela, M. C., Prieto, A., Ramírez, F. Schwarz, M., Silva, J., Silveira, M., Thomas, A. S., ter Steege, H., Stropp, J., Vásquez, R., Zelazowski, P., Dávila, E. A., Andelman, S., Andrade, A., Chao, K.-J., Erwin, T., Di Fiore, A., C., E. H., Keeling, H., Killeen, T. J., Laurance, W. F., Cruz, A. P., Pitman, N. C. A., Vargas, P. N., Ramírez-Angulo, H., Rudas, A., Salamão, R., Silva, N., Terborgh, J., and Torres-Lezama, A.: Drought sensitivity of the Amazon rainforest, *Science*, 323, 1344–1347, doi:10.1126/science.1164033, 2009.
- Piao, S., Ciais, P., Friedlingstein, P., de Noblet-Ducoudré, N., Cadule, P., Viovy, N., and Wang, T.: Spatiotemporal patterns of terrestrial carbon cycle during the 20th century, *Global Biogeochem. Cy.*, 23, 1–16, doi:10.1029/2008GB003339, 2009.
- Pitman, A. J., de Noblet-Ducoudré, N., Cruz, F. T., Davin, E. L., Bonan, G. B., Brovkin, V., Claussen, M., Delire C., Ganzeveld, L., Gayler, V., van den Hurk, B. J. J. M., Lawrence, P. J., van der Molen, M. K., Müller, C., Reick, C. H., Seneviratne, S. I., Strengers, B. J., and Voldoire, A.: Uncertainties in climate responses to past land-use change: First results from the LUCID intercomparison study, *Geophys. Res. Lett.*, 36, 1–6, doi:10.1029/2009GL039076, 2009.
- Poulter, B., Aragão, L., Heyder, U., Gumpenberger, M., Heinke, J., Langerwisch, F., Rammig, A., Thonicke, K., and Cramer, W.: Net biome production of the Amazon Basin in the 21st century, *Global Change Biol.*, 16, 2062–2075. doi:10.1111/j.1365-2486.2009.02064.x, 2010.
- Puma, M. J. and Cook, B. I.: Effects of irrigation on global climate during the 20th century, *J. Geophys. Res.*, 115, 1–15, doi:10.1029/2010JD014122, 2010.
- Rojas, O., Vrieling, A., and Rembold, F.: Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery, *Remote Sen. Environ.*, 115, 343–352, doi:10.1016/j.rse.2010.09.006, 2011.
- Roudier, P., Sultan, B., Quirion, P., and Berg, A.: The impact of future climate change on West African crop yields: What does the recent literature say?, *Global Environmental Change*, 21, 1073–1083, doi:10.1016/j.gloenvcha.2011.04.007, 2011.
- Sacks, W. J., Cook, B. I., Buening, N., Levis, S., and Helkowski, J. H.: Effects of global irrigation on the near-surface climate, *Clim. Dynam.*, 33, 159–175, doi:10.1007/s00382-008-0445-z, 2009.
- Salazar, L. F., Nobre, C. A., and Oyama, M. D.: Climate change consequences on the biome distribution in tropical South America, *Geophys. Res. Lett.*, 34, L09708, doi:10.1029/2007GL029695, 2007.
- Samanta, A., Ganguly, S., Hashimoto, H., Devadiga, S., Vermote, E., Knyazikhin, Y., Nemani,

- R. R., and Myneni, R. B.: Amazon forests did not green-up during the 2005 drought, *Geophys. Res. Lett.*, 37, 1–5, doi:10.1029/2009GL042154, 2010.
- Sampaio, G., Nobre, C., Costa, M. H., Satyamurty, P., Soares-Filho, B. S., and Cardoso, M.: Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion, *Geophys. Res. Lett.*, 34, L17709, doi:10.1029/2007GL030612, 2007.
- Seneviratne, S. I., Lüthi, D., Litschi, M., and Schär, C.: Land-atmosphere coupling and climate change in Europe, *Nature*, 443, 205–209, doi:10.1038/nature05095, 2006.
- Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture – climate interactions in a changing climate: A review, *Earth-Sci. Rev.*, 99, 125–161, doi:10.1016/j.earscirev.2010.02.004, 2010.
- Snyder, P. K., Delire, C., and Foley, J. A.: Evaluating the influence of different vegetation biomes on the global climate, *Clim. Dynam.*, 23, 279–302, doi:10.1007/s00382-004-0430-0, 2004.
- Takata, K., Saito, K., and Yasunari, T.: Changes in the Asian monsoon climate during 1700–1850 induced by preindustrial cultivation, *Proc. Natl. Acad. Sci.*, 106, 9586, doi:10.1073/pnas.0807346106, 2009.
- Teuling, A., Seneviratne, S., Stöckli, R., Reichstein, M., Moors, E., Ciais, P., Luysaert, S., van den Hurk, B. J. J. M., Ammann, C., Bernhofer, C., Dellwik, E., Gianelle, D., Gielen, B., Grunwald, T., Klumpp, K., Montagnani, L., Moureaux, C., Sottocornola, M., and Wohlfahrt, G.: Contrasting response of European forest and grassland energy exchange to heatwaves, *Nat. Geosci.*, 3, 722–727, doi:10.1038/ngeo950, 2010.
- van der Molen, M. K., Dolman, A. J., Ciais, P., Eglin, T., Gobron, N., Law, B. E., Meir, P., Peters, W., Phillips, O. L., Reichstein, M., Chen, T., Dekker, S. C., Doubková, M., Friedl, M. A., Jung, M., van den Hurk, B. J. J. M., de Jeu, R. A. M., Kruijt, B., Ohta, T., Rebel, K. T., Plummer, S., Seneviratne, S. I., Sitch, S., Teuling, A. J., van der Werf, G. R., Wang, G.: Drought and ecosystem carbon cycling, *Agr. Forest Meteorol.*, 151, 765–773, doi:10.1016/j.agrformet.2011.01.018, 2011a.
- van der Molen, M. K., van den Hurk, B. J. J. M., and Hazeleger, W.: A dampened land use change climate response towards the tropics, *Clim. Dynam.*, 37, 2035–2043, doi:10.1007/s00382-011-1018-0, 2011b.
- van Vuuren, Batlle-Bayer L., Chuwah, C., Ganzeveld, L., Hazeleger, W., van den Hurk, B. J. J. M., van Noije, T., O'Neill, B., and Strengers, B. J.: A comprehensive view on climate change: Coupling of Earth System and Integrated Assessment Models, *Environ. Res. Lett.*, submitted, 2012.

- Vautard, R., Yiou, P., D'Andrea, F., de Noblet, N., Viovy, N., Cassou, C., Polcher, J., Ciais, P., Kageyama, M., and Fan, Y.: Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit, *Geophys. Res. Lett.*, 34, 1–5, doi:10.1029/2006GL028001, 2007.
- 5 Wand, S. J. E., Midgley, G. Y. F., Jones, M. H., and Curtis, P. S.: Responses of wild C_4 and C_3 grass (Poaceae) species to elevated atmospheric CO_2 concentration: a meta-analytic test of current theories and perceptions, *Global Change Biol.*, 5, 723–741, doi:10.1046/j.1365-2486.1999.00265.x, 1999.
- 10 Wei, W., Weile, C., and Shaopeng, W.: Forest soil respiration and its heterotrophic and autotrophic components: Global patterns and responses to temperature and precipitation, *Soil Biol. Biochem.*, 42, 1236–1244, doi:10.1016/j.soilbio.2010.04.013, 2010.
- Wramneby, A., Smith, B., and Samuelsson, P.: Hot spots of vegetation-climate feedbacks under future greenhouse forcing in Europe, *J. Geophys. Res.*, 115, 1–12, doi:10.1029/2010JD014307, 2010.
- 15 Xu, L., Samanta, A., Costa, M. H., Ganguly, S., Nemani, R. R., and Myneni, R. B.: Widespread decline in greenness of Amazonian vegetation due to the 2010 drought, *Geophys. Res. Lett.*, 38, 2–5, doi:10.1029/2011GL046824, 2011.
- Zeng, N. and Yoon, J.: Expansion of the world's deserts due to vegetation-albedo feedback under global warming, *Geophys. Res. Lett.*, 36, 5, doi:10.1029/2009GL039699, 2009.
- 20 Zeng, N., Yoon, J. H., Marengo, J. A., Subramaniam, A., Nobre, C. A., and Birkett, C.M.: Causes and impacts of the 2005 Amazon drought, *Environ. Res. Lett.*, 3, 014002, doi:10.1088/1748-9326/3/1/014002, 2008.

227

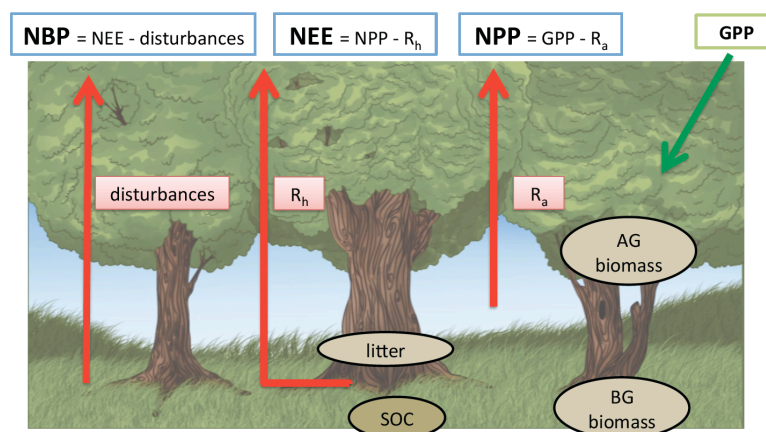


Fig. 1. Carbon stocks (circles) and fluxes (squares) in a terrestrial ecosystem. AG refers to aboveground; BG to belowground; SOC to Soil Organic Carbon; R_A to Autotrophic respiration; R_H to Heterotrophic respiration; NPP to Net Primary Production; NEE to Net Ecosystem Exchange; NBP to Net Biome Production.

228

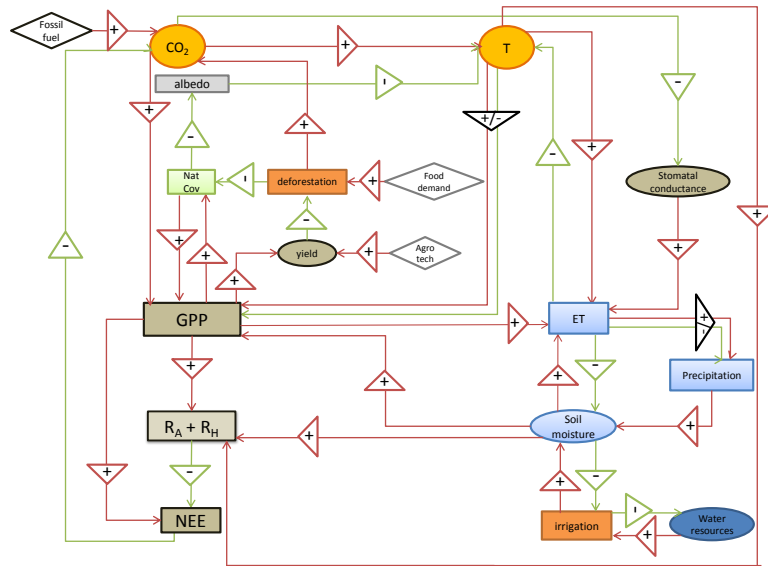


Fig. 2. Conceptual framework of interactions and processes between terrestrial ecosystems and climate. Red arrows mean that an increase (decrease) of a process/state will increase (decrease) another process/state; green arrows imply the reverse response. Circles refer to states, squares to fluxes/processes, triangles to responses and diamonds to external drivers. T refers to temperature; Nat Cov: Natural vegetation cover; GPP to Gross Primary Production; NEE to Net Ecosystem Exchange; R_A to autotrophic respiration; R_H to heterotrophic respiration; ET to evapotranspiration; Agro-tech to agro-technologies.

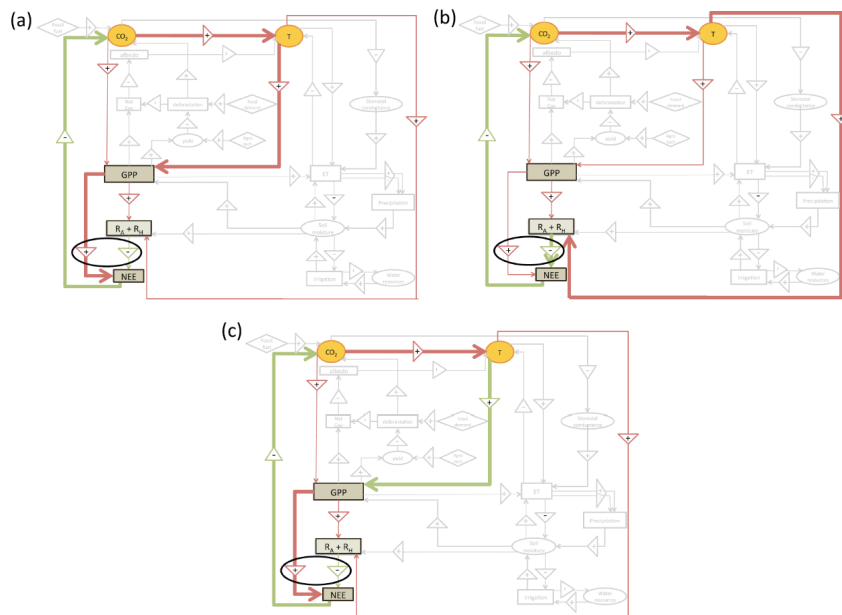


Fig. 3. Explanation of the conceptual framework by depicting possible temperature – carbon cycle feedbacks (thicker arrows make the feedback loops). **(a)** Negative feedback; GPP is more influenced by temperature (T) than ecosystem respiration (R_A , R_H); **(b)** positive feedback; ecosystem respiration is affected more by T ; **(c)** positive feedback; temperature affects negatively to GPP.

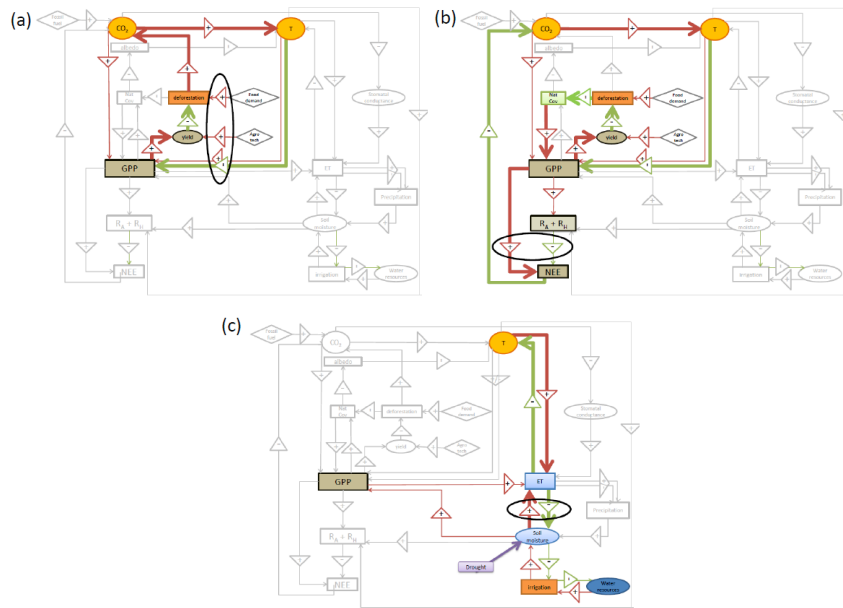


Fig. 4. (a, b) Positive carbon cycle – temperature feedbacks, when considering a negative impact of increasing temperature on crop yields, greater deforestation and low levels of adoption of agrotechnologies in SSA (c) Positive soil moisture-temperature feedback during a drought event. Purple arrow represents the climate forcing.

231

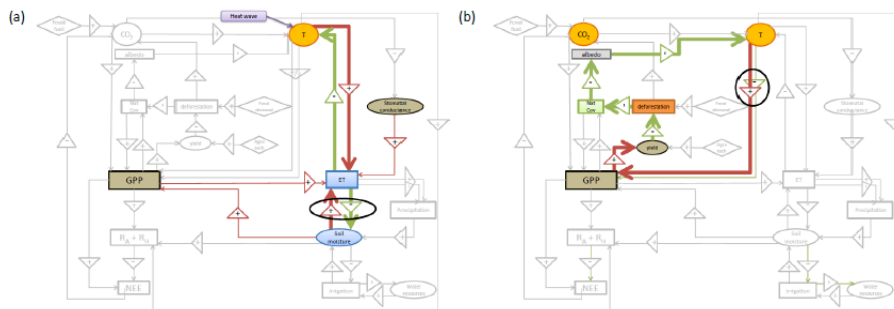


Fig. 5. (a) Positive soil moisture–temperature feedback during a heat wave event in Europe. Purple arrow depicts the climate forcing. (b) Positive vegetation cover-albedo feedback as a result of greater forest area in the Scandinavian Mountains, based on the study from Wramneby et al. (2010).

232

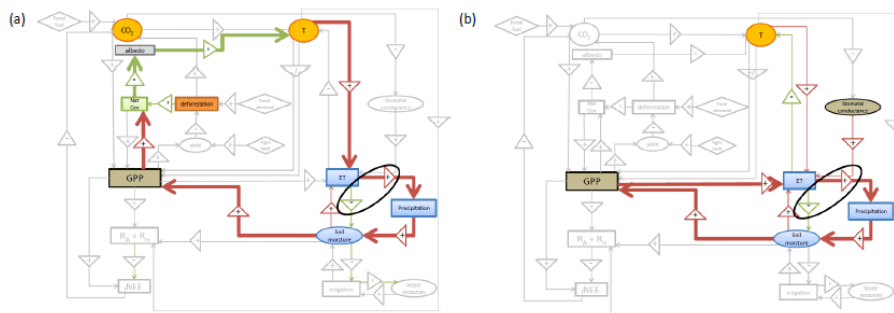


Fig. 6. (a) Positive vegetation cover-albedo feedback caused by deforestation in the Amazon Basin (b) Positive soil moisture-precipitation feedback, based on the study from Betts et al. (2004).

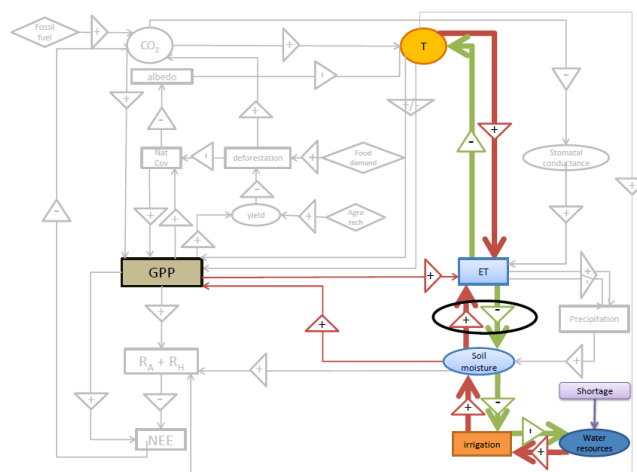


Fig. 7. Positive soil moisture-temperature feedback under water shortage (purple arrow) in South and Southeast Asia.