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Combined effects of climate and land-use change on the provision of ecosystem services in rice agro-ecosystems

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Abstract

Irrigated rice croplands are among the world's most important agro-ecosystems. They provide food for more than 3.5 billion people and a range of other ecosystem services (ESS). However, the sustainability of rice agro-ecosystems is threatened by continuing climate and land-use changes. To estimate their combined effects on a bundle of ESS, we applied the vegetation and hydrology model LPJmL to seven study areas in the Philippines and Vietnam. We quantified future changes in the provision of four essential ESS (carbon storage, carbon sequestration, provision of irrigation water and rice production) under two climate scenarios (until 2100) and three site-specific land-use scenarios (until 2030), and examined the synergies and trade-offs in ESS responses to these drivers. Our results show that not all services can be provided in the same amounts in the future. In the Philippines and Vietnam the projections estimated a decrease in rice yields (by approximately 30%) and in carbon storage (by 15%) and sequestration (by 12%) towards the end of the century under the current land-use pattern. In contrast, the amount of available irrigation water was projected to increase in all scenarios by 10%–20%. However, the results also indicate that land-use change may partially offset the negative climate impacts in regions where cropland expansion is possible, although only at the expense of natural vegetation. When analysing the interactions between ESS, we found consistent synergies between rice production and carbon storage and trade-offs between carbon storage and provision of irrigation water under most scenarios. Our results show that not only the effects of climate and land-use change alone but also the interaction between ESS have to be considered to allow sustainable management of rice agro-ecosystems under global change.

1. Introduction

Rice is the most consumed staple food for more than 3.5 billion people, with annual per capita consumption exceeding 100 kg in many Asian countries (Seck *et al* 2012). With a world population that is expected to increase from current 7.4 to 9.7 billion by 2050 (United Nations 2015) rice demand will continue to grow in the next decades. Even under ambitious scenarios of reducing food waste and distribution inequality (Ericksen *et al* 2009, Foley *et al* 2011), considerable increases in rice production will be necessary. These conditions place irrigated rice croplands among the world's most important agro-ecosystems (FAOSTAT 2014).

In addition to food production, rice agro-ecosystems simultaneously provide a number of other ecosystem services (ESS) that contribute to human well-being in rice producing regions as well as globally. These services include provision of fuel and fibre, regulation of water supply for irrigation and fishing, nutrient cycling and carbon sequestration, but also cultural services such as cultural identity associated with traditional rice farming (Burkhard *et al* 2015, Spangenberg *et al* 2014). Maintaining essential ESS, while meeting the increasing rice demand at the same time, represents a major challenge for rice producing countries, especially in Southeast Asia (Greenland 2006, Laborte *et al* 2012).

Rice agro-ecosystems, however, are affected by a range of natural and anthropogenic drivers, such as land use and climate change. In these irrigated cropping systems (Václavík *et al* 2013), rice terraces and other crop fields are often expanded, typically at the expense of natural forests, leading to substantial forest loss and degradation (Castella and Verburg 2007, Fox *et al* 2012, Settele 1998). Although much of the original landscapes in Southeast Asia had already been transformed centuries ago (Pongratz *et al* 2008), when native vegetation was turned into agricultural land, large environmental impacts from land use expansion and intensification still prevail (Field *et al* 2014, Houghton and Hackler 1999, Torres *et al* 2014).

In the future, ESS in rice agro-ecosystems will be affected by further increasing atmospheric CO_2 and associated climate change, which includes increasing temperature and shifts in rainfall regimes (Howden *et al* 2007). In Southeast Asia, temperatures are projected to rise regionally between 1.5 and 4 K depending on the scenario (Nakićenović *et al* 2000), but even moderate warming will likely reduce rice yields in the next coming decades (Peng *et al* 2004, Welch *et al* 2010). Additionally, projections of future precipitation show changes in the amount of rainfall, regionally varying between −20% to +20% (Meehl *et al* 2007) and a gradual increment in winter monsoon rainfall in Southeast Asia under most climate change scenarios (Siew *et al* 2013). Despite the complex interplay of factors, the question how the multiple interactions of drivers and their expected changes affect future provision of important ESS in rice agro-ecosystems has not been consistently investigated.

Considering the need to maintain various ESS in rice agro-ecosystems under changing climate and land use, integrative approaches are required to assess environmental as well as social-ecological impacts. While previous studies examined the potential effect of climate change on rice production (Welch *et al* 2010, Peng *et al* 2004, Naylor *et al* 2007), it has not yet been systematically examined how the combination of both climate and land-use change simultaneously impacts multiple ESS in rice agro-ecosystems. Such integrative approach is crucial to better understand whether the interaction of both drivers amplifies their impact on ESS (both leading to decrease or both leading to increase, i.e. amplification effect) or whether the projected change in one driver can balance out the effect of the other driver (i.e. offset effect). In addition, understanding the relationships among multiple ESS is increasingly recognized as essential to ensure multi-functionality of landscapes (Bennett *et al* 2009, Rodríguez *et al* 2006, Bennett *et al* 2015). Therefore, we need to examine whether ESS are bundled in either positive ways (synergies) or negative ways (trade-offs) in a response to common drivers that affect the changes in multiple services at the same time (Bennett *et al* 2009).

In this study, we use an integrative simulation approach to assess the combined effect of projected climate and land-use change on a bundle of ESS in rice agro-ecosystems in seven study areas in the Philippines and Vietnam. These areas represent suitable investigation systems, as both countries doubled their rice yield in only 20 years, reaching 44 and 18 million t yr^{-1} in 2012, respectively (FAOSTAT 2014). At the same time, climate and land-use changes in these regions affect ESS that are crucial for local communities and the sustainable cultivation of rice (Settele *et al* 2015). We specifically focus on four ESS: (a) carbon storage, (b) carbon sequestration by the vegetation, (c) provision of irrigation water and (d) rice production, because these services are provided by the natural vegetation (a–c) or the cropland (d). Therefore, the ESS strongly depend on land-use change (d); they are connected to the carbon cycle/balance (a–b), thus closely related to climate change; and they are expected to show either synergistic effects (e.g. forest expansion increases carbon storage and provision of irrigation water) or trade-off effects (e.g. loss of forest due to rice field expansion reduces carbon storage).

Here, we address the following research questions: (1) What are the combined effects of projected climate and land-use changes on the provision of selected ESS in rice agro-ecosystems (amplification vs. offset effect)? (2) How do the relationships among multiple ESS change under scenarios of climate and land-use change (synergies vs. trade-offs)? To answer these questions we make use of LPJmL (Sitch *et al* 2003, Gerten *et al* 2004, Bondeau *et al* 2007, Rost *et al* 2008), a dynamic global vegetation and hydrology model (DGVM), and apply it at fine spatial resolution of 30 m to capture local heterogeneities in the seven study areas representative for rice production systems in Southeast Asia.

The novelty of our study lies first in quantifying the combined effects of climate and land-use change on multiple ESS and examining the ESS interactions in response to these two drivers. Second, for the first time, we apply a DGVM at the landscape scale, which enables us to provide more nuanced information for stakeholders and decision-makers in each study area. We briefly discuss the potential consequences of estimated changes for future socioeconomic development of the regions and the implications of our results as a first step to examine possible local adaptations to climate change.

2. Methods and data

2.1. Study areas

The study was conducted in seven study areas in the Philippines ($n = 3$) and Vietnam ($n = 4$, figure 1) as part of a larger research project on sustainable rice production (LEGATO; Settele *et al* 2015). All areas were

Figure 1. Overview of the seven study areas in the Philippines and Vietnam. Highland sites are Lao Cai (VN_3) and Ifugao (PH_3). Lowland sites are Laguna (PH_1), Nueva Ecija (PH_2), Hai Duong (VN_1), Vinh Phuc (VN_2) and Tien Giang (VN_4).

approximately 15 × 15 km in size, located along a gradient of elevation and land use (figure 2(*a*)). The proportion of agricultural land ranged from 19%–96% and the forest coverage ranged from 76% to 0% (table S1, available at stacks.iop.org/ERL/12/015003/mmedia). Because the climatic conditions and the coverage of agricultural land differ substantially in regions with different elevation, we grouped the study areas for the analyses into lowland sites and highland sites. The five lowland sites, Laguna (PH_1), Nueva Ecija (PH_2), Hai Duong (VN_1), Vinh Phuc (VN_2) and Tien Giang (VN_4), are situated below 500 m a.s.l. and show less than 35% of natural vegetation. The two highland sites, Ifugao (PH_3) and Lao Cai (VN_3), are situated above 500 m a.s.l. and have more than 60% of natural vegetation left. The two highland sites in particular have a long history of sustainable rice production with traditional cultivation methods, such as building of rice terraces and manual planting and maintaining of the rice crop (Settele 1998). For detailed descriptions of the study areas see table S1 as well as Klotzbücher *et al* (2015) and Burkhard *et al* (2015).

2.2. Simulating ecosystem services

We used the vegetation and hydrology model LPJmL to simulate future changes in carbon storage, carbon sequestration, provision of irrigation water and rice production (table 1) until the end of the 21st century. LPJmL is a process-based dynamic global vegetation model that explicitly simulates ecosystem processes with fully coupled water and carbon cycles. Natural vegetation is represented with nine generic plant functional types, while agricultural land is represented with 16 user-defined crops and pasture (Bondeau *et al* 2007). The model simulates plant growth, production and phenology of the natural and agricultural vegetation (see also SI section 1.2). LPJmL has been proved to reproduce current patterns of biomass production (Cramer *et al* 2001, Sitch *et al* 2003), also including managed land and crops (Bondeau *et al* 2007, Fader *et al* 2010, Rost *et al* 2008, Müller *et al* 2016), as well as water dynamics (Biemans *et al* 2009, Gerten *et al* 2004, 2008, Gordon *et al* 2004, Wagner *et al* 2003). Additionally, LPJmL has already been shown to provide quantitative assessments of valuable ESS (Metzger *et al* 2008, Karp *et al* 2015).

For calculating the main processes, controlling the dynamics of vegetation, LPJmL uses climate data (temperature, precipitation and cloud cover), atmospheric CO_2 concentration (prescribed by the SRES scenario, Nakićenović *et al* 2000) and soil type (FAO/IIASA/ISRIC/ISSCAS/JRC 2012) as input. To simulate crop production, LPJmL uses prescribed annual fractional coverage of several crop types, thus accounting for land-use change. We developed region-specific land-use scenarios covering the years until 2030 which integrated narratives of possible futures obtained from experts' interviews and a global trade model (see section 2.4). By applying climate and land-use change scenarios for the 21st century, we were able to assess changes in the provision of four ESS described in the following paragraph. Details on the use of model results in the ESS assessment can be found in table 1 and the SI section 1.2.

Carbon storage quantifies the capacity of the vegetation to store assimilated carbon (for up to several decades) above and below ground. It is significantly larger in forests compared to grasslands and can therefore also be used as an indicator for forest habitats, which provide additional ESS such as timber wood and fire wood extraction as well as habitat for plant and animal species. *Carbon sequestration* is the balance between the capacity of the vegetation to absorb

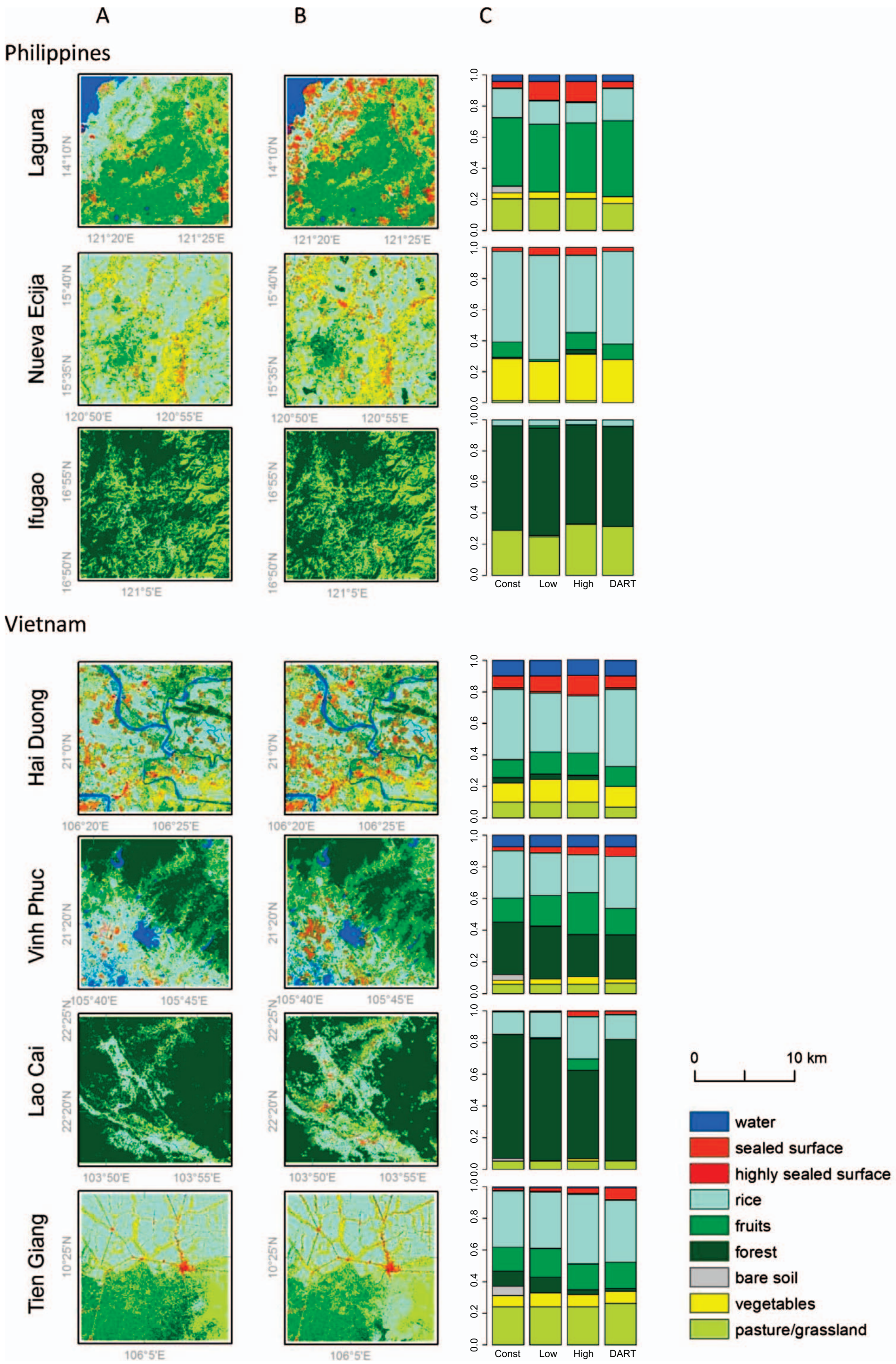

Figure 2. Land use classes in the seven study areas. (*a*) Observed land use class, (*b*) land use in 2030 in the expert scenario 'High-conversion' and (*c*) fraction of land use categories in 2030 in all land use change scenarios (Low-conversion, High-conversion and DART). The land use scenario 'Const' refers to the observed land use. Highland sites are Lao Cai (VN_3) and Ifugao (PH_3). Lowland sites are Laguna (PH_1), Nueva Ecija (PH_2), Hai Duong (VN_1), Vinh Phuc (VN_2) and Tien Giang (VN_4).

carbon from the atmosphere (via photosynthesis) and to respire carbon from living tissue (via autotrophic respiration) and dead organic material (via heterotrophic respiration); in LPJmL both are calculated on a daily basis. Changes in temperature and precipitation affect both processes—photosynthesis and respiration, thus controlling this ecosystem service and making it sensitive to climate change. The amount of *irrigation water* is an indicator for potential rice production, fish production and river (flow) maintenance (Steffen *et al* 2015). For our estimation we use the amount of water before LPJmL reduces it by irrigating crops. It therefore represents the potential irrigation that is restricting crop growth. *Rice production* itself describes its provisioning potential under future climate and land use change.

Table 1. Overview of the selected ecosystem services.

Ecosystem service (ESS)	Short definition	Indicator (model output)	Unit	Reaction to climate change	Reaction to land use change (deforestation)
Carbon storage	Amount of carbon that is stored in above and below ground living and dead biomass.	Sum of carbon stored in vegetation, litter and soil.	[kg C m^{-2}]	+ΔT causes higher heterotrophic respiration and lower photosynthesis causes lower carbon storage; +ΔT on high altitudes causes sparse vegetation gets more dense.	fewer forests cause less carbon storage
Carbon sequestration	Amount of carbon that is sequestered by natural vegetation and crops.	Annual sum of net primary production and carbon allocated in seeds, reduced by the annually respired carbon (heterotrophic respiration).	[g C m^{-2} yr^{-1}]	+ΔT causes higher respiration causes lower carbon sequestration.	more crops cause higher carbon sequestration
Irrigation water	Amount of water that is available for irrigation (while maintaining the environmental flow requirements of rivers, which is 45%–75% of the available water (Steffen *et al* 2015); amount before crop irrigation is calculated in the model.	25% of the annual sum of run-off water	[mm yr^{-1}]	+ΔT causes higher evaporation causes less irrigation water; +ΔP causes more irrigation water.	negligible
Rice production	Amount of rice harvested in the study area.	Carbon harvested from rice plants multiplied by the factor 1/0.45 to convert from carbon to biomass.	[t yr^{-1}]	+ΔT causes lower yield.	more rice area causes more rice production

2.3. Climate data and scenarios

To estimate future changes in the provision of examined ESS, we applied climate scenarios from the general circulation model MPI-ECHAM5, under the two SRES emission scenarios A2 and B1 (Nakićenović *et al* 2000), which were bias-corrected with CRU TS 3.0 (Harris *et al* 2014). We chose these two SRES scenarios because they cover two extreme emission trajectories (Meehl *et al* 2007). In the SRES B1 scenario an increase in temperature of about 1.5K–2K and a change in precipitation of ±10% are projected for our study areas. In the more severe A2 scenario the temperature is projected to increase by 3K–4K, while the precipitation will increase by about 10% (Christensen *et al* 2007).

To capture local climate heterogeneity in our study areas, we first scaled down the original 0.5 arc-degree global (observed and projected) climate data (see following paragraph) to a 30 m resolution using inverse distance interpolation (Shepard 1968). Second, we corrected the temperature and precipitation data according to the elevation in the study area with a temperature lapse rate of −5/1000 (5 K reduction per 1000 m elevation increase) and a precipitation lapse rate of 0.05/100 (5% increase per 100 m elevation increase) (Olea 1999). We validated our method against observed data from 25 meteorological stations close to our study areas. Details on the datasets for downscaling and validation and the validation results can be found in the SI section 1.3.

Finally, we applied our downscaling method to the climate projections. All climate scenarios are provided as monthly data which are then linearly interpolated to quasi-daily values in the LPJmL model. Atmospheric CO_2 concentration has been fixed to a level of 369.5 ppm to exclude the strong fertilization effect in LPJmL, which is caused by a lack of nutrient limitations in the model.

2.4. Land use data and scenarios

To describe the current land use conditions in each study area, we used previously developed land use classification, based on SPOT5 satellite images (www.astrium-geo.com/en/143-spot-satellite-imagery) obtained for the years 2009–2011 (Burkhard *et al* 2015). This remote sensing image interpretation distinguished nine land use categories: water, bare soil, sealed surface, highly sealed surface, rice, fruits plantations, vegetable fields, forest, and pastures/grassland (figure 2(*a*), table S1). We rescaled the land-use maps from the original 2.5 m resolution to a 30 m resolution.

Three potential land-use change (LUC) scenarios were developed, covering a wide range of possible developments until the year 2030. Two scenarios were developed in close cooperation with social scientists and local stakeholders (farmers, land owners, etc.) in the study area. These scenarios were specifically tailored for the study areas to provide insights into possible future developments for rice, pasture, settlements and natural forest, accounting for local/country-specific regulations and historical land-use legacies. We asked our local experts for one more conservative and one more extreme assessment to provide a range of potential future trajectories. From these expert opinions, narratives were developed that then built the basis of our spatially and temporally explicit land-use scenarios. The 'Low-conversion' scenario represents low rates of LUC, in contrast to the 'High-conversion' scenario presenting high rates of LUC (for scenario overview and corresponding trends see table S6). The third scenario, 'DART', examines how global land-use change patterns, based on the world economy DART-BIO model (Calzadilla *et al* 2014), might affect the small-scale study areas. The quantity and location of change provided by the LUC scenarios were calculated for each land-use category on a yearly basis based on a set of rules, using ArcGIS 10.3 (ESRI, Redlands, CA) and Python (Python Software Foundation, version 2.7, www.python.org). For details see supplementary section 1.5. Figure 2(*b*) shows an example of the High-conversion scenario for the projected situation in the year 2030. The scenario without changes in land use ('Const') represents the control situation.

2.5. Simulation experiments and analyses

We conducted simulations from 1901 until 2099, preceded by a 1000 year spin-up period in which climate data from 1901−1930 have been recycled, to initialize the vegetation from bare ground and to bring the carbon pools into equilibrium. The soil input was based on data from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). From 1901 until the year of the SPOT land use data, the land use forcing was kept constant, assuming only minor changes in the fraction of forest/cropland in the last century (Pongratz *et al* 2008). Although some changes in cropland until 1992 were identified by the large-scale estimates of Pongratz *et al* (2008), Settele *et al* (1998) suggest that in the Philippines and in Vietnam land-use changes occurred mostly at a local scale, including shifts in the distribution of rice fields and in abandonment or establishment of terraces. Therefore, keeping the land-use input constant for the 20th century is a reasonable assumption, and the uncertainties in the assumed past trends had only minimal effect on the projected changes of ESS. From the year of the SPOT data onwards the different trends from the LUC and the 'Const' scenarios were applied until 2030. Realistic scenarios of LUC for more than 20 years are difficult to develop. However, the time until 2030 is not long enough to see large climate change effects (Naylor *et al* 2007). Therefore, we continued our simulation until the end of the century to further assess the combined effects of climate and land-use change, while keeping the land use constant after 2030.

To analyse changes in the studied ESS (section 2.2), we calculated the annual average (2000–2099) smoothed as a 10 year running mean. The effect of climate change alone can be assessed by analysing the constant land-use change scenario (Const). To estimate the LUC effects alone we subtracted the Const-scenario results from the results of each LUC scenario simulation (Low-conversion, High-conversion, and DART).

To quantify synergies and trade-offs among projected ESS we calculated the Pearson correlation coefficient for each pair of services. This correlation provides information about the way (positive or negative) and the degree in which the services relate to each other. Therefore it helps identifying synergies (significant positive correlation) and trade-offs (significant negative correlation) between ESS in terms of their response to climate and land-use drivers. For correlations under combined scenarios of climate and land-use change we used the 10 year running mean of the period 2000–2099 and for correlations under LUC only we used the 10 year running mean of the period 2010–2030, because the land-use scenarios end in 2030.

3. Results

For most ESS and scenarios, combined climate and land-use change reduced the provision of ESS when compared to the baseline period 2001–2010 (figures 3 and 4 for SRES A2; figure S4 and figure S5 for SRES B1). With the exception of irrigation water, climate change alone caused a considerable decrease in ESS by the end of this century (figure 3 (black boxes, representing no land-use change) and figure 4(*a*)). In contrast, the response to LUC depended largely on the considered land-use scenario (see also figure S2 table S8 for absolute values).

Carbon storage declined by 5%−30% by the end of the century, with the highest decrease in the lowland sites under the DART scenario (figure 3(*b*), light-grey boxes). The overall negative effect of climate change was typically amplified by LUC, especially under the more drastic High-conversion scenario (figure 4(*c*)). However, in the case of highland sites under Low-conversion scenario (figure 3(*a*) and figure 4(*b*)), LUC did partially offset the negative effect of projected climate change on carbon storage.

Carbon sequestration showed a slight overall decrease by 2099 (figure 3), although it showed mid-century increases in the lowland sites and continued to increase until the end of the century in the highland sites under the High-conversion scenario (+25%). The periodicity in this ESS, as shown in figure 4, is caused by the climate input (e.g. El Niño events or repeating climate characteristics), which has direct effects on the temperature and therefore influences the carbon sequestration. Nevertheless, the overall trend is negative towards 2099. LUC was only able to temporarily offset the negative effects of climate change, especially

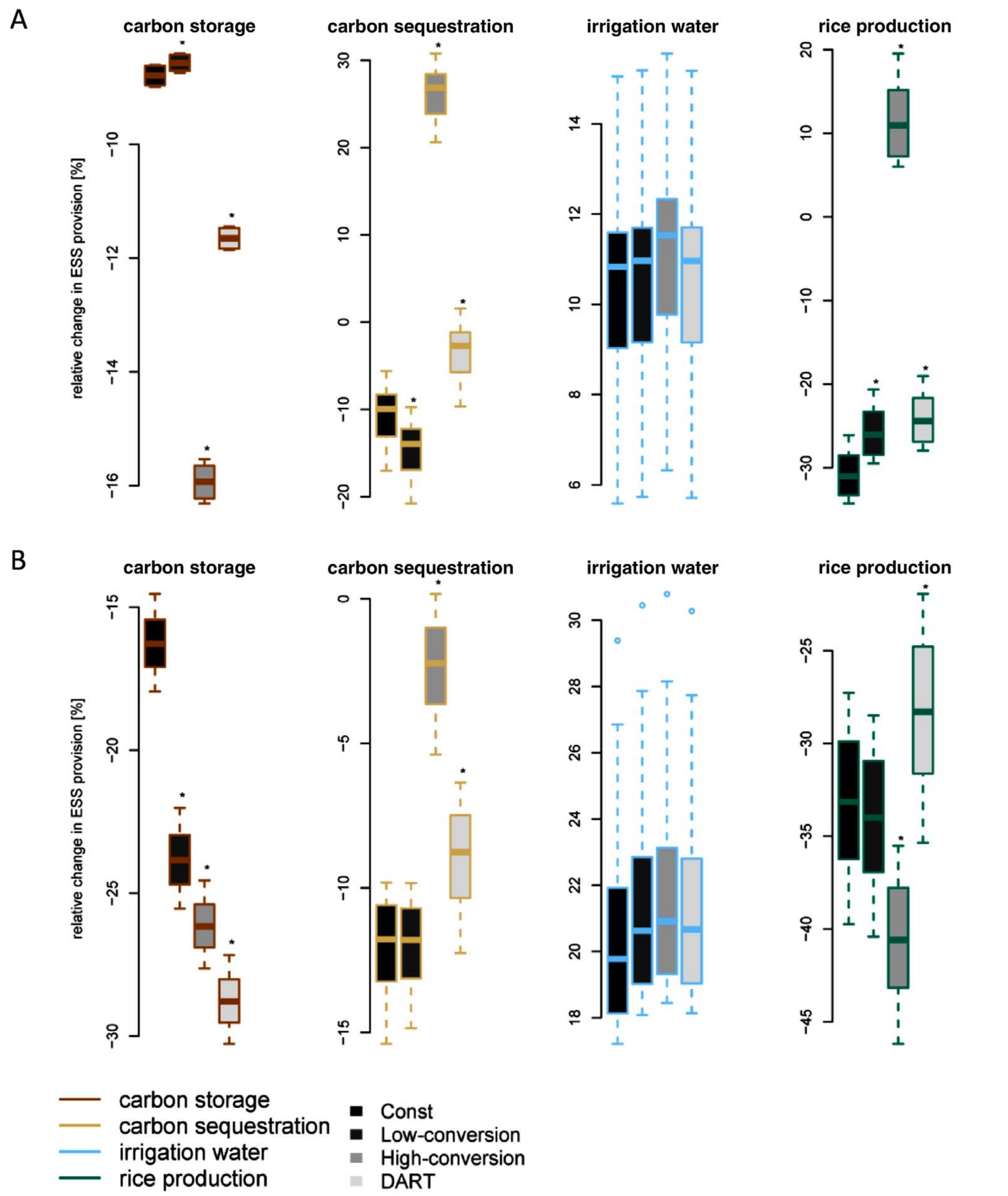

Figure 3. Combined effects of climate and land-use change shown as relative change in the provision of four ESS (compared to the baseline period 2001–2010, indicated by the colors) under the SRES scenario A2. Boxplots compiled for 2080–2099 in (*a*) highland sites and (*b*) lowland sites. Different land-use scenarios indicated by different gray filling of the boxes. Asterisks indicate a significant difference to the constant land use scenario (Const), $p < 0.05$.

when greater shifts in land use were assumed, as in the High-conversion scenario (figure 4(*c*)).

The provision of irrigation water showed an overall positive trend with mean increases of +11% in highland sites (figure 3(*a*)) and +21% in lowland sites (figure 3(*b*)). This trend was driven mainly by climate change with only marginal amplification by LUC, irrespective of the LUC scenario. Like the carbon sequestration, irrigation water shows periodically repeating patterns, which can also be explained by the climate input (primarily precipitation). These two services are estimated on a short term (few months) and are therefore more sensitive to short-term fluctuations than the carbon storage and the production of rice.

In contrast to irrigation water, rice production showed a clear response to LUC. While the combination of both drivers had mostly negative effects on rice production in the long term, leading to losses typically between 20% and 40% by 2099, changes in land use in the highlands were able to offset these effects in the first decades of the century. In the High-conversion scenario, the increase by 2030 was strong enough (50%) to override climate change effects even after the period of assumed land-use change, leading to overall 10% increase by 2099 (figure 3(*a*) and figure 4(*c*)). The strong decrease in rice production after 2030 is caused solely by the negative effects of climate change, with higher minimum temperatures reducing yields (Peng *et al* 2004, Welch *et al* 2010). In the lowland sites, where options for cropland expansions are limited, LUC amplified climate-change induced decline in rice production. All rice production estimates

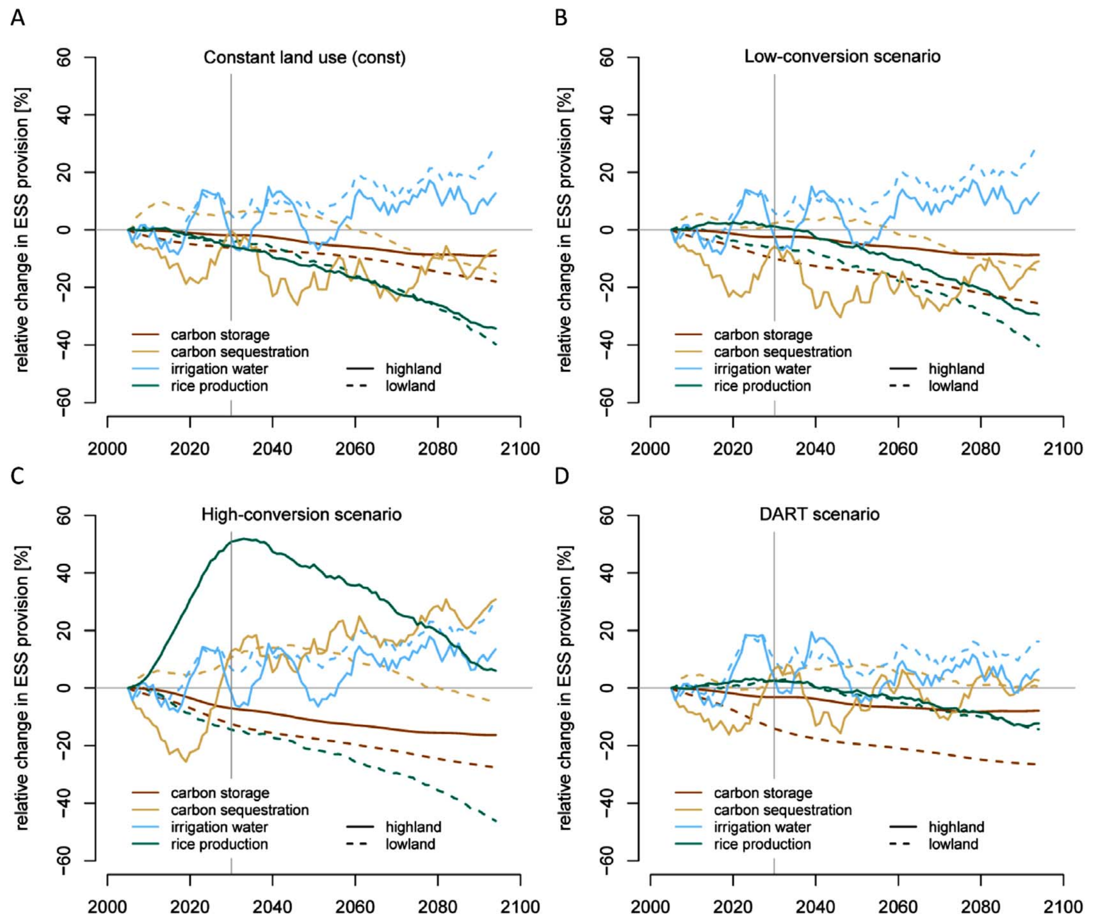

Figure 4. Time series of combined effects of climate and land use change shown as relative changes in the provision of four ecosystem services (compared to the baseline period 2001–2010) under the SRES scenario A2. The panel shows ESS dynamics for constant land use ((*a*), representing climate change alone) and the three different land use change scenarios ((*b*) low conversion, (*c*) high conversion, (*d*) conversion according to DART) (10 year running mean). The grey line indicates the last year of the land-use change scenarios.

were validated against on-site measurements. The results of this analysis showed that the simulated yields were comparable to measured yields as well to the yields reported by farmers (table S5).

The correlation analysis, using Pearson correlation coefficient *r*, identified whether the effects of climate and land-use change on provision of multiple ESS were in the same direction for two services (positive correlation indicates synergy, i.e. enhancing both ESS or diminishing both ESS) or in opposite directions (negative correlation indicates trade-off, i.e. diminishing one service while enhancing the other). The 'LUC only' columns in tables 2(*a*) and (*b*) show the effects of land-use change alone, while the other columns show the combined effects of climate and land-use change. Most pair-wise relationships were significant (table 2), especially for the lowland sites (table 2(*b*)), suggesting clear synergies and trade-offs among individual ESS. In lowlands, carbon storage and rice production, among others, were always positively correlated (synergy) with *r* ranging between 0.790 and 0.999, while carbon storage and irrigation water in lowlands were mostly negatively correlated (trade-off) with *r* ranging between −0.989 and 0.998 and nearly independent of the climate and the land-use change scenario. For some services the relationship changed slightly depending on (a) the climate scenario, showing large differences between the climate-change scenarios, e.g. irrigation water and rice production in highlands, or on (b) the LUC scenario, e.g. carbon sequestration and carbon storage in highland, or on (c) a combination of both drivers, e.g. carbon sequestration and irrigation water in lowlands.

4. Discussion

Our results show that future changes in climate and land use lead to significant declines in the provision of three out of four quantified ESS by the end of the century. With the exception of irrigation water, whose provision increases due to increased precipitation levels, climate change reduces the supply of the considered ESS. The additional effect of LUC is smaller (figure S3). Where unmanaged land is still available, new land conversion may allow partially offsetting negative climate change effects, but only at the expense of carbon storage in natural vegetation and therewith at the expense of natural habitat.

The future climate-induced reduction in carbon storage is mainly caused by lower photosynthesis rate

Table 2. Pearson correlation coefficient between the ecosystem services for highland sites (A) and lowland sites (B). Correlation under land use change and climate change (either under SRES A2—CC_{A2}, or SRES B1—CC_{B1}) together for 2000–2099, or land-use change only (LUC only) for 2000–2030 Order of land use scenarios within climate scenarios is Const, Low-conversion, High-conversion, DART. Red indicates a positive correlation (> +0.5), while blue indicates a negative correlation (< −0.5). Significance indicated by $*$ for $p < 0.05$ and $**$ for $p < 0.01$.

A

	carbon storage			carbon sequestration			irrigation water			rice production		
	CC_{A2} +LUC	CC_{B1} +LUC	LUC only	CC_{A2} +LUC	CC_{B1} +LUC	LUC only	CC_{A2} +LUC	CC_{B1} +LUC	LUC only	CC_{A2} +LUC	CC_{B1} +LUC	LUC only
carbon storage	1(Const)	1	NA	carbon storage/ carbon sequestration: more sensitive to **LUC** than to **CC** scenario			carbon storage/ irrigation water: more sensitive to **CC** than to **LUC** scenario			carbon storage/ rice production: more sensitive to **LUC** than to **CC** scenario		
	1(Low)	1	1									
	1(High)	1	1									
	1(DART)	1	1									
carbon sequestration	+0.284**	+0.185	NA	1	1	NA	carbon sequestration/ irrigation water: more sensitive to **LUC** than to **CC** scenario			carbon sequestration/ rice production: sensitive to **LUC** scenario		
	+0.315**	+0.247*	+0.617*	1	1	1						
	−0.890**	−0.889**	−0.984**	1	1	1						
	−0.266*	−0.395**	−0.960**	1	1	1						
irrigation water	−0.551**	−0.001	NA	−0.256*	−0.169	NA	1	1	NA	irrigation water/ rice production: more sensitive to **CC** than to **LUC** scenario		
	−0.566**	−0.063	+0.741**	−0.266*	−0.234*	+0.562	1	1	1			
	−0.573**	−0.160	−0.961**	+0.442**	+0.095	+0.925**	1	1	1			
	−0.561**	−0.102	−0.829**	+0.033	−0.103	+0.938*	1	1	1			
rice production	+0.980**	+0.944**	NA	+0.212*	+0.138	NA	−0.552**	−0.082	NA	1	1	NA
	+0.944**	+0.895**	−0.307	+0.144	+0.139	−0.814**	−0.525**	+0.040	−0.067	1	1	1
	+0.001	−0.518**	−0.996**	+0.037	+0.533**	+0.965**	−0.052	+0.424**	+0.967**	1	1	1
	+0.901**	+0.834**	−0.998**	−0.337**	−0.328**	+0.951**	−0.514**	+0.086	+0.804**	1	1	1

B

	carbon storage			carbon sequestration			irrigation water			rice production		
	CC_{A2} +LUC	CC_{B1} +LUC	LUC only	CC_{A2} +LUC	CC_{B1} +LUC	LUC only	CC_{A2} +LUC	CC_{B1} +LUC	LUC only	CC_{A2} +LUC	CC_{B1} +LUC	LUC only
carbon storage	1(Const)	1	NA	carbon storage/ carbon sequestration: more sensitive to **LUC** than to **CC** scenario			carbon storage/ irrigation water: more sensitive to **CC** than to **LUC** scenario			carbon storage/ rice production: more sensitive to **LUC** than to **CC** scenario		
	1(Low)	1	1									
	1(High)	1	1									
	1(DART)	1	1									
carbon sequestration	+0.918**	+0.782**	NA	1	1	NA	carbon sequestration/ irrigation water: sensitive to **CC** and **LUC** scenario			carbon sequestration/ rice production: sensitive to **CC** and **LUC** scenario		
	+0.831**	+0.652**	−0853**	1	1	1						
	+0.272**	−0.472**	−0.985**	1	1	1						
	+0.537**	−0.074	−0.947**	1	1	1						
irrigation water	−0.901**	−0.628**	NA	−0.830**	−0.487**	NA	1	1	NA	irrigation water/ rice production: sensitive to **CC** scenario		
	−0.906**	−0.621**	−0.917**	−0.822**	−0.580**	+0.618*	1	1	1			
	−0.906**	−0.644**	−0.984**	−0.391**	+0.197	+0.957**	1	1	1			
	−0.899**	−0.637**	−0.999**	−0.662**	−0.274**	+0.939**	1	1	1			
rice production	+0.981**	+0.963**	NA	+0.962**	+0.853**	NA	−0.877**	−0.549**	NA	1	1	NA
	+0.964**	+0.986**	+0.995**	+0.933**	+0.724**	−0.829**	−0.893**	−0.598**	−0.936**	1	1	1
	+0.980**	+0.996**	+0.999**	+0.443**	−0.431**	−0.976**	−0.920**	−0.675**	−0.989**	1	1	1
	+0.821**	+0.790**	−0.996**	+0.866**	+0.308**	+0.916**	−0.809**	−0.380**	+0.998**	1	1	1

and higher respiration under elevated temperatures (Ryan 1991). This trend is further amplified because under most LUC scenarios the extent of natural vegetation decreases, and therewith also carbon stored in forests. In contrast to carbon storage, the sequestration of carbon is likely to increase with projected LUC in all cases, except for the High-conversion scenario in highland sites. Carbon sequestration represents the ability of the vegetation to absorb carbon. In systems at equilibrium, such as old growth forest, the maintenance respiration is higher than in agricultural systems, which leads to a lower NPP. As a consequence, the carbon sequestration in crop systems is much higher, although trees have larger leaf area available for photosynthesis. Therefore, the expansion of agricultural areas with fast growing rice and vegetables, which exhibit low rates of maintenance respiration (Ryan 1991), will lead to an increase in carbon sequestration. This is especially evident in the highland sites under the High-conversion LUC scenario. In these cases, large forest-to-cropland conversions are expected. This changes the ratio of trees (less trees, with lower carbon sequestration) to crops (more crops, with higher carbon sequestration), causing a substantial offset of the negative climate change impact by the year 2100.

The availability of water for irrigation is a major prerequisite for rice production. Despite the projected increase in its provision under all considered scenarios, climate change leads to a decline in rice production which is in agreement with previous studies (Peng *et al* 2004, Welch *et al* 2010). Where rice production can only be increased through expansion of rice terraces as projected by our LUC scenarios in the highland sites, trade-offs to carbon storage emerge due to significant losses of natural forest vegetation, however this trade-off can only be assessed by considering land-use change only. In the lowland sites, where nearly no additional land is available for agricultural expansion and the extent of settlements is likely to grow, we project an additional decline in rice production compared to climate change only (figures 3 and 4).

In addition to the effects arising from land available for conversion, the observed differences that we found between highland and lowland sites for most projections of ESS can be mainly attributed to the lower cropland coverage and lower temperatures in the highland compared to the lowland sites. The negative effects of climate change are less pronounced in the highland sites, because the increase in carbon storage in the highest altitudes caused by a temperature increase can compensate for losses in lower lying areas. This positive effect, however, has its limitation due to the decreasing available area in higher altitudes. Among our study areas, Lao Cai (VN_3) is the highest in elevation and would benefit most from increasing temperatures, since the mountain tops are only sparsely covered with vegetation. The other highland site (Ifugao, PH_3) is at lower elevation and would benefit less because the mountain tops are already covered with vegetation.

Our findings narrow the scope of potential land-use options that can be adopted to reduce the threat posed by future climate change to ESS in rice agro-ecosystems. The three LUC scenarios developed for this study allowed us to assess a range of such options. However, in all cases the potential of land use for local adaptation to climate change is limited. In the case of rice production, for example, the expansion of rice terraces would have to be drastic (see also figure 2(*c*) Lao Cai) to even partially offset the impact of climate change. In addition, our results indicate that local policies promoting such type of LUC might work only in the horizon of a few decades, but alone would be insufficient to mitigate climate change in the long term. Therefore, local policies aiming at sustainable rice production and food security in the face of climate change should consider other adaptation strategies suitable for rice agro-ecosystems, including crop diversification and rotation, the use of stress-tolerant rice varieties, adjustments of sowing season, or methods of ecological engineering (Banerjee *et al* 2016, Kumar 2016, Li *et al* 2015).

Managing rice agro-ecosystems for multiple ESS is even more challenging because several ESS are often provided by the same land-use type but they do not always respond the same way to underlying drivers (Haase *et al* 2012). We identified such trade-offs, e.g. between irrigation water and all other ESS, as the provision of irrigation water shows consistently positive response to combined climate and land-use change effects while the provision of other ESS declines. Similarly, trade-offs between rice production and carbon storage were found as a response to LUC especially in highland regions of Lao Cai (VN_3) and Ifugao (PH_3) (table 2(*a*)). However, the trade-offs between ESS are often not obvious because both ESS considered are heavily influenced by climate change, which masks the effects of LUC (table 2(*a*)). The identified trade-off between rice production and carbon storage—under land-use change only—corroborates findings by Burkhard *et al* (2015) who documented trade-offs between crop production and a range of other ESS, including biodiversity, crop pollination and recreation. Especially when high rates of LUC are assumed, the encroachment of crop fields in natural forests not only leads to a reduction in carbon storage but also reduces potential timber and firewood extraction and affects habitat for plant and animal species. Therefore, we caution that, although we quantified the response of arguably the most important ESS in rice agro-ecosystems, more detailed and context-specific assessments are needed to understand the possible outcomes of climate change and land management strategies (Castonguay *et al* 2016). In addition to rice production, these assessments should consider other non-provisioning ecosystem services, impacts on biodiversity, resilience of rice agro-ecosystems, and cultural and societal implications (Förster *et al* 2015).

5. Conclusion

Understanding the effects of climate and land-use change on the provision of ESS and identifying synergies and trade-offs in their responses is crucial for maintaining multi-functional production systems. Our study of rice agro-ecosystems showed that the trend in the ESS provision is relatively clear if we consider climate change only, but it becomes more complex when LUC is included, leading to opposite trends depending on the severity of environmental change and the study area. In general, climate change and LUC reduced ESS provision in most of the considered scenarios, both in highland (10 out of 16) and lowland sites (12 out of 16). Only high land-conversion rates were able to partially offset negative climate change effects. With a projected temperature increase for the Philippines and Vietnam of up to 4 K by 2100, rice production can likely be maintained only at the expense of natural vegetation, whose reduction is typically accompanied by loss of native habitat and biodiversity with poorly understood cultural and societal implications. Therefore, locally specific land-use policies and development plans have to consider not only the provision of crops but also regulating and cultural services to maintain future human well-being and natural resources of rice agro-ecosystems in Southeast Asia. This study illustrates the importance of considering small scale land-use patterns and climate-change scenarios to assess the complex interactions of several ESS and to inform local decision makers and stakeholders.

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