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

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1. Methods – supporting material

1.1. Details for study areas

Table S1: Description of the study areas (each 15×15km). Note that the coverage of settlements, crop land and forest does not necessarily sum up to 100% because there is also water and bare ground in most study areas.

| Name       | Location (lon/lat) | Elevation [m a.s.l.] | Land use intensity | Coverage of settlements [%] | Coverage of crop land [%] | Coverage of forest [%] | Year of SPOT5 image |
|------------|-------------------|----------------------|-------------------|-----------------------------|--------------------------|-----------------------|---------------------|
| Philippines |                   |                      |                   |                             |                          |                       |                     |
| Laguna (PH_1) | 121.307 to 121.442 / 14.104 to 14.240 | 3 to 641 Ø 112 (lowland site) | high | 4.45 | 87.05 | 0.0 | 2009 |
| Nueva Ecija (PH_2) | 120.826 to 120.963 / 15.695 to 15.558 | 11 to 84 Ø 41 (lowland site) | high | 2.86 | 96.08 | 0.0 | 2008 |
| Ifugao (PH_3) | 121.028 to 121.164 / 16.828 to 16.964 | 481 to 2001 Ø 1085 (highland site) | low | 0.10 | 32.71 | 67.09 | 2011 |
| Vietnam |                   |                      |                   |                             |                          |                       |                     |
| Hai Duong (VN_1) | 106.326 to 106.470 / 20.945 to 21.080 | 3 to 180 Ø 11 (lowland site) | high | 8.18 | 78.76 | 3.68 | 2010 |
| Vinh Phuc (VN_2) | 105.655 to 105.791 / 21.276 to 21.412 | 0 to 544 Ø 78 (lowland site) | medium | 3.38 | 53.21 | 32.56 | 2010 |
| Lao Cai (VN_3) | 103.806 to 103.951 / 22.286 to 22.420 | 492 to 2778 Ø 1441 (highland site) | low | 1.18 | 19.33 | 75.91 | 2010 |
| Tien Giang (VN_4) | 106.026 to 106.160 / 10.340 to 10.475 | 1 to 84 Ø 8 (lowland site) | high | 1.74 | 79.76 | 10.94 | 2011 |

1 at current state (at year of SPOT data); * represents the sum of fruits, vegetables, rice and pasture/grassland
1.2. Simulated ecosystem services

LPJmL is a process-based dynamic global vegetation model (DGVM), that explicitly simulates ecosystem processes with fully coupled water and carbon cycles, and is able to reproduce local carbon and water flux dynamics (Sitch et al. 2003; Gerten et al. 2004; Bondeau et al. 2007; Rost et al. 2008). The simulation of plant physiology, respiration and carbon cycling is still based on the original LPJ publication (Sitch et al. 2003), extended by with updated hydrological processes (Gerten et al. 2004, 2008; Rost et al. 2008). Vegetation is represented in the model with nine generic plant functional types (PFTs), representing the potential natural vegetation. The LPJ model changed to LPJmL with the addition of managed land which allows the simulation of 16 user-defined crops and pasture (Bondeau et al. 2007) in the managed land. In analogy to natural vegetation, LPJmL evaluates full coupled carbon and water fluxes, including crop yields, for the agricultural area. The model does not explicitly simulate several cultivars of crops, but it rather mimics the effect of cultivars by assuming an optimal management of the crop types for each site.

The two main ESS that we examined were carbon storage and carbon sequestration. Carbon storage consists of vegetation carbon (living above and below-ground biomass), litter carbon (dead above-ground biomass) and soil carbon (dead below-ground biomass). Carbon sequestration differs for different systems. In systems at equilibrium (e.g. old growth forest) the maintenance (autotrophic) respiration is higher than in agricultural system, thus the NPP is lower. This leads, although trees have a much larger leaf area available, to the higher carbon sequestration in crop systems which are additionally highly managed systems.

The carbon sequestration also includes the heterotrophic respiration of soil organic carbon, which spatial distribution within the soil column is not explicitly included. The integration of photosynthesis and respiration over several decades then amounts to carbon stored above and below-ground (biomass, litter and soil carbon).

Carbon storage and carbon sequestration are sometimes considered ESS indicators rather than actual services. However, we apply the currently more common approach and classify them as separate ESS, as they are represented by fundamentally different processes (e.g. see the TEEB classification, TEEB 2009).

1.3. Down-scaled climate input

We scaled down the original 0.5 arc-degree global climate data to a 30 m resolution to capture local climate heterogeneity in our study areas. For the lapse-correction we used a digital elevation model with a resolution of 30m (ASTER Global DEM Version 2, NASA 2013). DEM images were clipped to an extent of approximately 17×17km to avoid edge effects for each site.
To validate our method we downscaled global observed data for precipitation and temperature from the last century, namely WATCH ERA 40 (Weedon et al. 2011) and the CRUTS3.0 data set (Harris et al. 2014), and compared them against local observational of 25 stations (see Table S2 to Table S4). The global observation dataset WATCH provides daily data for temperature [°C], precipitation [mm] and radiation [Joule m⁻²] from 1951 to 2001 at a spatial resolution of 0.5°×0.5° lat/lon. The second global observation dataset, CRU, provides monthly data for temperature [°C] and precipitation [mm] from 1900 to 1998. Local observations were obtained from NOAA’s National Climatic Data Center (NCDC) and from NOAA’s Global Historical Climatology Network (GHCN) Version 3.2.0 November 2012 (http://www.ncdc.noaa.gov/cdo-web, access Nov. 2012). Local precipitation data for the Vietnamese site Lao Cai was obtained from the National Center for Hydro-meteorological Forecasting (NCHMF, http://www.nchmf.gov.vn, access Nov. 2012). We pre-processed all observed data to monthly mean. Downscaled WATCH and CRU climate data were validated against local observations showing the p-value and the Nash-Sutcliffe coefficient for temperature and precipitation, respectively (Tables S2 and S3). For most of the study areas the downscaled observed data show high agreement with local observations. The lower agreement for temperature for two Philippine sites (PH_2 and PH_3) can be explained by the large spatial heterogeneity of climate conditions, especially in the highland areas (PH_3) and the quality of local data used for validation. For the lowland sites PH_2 the only data available for validation came from a nearby mountain area (1500m a.s.l and 1900m a.s.l.), whereas PH_2 is at about 50m. All seven study areas showed high agreement for precipitation.

Table S2: Overview of stations and observed climate data, including datasets, periods of observation.

| Site     | corresponding Study area | Coordinates lon/lat | dataset  | Temperature observation years | Precipitation observation years |
|----------|--------------------------|---------------------|----------|-------------------------------|--------------------------------|
| Philippines                                  |                       |                     |          |                               |                                 |
| 1 AMBULONG PH_1                             | 121.050/ 14.080       | GHCN                | 1951-1975 | 1913-1975                     |
| 2 APARRI PH_3                               | 121.630/ 18.070       | GHCN                | 1886-2012 | 1902-2012                     |
| 3 BAGUIO PH_2/PH_3                          | 120.600/ 16.400       | GHCN                | 1951-2012 | 1902-2012                     |
| 4 BALER PH_3                                | 121.600/ 15.800       | GHCN                | 1952-1975 | 1902-1975                     |
| 5 BOLINAO PH_3                              | 119.930/ 16.380       | GHCN                | 1903-2012 | 1886-2012                     |
| 6 CABANATUAN PH_3                           | 120.970/ 15.480       | GHCN                | 1951-2012 | 1952-2012                     |
| 7 CALAYAN PH_3                              | 121.470/ 19.270       | GHCN                | 1951-1975 | 1951-1975                     |
| 8 CASIGURAN PH_3                            | 122.120/ 16.280       | GHCN                | 1952-1975 | 1951-1975                     |
| 9 CLARK PH_3                                | 120.550/ 15.183       | NCDC                | 1949-1967 | 1949-1967                     |
| 9 CLARK PH_3                                | 120.550/ 15.183       | NCDC                | 1949-1967 | 1949-1967                     |
### Validation results for the downscaled temperature data

- **Philippines**
- **Vietnam**

| Site | Temperature WATCH | p-Value | Temperature CRU | p-Value | Temperature WATCH | p-Value | Temperature CRU | p-Value |
|------|-------------------|---------|-----------------|---------|-------------------|---------|-----------------|---------|
| **Philippines** | | | | | | | | |
| 1 | AMBULONG (PH_1) | 0.614±0.119 | 0.118±0.051 | 0.884±0.036 | 0.393±0.199 | | | |
| 2 | APARRI (PH_3) | 0.0005±0.0002 | 0 | -1.605±0.181 | -23.895±8.318 | | | |
| 3 | BAGUIO (PH_2/PH_3) | 0.012±0.014 | 0.024±0.099 | -1.646±0.650 | -9.655±7.926 | | | |
| 4 | BALER (PH_3) | 0 | 0 | - | - | | | |
| 5 | BOLINAO (PH_3) | 7.42×10^{-6}±4.63×10^{-6} | 0 | -5.635±0.651 | -27.250±10.560 | | | |
| 6 | CABAÑATUAN (PH_3) | 0.005±0.002 | 0 | -0.568±0.123 | -18.000±6.703 | | | |
| 7 | CASIGURAN (PH_3) | 6.14×10^{-3}±1.36×10^{-3} | 0 | -0.645±0.094 | -23.364±9.997 | | | |
| 8 | CLARK (PH_3) | 5.14×10^{-5}±1.82×10^{-5} | 0 | -4.343±0.287 | -22.289±8.559 | | | |
| 9 | IBA (PH_3) | 0 | 0 | -16.679±0.731 | -63.569±13.657 | | | |
| 10 | LAOAG (PH_3) | 2.42×10^{-5}±1.21×10^{-5} | 0 | -3.790±0.318 | -43.183±13.842 | | | |
| 11 | LUZON CLARK AFB (PH_3) | 1.93×10^{-3}±7.13×10^{-6} | 0 | -6.231±0.377 | -30.425±11.145 | | | |
| 12 | MABINI PANGASINAN (PH_3) | 0 | 0 | -16.729±0.872 | -63.663±13.666 | | | |
| 13 | SANGLEY POINT (PH_1) | 0.547±0.103 | 0.011±0.006 | 0.879±0.041 | -0.492±0.265 | | | |

Table S3: Validation results for the downscaled temperature data. p-value and Nash-Sutcliffe coefficient (NSC, from ~ −∞ to 1, perfect match is 1) (Nash & Sutcliffe 1970). Mean±SD of p-Value and NSC; in bold p-value >0.5, 0<NSC<1.
| Site                          | Precipitation WATCH | p-value | Precipitation CRU | p-value | Precipitation WATCH NSC | Precipitation CRU NSC |
|------------------------------|---------------------|---------|-------------------|---------|-------------------------|----------------------|
| **Philippines**              |                     |         |                   |         |                         |                      |
| 1   AMBULONG (PH_1)          | 0.956±0.024         | 0.713±0.131 | 0.677±0.017     | 0.651±0.060 |
| 3   BAGUIO (PH_2/PH_3)       | 0.759±0.020         | 0.627±0.021 | 0.869±0.002     | 0.875±0.004 |
| 3   BAGUIO (PH_2/PH_3)       | 0.259±0.018         | 0.652±0.182 | 0.542±0.034     | 0.784±0.088 |
| 4   BALER (PH_3)             | 0.642±0.021         | 0.292±0.104 | -                 | -                   |
| 5   BOLINAO (PH_3)           | 0.645±0.033         | 0.414±0.163 | 0.866±0.007     | 0.574±0.223 |
| 6   CABANATUAN (PH_3)        | 0.642±0.021         | 0.296±0.108 | 0.761±0.015     | -0.716±0.530 |
| 7   CALAYAN (PH_3)           | 0.402±0.028         | 0.503±0.216 | -1.271±0.025    | -8.029±2.430 |
| 8   CASIGURAN (PH_3)         | 0.183±0.009         | 0.674±0.191 | -1.193±0.006    | -4.463±1.645 |
| 7   CLARK (PH_3)             | 0.570±0.016         | 0.301±0.115 | 0.859±0.003     | 0.533±0.240 |
| 10  CLAVERIA CAGAYAN (PH_3)  | 0.647±0.033         | 0.418±0.200 | -0.328±0.020    | -5.014±2.474 |
| 11  CONSUELO STA FE NUEVA VIZ (PH_2/PH_3) | 0.852±0.014 | 0.967±0.023 | 0.882±0.006     | 0.828±0.025 |
| 11  CONSUELO STA FE NUEVA VIZ (PH_2/PH_3) | 0.630±0.085 | 0.292±0.105 | -                 | -                   |
| 12  IBA (PH_2/PH_3)          | 0.623±0.019         | 0.291±0.099 | 0.867±0.007     | 0.114±0.311 |
| 13  LAOAG (PH_3)             | 0.941±0.030         | 0.313±0.137 | 0.888±0.001     | -0.087±0.497 |
| 14  LUZON CLARK AFB (PH_3)   | 0.690±0.018         | 0.413±0.137 | 0.862±0.003     | 0.678±0.165 |
| 15  MABINI PANGASINAN (PH_3) | 0.642±0.021         | 0.292±0.104 | 0.759±0.028     | -0.734±0.530 |
| 16  SANGLEY POINT (PH_1)     | 0.855±0.036         | 0.710±0.099 | 0.615±0.010     | 0.540±0.072 |
| 17  STA CRUZ LAGUNA (PH_1)   | 0.581±0.035         | 0.835±0.103 | -0.196±0.058    | 0.427±0.066 |
| 18  TUGUEGARAO (PH_3)        | 0.678±0.033         | 0.168±0.079 | 0.391±0.035     | -4.244±1.940 |
| 19  VIGAN (PH_3)             | 0.945±0.067         | 0.566±0.169 | 0.796±0.010     | 0.825±0.107 |
| **Vietnam**                  |                     |         |                   |         |                         |                      |
| 20  BINH THUY (VN_4)         | 0.686±0.010         | 0.480±0.097 | 0.824±0.002     | 0.089±0.182 |
| 21  HA NOI (VN1/VN_2)        | 0.117±0.005         | 0.136±0.012 | 0.176±0.010     | 0.268±0.017 |
| 21  HA NOI (VN1/VN_2)        | 0.111±0.006         | 0.112±0.022 | 0.145±0.011     | 0.177±0.040 |

Table S4: Validation results for the downscaled precipitation data. p-value and Nash-Sutcliffe coefficient (NSC, from ~∞ to 1, perfect match is 1) (Nash & Sutcliffe 1970). Mean±SD of p-Value and NSC; in bold p-value >0.5, 0<NSC<1.
Applying LPJmL for the first time on the resolution of 30 m made it possible to assess small-scale effects of global change on selected ESS. This is especially important for understanding the local land-use impacts in the homogeneously structured lowland sites as well as effects of changing temperature, which are especially pronounced in the heterogeneously structured highland sites (Pappas et al. 2015). Using fine-scale input data is also important to avoid adding further uncertainties in crop yield modelling (Hoffmann et al. 2016). However, fine-scale climate data can potentially introduce further uncertainties, depending on the down-scaling method applied. Our downscaled climate data shows high agreement with observation data for most of the study areas. The smaller agreement for two Philippine sites due to scarcity of observation data might lead to a slight under-/overestimation of change in ESS provision, but leaving the general pattern unaltered.

To assess changes in ESS we applied two different climate change scenarios, which cover two extreme emission trajectories as prescribed by SRES A2 and SRES B1 (Meehl et al. 2007). The SRES scenarios are comparable to recently developed RCP/SSP scenarios (van Vuuren et al. 2011; Riahi et al. 2017), which are lately applied in many studies. However, the SRES scenarios are still widely used (Fujimori et al. 2017; Zhu et al. 2017; e.g. Vermaat et al. 2017), as they allow easy interpretation and form special cases of the widened future climate and socio-economic pathways. For the DART-based land-use change scenario we applied the version utilizing SRES A1B. However, on such a small scale as being assessed by our study there is no feedback with the climate to be expected. Therefore we developed our High- and Low-conversion land-use change scenarios independently of climate change.

1.4. Validation of simulated rice yield
We compared on-site observation and farmers measures with simulation results. Observations took place between 2012 and 2014, farmer interviews in each study area were conducted between October 2011 and March 2012, simulated yield represents mean yield between 2010 and 2015.

| Study area          | observed          | farmers’ records | simulated          |
|---------------------|-------------------|------------------|--------------------|
| Laguna (PH_1)       | 4.379 ± 0.038     | 4.2 ± 1.2        | 3.009 ± 0.173      |
| Nueva Ecija (PH_2)  | 5.010 ± 0.921     | 5.6 ± 2.2        | 3.294 ± 0.198      |
| Ifugao (PH_3)*      | 2.142 ± 0.174     | NA               | 5.606 ± 0.217      |
| Hai Duong (VN_1)    | 3.314 ± 1.067     | 5.6 ± 0.7        | 3.052 ± 0.182      |
| Vinh Phuc (VN_2)    | 2.666 ± 0.340     | 5.5 ± 1.5        | 2.908 ± 0.173      |

* indicate highland study areas.
The values for simulated, observed and recorded rice yields are in the same range for most of the study areas. The uncertainties within the observed and the simulated yields are comparable, while the uncertainty within farmer’s records are the largest, especially for PH_2 and VN_4. The simulated values are for most of the study areas in the range of observations and records. However, for PH_1, PH_2 and VN_4 the simulated data underestimate the rice yield by about 35%. This is mainly due to the fact that LPJmL was not specifically adapted to model rice yields in these areas. It did not fully include multicropping (as practiced in PH_1 and PH_2) and might underestimate the yield under cooler conditions (as in VN_4). Nevertheless, our results show that the general amount of rice produced in this agro-ecosystem can be reproduced by the model and the trends in the changes due to climate and land-use change are valid.

### 1.5. Development of land-use change scenarios

**Scenario based on DART-BIO model**

One scenario was developed based on the world economy DART-BIO model (Calzadilla, Delzeit & Klepper 2014), utilizing SRES A1B, which accounts for socio-economic developments such as population growth and changes in consumption patterns to simulate the developments of crop quantities and prices (of rice for example). The DART-BIO model uses different land use types according to different crop suitability, productivity potential, and environmental impact in each of the agro-ecological zones (AEZs). We applied the simulated future changes in the AEZs to which our seven study sites belonged and matched the model’s agricultural categories to our SPOT-based land use categories to obtain estimates of the amount of projected land use change.

**Expert-based scenarios**

Together with local experts and stakeholders we developed two expert-based storylines for each study area. The ‘Low-conversion’ storyline represents a conservative scenario with relatively low rates of land conversions, while the ‘High-conversion’ storyline represents a more extreme scenario with relatively high rates of land-use change. The general description of the identified trends in land transformation and their quantification is provided by Table S6.
Table S6: Overview of the trends for development provided by local experts and the corresponding trends in the scenarios.

| General description of trends from experts | Quantified trends in scenarios |
|--------------------------------------------|--------------------------------|
| **Laguna (PH_1)**                          |                                |
| - increasing population,                   | - large increase in settlements from 4.5% to 12.4% ('Low') and to 13.4% ('High') |
| - more settlements (with corresponding increase in garden area -fruits/vegetables) | - changes in garden area – fruits from 44.1% to 43.6% ('Low') and to 44.0% ('High'), vegetables from 4% to 4.5% ('Low') and 5.0% ('High') |
| - less rice fields (loss of rice area to settlements, Philippines import rice) | - reduction in rice area from 18.7% to 15.0% ('Low') and to 13.1% ('High') |
| - possible reduction in forest (but no reduction in forest possible) | - no change in pasture (20.3%) |
| **Nueva Ecija (PH_2)**                     |                                |
| - increasing population                    | - large increase in settlements from 2.9% to 5.7% ('Low' and 'High') |
| - more settlements but less gardens         | - constant fruit area (9.9%) |
| - fruits constant                          | - change in vegetable area from 26.8% to 16.2% ('Low') and to 30.4% ('High') |
| - more or less rice area                    | - change in rice area from 57.4% to 66.1% ('Low') and to 48.8% ('High') |
| - rice replaces vegetables                  | - no change in pasture (1.9%) |
| - possible slight increase in forest cover  | - slight increase in forest from 0% to 3% ('High') |
| **Ifugao (PH_3)**                          |                                |
| - increasing population                     | - slight increase in settlements from 0.1% to 0.3% ('High') |
| - more settlements                          | - slight increase in gardens – fruits from 0% to 1.4% ('Low'), vegetables from 0.0% to 0.7% ('Low') |
| - little more gardens                       | - slight reduction in rice area from 3.7% to 3.0% ('High') |
| - no expected increase in rice area (constant or decrease) | - change in pasture from 29.0% to 25.0% ('Low') and to 33.0% ('High') |
| - possible reduction in forest              | - changes in forest from 67.1% to 69.1% ('Low') and to 63.7% ('High') |
| **Hai Duong (VN_1)**                        |                                |
| - more settlements (at the expense of rice) | - increase in settlements from 8.2% to 10.5% ('Low') and 12.8% ('High') |
| - more gardens                              | - increase in gardens - fruits from 12.1% to 14.7% ('Low') and 14.5% ('High'), vegetables from 10.7% to 13.0% ('Low') and 12.9% ('High') |
| - less rice                                 | - decrease of rice from 42.2% to 35.1% ('Low') and 33.8% ('High') |
| - little less forest                         | - no change in pasture (13.7%) |
|                                          | - slight decrease in forest from 3.7% to 3.0% ('High') |
Vinh Phuc (VN_2)
- more settlements
- more gardens (follow the same trends as settlements)
- less rice
- little reduction in forest
- increase of settlements from 3.4% to 4.7% ('Low') and to 5.9% ('High')
- increase in gardens – fruits from 14.8% to 19.3% ('Low') and to 26.2% ('High'), vegetables from 2.9% to 3.8% ('Low') and to 5.1% ('High')
- decrease in rice area from 29.7% to 26.7% ('Low') and to 23.8% ('High')
- no change in pasture (5.8%)

Lao Cai (VN_3)
- more settlements
- conversion of forest to gardens or pasture
- no direct conversion from forest to settlement
- more rice
- less forest
- increase of settlements from 1.2% to 1.7% ('Low') and to 5.8% ('High')
- increase of gardens – fruits from 0% to 1.4% ('Low') and to 7.5% ('High'), vegetables from 0% to 0.2% ('Low') and to 1.2% ('High')
- increase in rice area from 12.5% to 15.2% ('Low') and to 25.2% ('High')
- no change in pasture (6.8%)
- decrease of forest from 75.9% to 74.6% ('Low') and to 53.3% ('High')

Tien Giang (VN_4)
- more settlements
- more gardens (following the same trend as settlements)
- no reduction in rice area (rather increase in rice area)
- little reduction in forest
- increase in settlements from 1.7% to 2.6% ('Low') and to 4.1% ('High')
- increase in gardens – fruits from 13.3% to 17.0% ('Low') and to 14.7% ('High'), vegetables from 8.0% to 10.1% ('Low') and to 8.7% ('High')
- increase in rice area from 35.0% to 43.7% ('High')
- no change in pasture (23.5%)
- decrease of in forests from 10.9% to 4.4% ('High')
Laguna (PH_1)

| Landcover Class | Observed 2009 | Projected 'Low' | Projected 'High' | DART |
|-----------------|--------------|----------------|-----------------|------|
| Forest          | 0%           | 0%             | 0%              | 0%   |
| Fruits          | 44.1%        | 43.6%          | 44.0%           | 48.8%|
| Vegetables      | 4.0%         | 4.5%           | 5.0%            | 4.4% |
| Rice            | 18.7%        | 15.0%          | 13.1%           | 20.7%|
| Meadow          | 20.3%        | 20.3%          | 20.3%           | 17.4%|
| Settlements     | 4.5%         | 12.4%          | 13.4%           | 4.5% |

Nueva Ecija (PH_2)

| Landcover Class | Observed 2008 | Projected 'Low' | Projected 'High' | DART |
|-----------------|--------------|----------------|-----------------|------|
| Forest          | 0%           | 0%             | 3.0%            | 0%   |
| Fruits          | 9.9%         | 9.9%           | 9.9%            | 10.3%|
| Vegetables      | 26.8%        | 16.2%          | 30.4%           | 27.5%|
| Rice            | 57.4%        | 66.1%          | 48.8%           | 59.2%|
| Meadow          | 1.9%         | 1.9%           | 1.9%            | 0%   |
| Settlements     | 2.9%         | 5.7%           | 5.7%            | 2.9% |

Ifugao (PH_3)

| Landcover Class | Observed 2011 | Projected 'Low' | Projected 'High' | DART |
|-----------------|--------------|----------------|-----------------|------|
| Forest          | 67.1%        | 69.1%          | 63.7%           | 64.2%|
| Fruits          | 0%           | 1.4%           | 0%              | 0%   |
| Vegetables      | 0%           | 0.7%           | 0%              | 0%   |
| Rice            | 3.7%         | 3.7%           | 3.0%            | 4.1% |
| Meadow          | 29.0%        | 25.0%          | 33%             | 31.5%|
| Settlements     | 0.1%         | 0.1%           | 0.3%            | 0.1% |
Hai Duong (VN_1)

| landcover class | observed 2010 | projected 'Low' | 'High' | 'DART' |
|-----------------|--------------|-----------------|--------|--------|
| forest          | 3.7%         | 3.7%            | 3.0%   | 0%     |
| fruits          | 12.1%        | 14.7%           | 14.5%  | 13.4%  |
| vegetables      | 10.7%        | 13.0%           | 12.9%  | 11.8%  |
| rice            | 42.2%        | 35.1%           | 33.8%  | 46.7%  |
| meadow          | 13.7%        | 13.7%           | 13.7%  | 10.5%  |
| settlements     | 8.2%         | 10.5%           | 12.8%  | 8.2%   |

Vinh Phuc (VN_2)

| landcover class | observed 2010 | projected 'Low' | 'High' | 'DART' |
|-----------------|--------------|-----------------|--------|--------|
| forest          | 32.6%        | 32.6%           | 26.0%  | 27.3%  |
| fruits          | 14.8%        | 19.3%           | 26.2%  | 16.4%  |
| vegetables      | 2.9%         | 3.8%            | 5.1%   | 3.2%   |
| rice            | 29.7%        | 26.7%           | 23.8%  | 32.8%  |
| meadow          | 5.8%         | 5.8%            | 5.8%   | 6.3%   |
| settlements     | 3.4%         | 4.7%            | 5.9%   | 6.9%   |

Lao Cai (VN_3)

| landcover class | observed 2010 | projected 'Low' | 'High' | 'DART' |
|-----------------|--------------|-----------------|--------|--------|
| forest          | 75.9%        | 74.6%           | 53.3%  | 74.2%  |
| fruits          | 0%           | 1.4%            | 7.5%   | 0%     |
| vegetables      | 0%           | 0.2%            | 1.2%   | 0%     |
| rice            | 12.5%        | 15.2%           | 25.2%  | 13.8%  |
| meadow          | 6.8%         | 6.8%            | 6.8%   | 7.4%   |
| settlements     | 1.2%         | 1.7%            | 5.8%   | 4.4%   |
Spatial representation of land-use change scenarios

All scenarios, which were developed in the form of narratives, were transformed into GIS data/maps. For each scenario and study area, we generated spatially-explicit projections of potential land-use changes on a yearly basis, starting at the year of the SPOT satellite image available for the respective site (2009-2011) until 2030.

We developed an algorithm using ArcGIS 10.3 (ESRI, Redlands, CA) and Python 2.7 (Python Software Foundation, version 2.7, www.python.org) to compute the actual quantity and location of estimated land use transitions. The quantity of change for each land use category estimated by experts or by the DART-BIO model was projected until 2030 using a linear trend applied to annual timesteps. The spatial location of land conversion for each year was calculated based on a set of spatial rules considering the distance to existing land use classes in the previous year. We applied 4 main groups of rules:

1. Expansion (gain) of a land use class occurs close to existing areas of that land use class (i.e. new settlements occur close to already existing settlements, new rice close to already existing rice).
2. Reduction (loss) of a land use class occurs in areas that are far from settlements (i.e. rice fields are abandoned first in areas far from settlements).
3. Gardens (fruits and vegetables) follow the same trend as settlements (e.g. if settlements increase by a certain percentage annually, gardens increase at the same percentage annually).
4. The ratio between fruits and vegetables remains constant at the level as it was identified in the land use classification based on the SPOT satellite images.

Multiple transitions between land use class were possible within each timestep. To ensure consistency, the sequence of conversions followed a predefined order, e.g. conversions to
settlements occurred first on bare land, then on rice fields, etc. The matrix in Table S1 shows the sequence of conversion applied for all scenarios. The blank fields in the table signify that such conversion was not assumed, e.g. settlements cou not convert to other types of land use.

### Table S7: Order of conversions from one to another land use class.

| to / from | bare | forest | fruits | vegetables | rice | meadow | settlements |
|-----------|------|--------|--------|------------|------|--------|-------------|
| bare      |      |        |        |            |      |        |             |
| forest    |      |        |        |            |      |        |             |
| fruits    | 6    | 10     |        |            | 16   | 19     |             |
| vegetables| 7    | 11     | 13     | 14         | 9    | 18     |             |
| rice      | 12   | 15     | 13     | 14         |      |        |             |
| meadow    | 21   |        |        |            |      |        |             |
| settlement| 1    | 5      | 3      | 4          | 2    |        |             |

### Limitations
There are also uncertainties inherent in the assumptions used to develop the three LUC scenarios for each study area. We based these either on expert’s knowledge or on results of the world economy model DART-BIO (Calzadilla et al. 2014). While the DART scenario showed similar trends for all study areas, the expert-based scenarios were site specific. We limited the uncertainties in the scenario development by applying a co-design approach, including local stakeholders and scientists, which gave us the opportunity to include local characteristics and to make the scenarios more realistic. Thus, our study design is in agreement with the recommendations of previous studies (Harmáčková & Vačkář 2015; e.g. Wiggering & Steinhardt 2015) who suggested that small-scale and site-specific LUC scenarios are needed to systematically assess the effects of local management and climate change effects. However, we are aware that this approach was influenced by the selection of stakeholders involved. In addition, our land-use scenarios are limited in the sense that they solely focused on land expansion, while ignoring potential changes in land-use intensity and management. Management practices in rice agro-ecosystems can be heterogeneous, varying largely between individual farmers, and they cannot be directly accounted for in the dynamic vegetation model, which focusses on generic processes. Therefore, our results need to be interpreted with the knowledge that site-specific management, e.g. pesticide application or crop rotation, may also have a significant effect on the considered ESS.
2. Results – supporting material

Table S8: Provided ecosystem services in the beginning end the end of the current century. Red numbers indicate an increase in 2099 compared to 2000, while blue numbers indicate a decrease. Order of land use scenarios within SRES scenarios is Const, Low, High, DART.

|                | highland sites | lowland sites |
|----------------|----------------|---------------|
|                | 2000           | 2090-99       | 2000           | 2090-99       |
|                | average        | average       | average        | average       |
|                | SRES A2        | SRES B1       | SRES A2        | SRES B1       |
| carbon storage | 23.86          | 21.73         | 22.70          | 11.16         |
| [kg C m\(^{-2}\)] |                | 21.79         | 22.76          | 9.15          |
|                |                | 19.97         | 20.81          | 9.74          |
|                |                | 21.04         | 21.97          | 8.13          |
|                |                |                |                | 8.83          |
|                |                |                |                | 8.07          |
|                |                |                |                | 8.51          |
|                |                |                |                | 7.78          |
|                |                |                |                | 8.20          |
| carbon sequestration | 330.18         | 307.03        | 310.85         | 725.57        |
| [g C m\(^{-2}\) yr\(^{-1}\)] |                | 294.62        | 297.69         | 613.89        |
|                |                | 432.32        | 426.52         | 694.96        |
|                |                | 331.64        | 335.31         | 678.03        |
|                |                |                |                | 768.22        |
| irrigation water | 1029.80         | 1160.92       | 1093.23        | 879.52        |
| [mm yr\(^{-1}\)] |                | 1162.26       | 1094.98        | 1148.69       |
|                |                | 1169.10       | 1097.23        | 1151.75       |
|                |                | 1162.34       | 1094.53        | 1147.20       |
| rice production | 9.02           | 5.93          | 7.20           | 15.52         |
| [kT yr\(^{-1}\)] |                | 6.36          | 7.73           | 15.35         |
|                |                | 9.56          | 11.62          | 13.85         |
|                |                | 6.50          | 7.89           | 16.65         |
|                |                |                |                | 22.09         |

A

![Graph A: SRES A2 and SRES B1 for carbon storage](image)

B

![Graph B: SRES A2 and SRES B1 for carbon sequestration](image)
Figure S2: Time series as 10-year running mean for (A) stored carbon \([\text{g C m}^{-2}]\), (B) for carbon sequestration \([\text{g C m}^{-2} \text{yr}^{-1}]\), (C) for the provision of irrigation water \([\text{mm yr}^{-1}]\) and (D) for rice production on the study area \([\text{kT yr}^{-1}]\). The range of values for the respective other SRES scenario is indicated as grey area.
Figure S3: Relative changes (compared to 2000) in the provision of ES caused by LUC alone (difference in relative change between climate change only simulation (const) and the three land use change scenarios in the SRES scenario A2. Time series indicate values for constant land use and the three different land use change scenarios (10-year running mean). Figure Analogue to Figure 4 in main text.

Figure S4: Relative change in the provision of the four ecosystem services (compared to 2000) in the SRES scenario B1. Boxplots for 2080-2099 in highland sites (A) and lowland sites (B). Asterisks indicate significant difference to constant land use scenarios (const), p<0.05.
Figure S5: Relative change in the provision of the four ecosystem services (compared to 2000) in the SRES scenario B1. Time series indicate values for constant land use and the three different land use change scenario (10-year running mean).

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