Supplementary Material

Mapping and analysing cropland use intensity from a NPP perspective

Maria Niedertscheider, Thomas Kastner, Tamara Fetzel, Helmut Haberl, Christine Kroisleitner, Christoph Plutzar, Karl-Heinz Erb

1. Supplementary text

1.1. Description of the input data sets and potential related uncertainties

Gridded global maps of crop yields and areas planted for 175 different crops were derived from the EarthStat database (Monfreda et al. 2008). These data sets are based on agricultural inventory data, combining national and sub-national census statistics and match spatial patterns of the M3 global cropland map (Ramankutty et al. 2008), which was derived through a combination of remote sensing and statistical data. For more metadata information refer to the EarthStat website and related publications (www.earthstat.org). Crop maps are available on a 5 arcminutes resolution (ca. 10x10km at the equator) and present average values between the years 1997 and 2003.

Nitrogen (N) application rates provided in kg N per gridcell were also taken from the EarthStat (Mueller et al. 2012) and match the resolution and spatial pattern of the M3 crop yield map (Ramankutty et al. 2008). This dataset is based on (sub-) national data combining statistical data and expert guesses from a range of different sources. Nitrogen application rates also include consumption on pasture land. Hence, N-application on pasture land (derived through multiplying fertilization rates with km2 pasture land per grid cell given by Ramankutty et al. 2008) has to be subtracted from total N consumption in order to derive N application on croplands only.

Note that the spatial resolution of 5 arcminutes for N and cropland maps is a potential source of uncertainty, because it likely does not allow capturing small-scale croplands in mosaic landscapes. Hence agronomic relevance and relevance for agricultural planning is limited (Fritz et al. 2013; Thenkabail et al. 2010). Also, since these maps are homogenized with statistical data, potential drawbacks in statistical accounts are also inherited in the gridded maps. These issues likely explain some of the differences in spatial cropland patterns between maps based on remote sensing techniques alone and the maps used in this study. Since the aim of this study was to investigate the relation between N inputs and NPP_{act} on croplands, and both maps follow similar methodological logics, we consider the underlying maps as appropriate for our purpose.
We used the share of areas equipped with irrigation (Döll & Siebert 2000) as a proxy for irrigation inputs in this study. Note, that the mere presence of irrigation infrastructure does not necessarily imply that a field is actually irrigated. A benefit of using this maps is that it is also based on a combination of remote sensing data and agricultural statistics, thus resembling methodological features of the crop yield and N maps and it has the same spatial resolution as these maps.

Potential productivity ($\text{NPP}_{\text{pot}}$) is defined as the productivity of ecosystems under exclusion of human land use (but under current climate). The $\text{NPP}_{\text{pot}}$ map used in this study was derived by the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM, Sitch et al. 2003). In order to highlight potential uncertainties in the LPJ-map we compared $\text{NPP}_{\text{pot}}$ patterns on croplands on a country-basis with $\text{NPP}_{\text{pot}}$ results derived through an empirical model (Lieth 1975) which considers the relation between temperature and precipitation as the key determinant for NPP patterns (Figure S6). This empirical model is widely known as the Miami model and compared to LPJ-model outputs it is closer to real data per se. We calculated $\text{NPP}_{\text{pot}}$ based on this formula using temperature and climate data from the WorldClim database (Hijmans et al. 2005). Results reveal high correlation between both maps (correlation coefficient of 0.82, refer to Figure S6), but disagreement slightly increased at higher $\text{NPP}_{\text{pot}}$ levels.

Figure S6 proofs that uncertainty related to $\text{NPP}_{\text{pot}}$ can be rather high for several countries and it is impossible to judge which model provides the more appropriate results. To our view the benefits of using LPJ-model outputs over the empirical model include an advanced representation of the water cycle (Gerten et al. 2004), integration of river flows, fire-response attributes and competition between ten plant functional types. In terms of these features the Lieth model is rather reductionist, but nevertheless it is more close to “real data”, because it uses an empirically derived formula and actual climate data. The rich experience with LPJ-derived NPPot in several HANPP studies at the global, regional and national level (Plutzar et al. 2015; Niedertscheider et al. 2014; Niedertscheider & Erb 2014; Niedertscheider et al. 2012; Kastner 2009; Haberl et al. 2007), was another argument for implementation in this study.

1.2. Calculating biomass harvest scenarios under redistribution of global N

We used the linear models for biomass harvest and N-inputs (Table S3) in order to calculate biomass harvest scenarios (refer to Table 2 in the main text). Similar to Figure 5 in the main text the linear model is based on N-input classes with equal intervals of 2.5 kgN/ha/yr. Since we were interested in analysing the potentials to increase harvest per each class of N, we used the harvest level at the upper third quartile for the linear model. We did not use the maximum harvest level in order to avoid artefacts and to provide a likely more realistic and conservative assumption. Global N and NPP profiles for all biomes are shown in Table S4.
2. Supplementary figures

Figure S1: Potential/natural NPP on global croplands expressed in gC/m²/yr.

Figure S2: current NPP (NPP<sub>act</sub>) on global croplands expressed in gC/m²/yr.
Figure S3: Levels of used biomass per area [gC/m2/yr] broken down to the five biomes and shown separately for each class of N-NPAct% (a-i); the color codes match Figure 3 in the main text. The secondary axis (hollow dot) shows the contribution to the global biomass production.
Figure S4: Effects of increasing levels of irrigation (shown as classes in intervals of 1% irrigated cropland) on NPP_{act} % of NPP_{pot} (top figures) shown separately for the main biomes (b-f) and globally (a). Graphs represent box plots of the 2nd and 3rd quartile (grey shaded area) per irrigation class, the black dots indicate the median of NPP_{act}. R^2 values refer to correlation between the NPP_{act} median of each group and Nitrogen inputs.
Figure S5: Global biomes adapted from Olson et al. (2001). White areas are biomes without pixels of more than 5% cropland coverage. Refer to table S2 for the classification scheme.

Figure S6: Comparison between empirical derived NPPpot after the Lieth formula and NPPpot derived from the LPJ-DGVM used in this study. The correlation is based on NPPpot for croplands on a country basis. Both maps show high correlation, with a coefficient of $R^2 = 0.82$. 
3. Supplementary Tables

Table S1: Crop factors used to convert crop yields in fresh weights into Carbon units. DM refers to the dry matter fraction, HI refers to the harvest index and RS refers to the root shoot ration. The Carbon content (CC) of dry matter fractions was assumed 50% for all crops. HI and DM factors are based on Krausmann et al. (2008; 2013), who distinguish HI-s for five different world regions. In case of lacking information, data was supplemented with factors given by Monfreda et al. (2008). Both authors derived their crop factors from literature.

| Crop                  | DM  | RS  | HI               |
|-----------------------|-----|-----|------------------|
|                       | Globa l factor | Globa l factor | East Asia | East Europe | Latin America | North Africa and W. Asia | North America and Oc. | South and Central Asia | Subsaharan Africa | West Europe |
| Barley                | 0.86 | 0.5 | 0.4           | 0.4       | 0.4          | 0.45  | 0.35           | 0.35           | 0.45           |
| Beans, Dry            | 0.9  | 0.74 | 0.7           | 0.5       | 0.7          | 0.7   | 0.7            | 0.7            | 0.5            |
| Broad Beans, Dry      | 0.9  | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.5            | 0.7            | 0.5            |
| Buckwheat             | 0.89 | 0.8 | 0.4           | 0.4       | 0.4          | 0.45  | 0.37           | 0.3            | 0.5            |
| Canary Seed           | 0.9  | 0.88 | 0.4           | 0.4       | 0.4          | 0.45  | 0.37           | 0.3            | 0.5            |
| Cassava               | 0.3  | 0.85 | 0.55          | 0.55      | 0.55         | 0.55  | 0.55           | 0.55           | 0.55           |
| Chick-Peas            | 0.89 | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.7            | 0.7            | 0.5            |
| Cow Peas, Dry         | 0.89 | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.7            | 0.7            | 0.5            |
| Fonio                 | 0.86 | 0.8 | 0.4           | 0.4       | 0.4          | 0.4   | 0.45           | 0.37           | 0.3            |
| Lentils               | 0.89 | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.5            | 0.7            | 0.5            |
| Lupins                | 0.85 | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.5            | 0.7            | 0.5            |
| Maize                 | 0.86 | 0.85 | 0.25          | 0.35      | 0.25         | 0.25  | 0.45           | 0.22           | 0.22           |
| Millet                | 0.88 | 0.88 | 0.25          | 0.35      | 0.25         | 0.25  | 0.45           | 0.22           | 0.22           |
| Oats                  | 0.86 | 0.71 | 0.4           | 0.4       | 0.4          | 0.45  | 0.37           | 0.3            | 0.5            |
| Peas, Dry             | 0.89 | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.5            | 0.7            | 0.5            |
| Pigeon peas           | 0.89 | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.5            | 0.7            | 0.5            |
| Potatoes              | 0.22 | 0.8 | 0.5           | 0.5       | 0.5          | 0.5   | 0.5            | 0.5            | 0.5            |
| Quinoa                | 0.86 | 0.8 | 0.4           | 0.4       | 0.4          | 0.4   | 0.45           | 0.37           | 0.3            |
| Rapeseed              | 0.88 | 0.8 | 0.3           | 0.35      | 0.3          | 0.35  | 0.3            | 0.3            | 0.35           |
| Rye                   | 0.86 | 0.76 | 0.4           | 0.4       | 0.4          | 0.45  | 0.37           | 0.3            | 0.5            |
| Sorghum               | 0.89 | 0.8 | 0.25          | 0.35      | 0.25         | 0.25  | 0.45           | 0.22           | 0.22           |
| Soybeans              | 0.9  | 0.85 | 0.45          | 0.4       | 0.4          | 0.45  | 0.4            | 0.4            | 0.45           |
| Sugar beets           | 0.23 | 0.8 | 0.6           | 0.65      | 0.6          | 0.65  | 0.6            | 0.6            | 0.65           |
| Sugar cane            | 0.175| 0.85 | 0.6           | 0.6       | 0.6          | 0.6   | 0.6            | 0.6            | 0.6            |
| Sweet potatoes        | 0.3  | 0.8 | 0.5           | 0.5       | 0.5          | 0.5   | 0.5            | 0.5            | 0.5            |
| Triticale             | 0.86 | 0.8 | 0.4           | 0.4       | 0.4          | 0.4   | 0.45           | 0.37           | 0.3            |
| Vetches               | 0.9  | 0.85 | 0.7           | 0.5       | 0.7          | 0.7   | 0.5            | 0.7            | 0.5            |
| Wheat                 | 0.86 | 0.81 | 0.4           | 0.4       | 0.4          | 0.45  | 0.37           | 0.3            | 0.5            |
| Yams                  | 0.26 | 0.8 | 0.5           | 0.5       | 0.5          | 0.5   | 0.5            | 0.5            | 0.5            |
| Item                                      | Value1 | Value2 | Value3 |
|-------------------------------------------|--------|--------|--------|
| Abaca                                     | 0.8    | 0.5    | 0.28   |
| Agave Fibers, other                      | 0.8    | 0.5    | 0.28   |
| Alfalfa                                   | 0.2    | 0.53   | 1      |
| Almonds                                   | 0.96   | 0.75   | 0.28   |
| Anise, Badian and Fennel                 | 0.8    | 0.5    | 0.28   |
| Apples                                    | 0.15   | 0.75   | 0.3    |
| Apricots                                  | 0.15   | 0.75   | 0.3    |
| Areca                                     | 0.8    | 0.5    | 0.28   |
| Artichokes                                | 0.15   | 0.85   | 0.45   |
| Asparagus                                 | 0.08   | 0.85   | 0.45   |
| Avocados                                  | 0.26   | 0.75   | 0.3    |
| Bambara beans                             | 0.9    | 0.85   | 0.49   |
| Bananas                                   | 0.25   | 0.75   | 0.3    |
| Beets for fodder                          | 0.12   | 0.85   | 1      |
| Berries, other                            | 0.19   | 0.75   | 0.3    |
| Blueberries                               | 0.17   | 0.75   | 0.3    |
| Brazil                                    | 0.8    | 0.75   | 0.28   |
| Cabbage for fodder                        | 0.08   | 0.85   | 1      |
| Cabbage                                   | 0.08   | 0.85   | 1      |
| Carobs                                    | 0.3    | 0.75   | 0.3    |
| Carrots                                   | 0.12   | 0.85   | 0.45   |
| Carrots for fodder                        | 0.12   | 0.85   | 1      |
| Cashewapple                               | 0.14   | 0.75   | 0.28   |
| Cashew nuts                               | 0.19   | 0.75   | 0.3    |
| Castor beans                              | 0.73   | 0.8    | 0.52   |
| Cauliflower                               | 0.09   | 0.85   | 0.45   |
| Cereals, other                            | 0.88   | 0.8    | 0.4    |
| Cereals, other                            | 0.88   | 0.8    | 0.4    |
| Cherries                                  | 0.2    | 0.75   | 0.3    |
| Chestnuts                                 | 0.92   | 0.75   | 0.28   |
| Chicory                                   | 0.8    | 0.8    | 0.28   |
| Chillies & Peppers, Green                 | 0.08   | 0.85   | 0.45   |
| Cinnamon                                  | 0.8    | 0.5    | 0.28   |
| Citrus Fruit, other                       | 0.13   | 0.75   | 0.3    |
| Clover                                    | 0.2    | 0.5    | 1      |
| Cloves                                    | 0.8    | 0.5    | 0.28   |
| Cocoa                                     | 0.8    | 0.5    | 0.28   |
| Coconuts                                  | 0.6    | 0.5    | 0.28   |
| Coffee, Green                             | 0.9    | 0.5    | 0.28   |
| Coir                                      | 0.8    | 0.8    | 0.28   |
| Seed cotton                               | 0.9    | 0.86   | 0.55   |
| Cranberries                               | 0.12   | 0.75   | 0.3    |
| Cucumbers                                 | 0.04   | 0.85   | 0.45   |
| Currants                                  | 0.16   | 0.75   | 0.3    |
| Item                          | 2009 | 2010 | 2011 |
|-------------------------------|------|------|------|
| Dates                         | 0.78 | 0.75 | 0.3  |
| Eggplants                     | 0.08 | 0.85 | 0.45 |
| figs                          | 0.23 | 0.8  | 0.28 |
| Fibre Crops, other            | 0.8  | 0.8  | 0.28 |
| Fibre Crops, other            | 0.8  | 0.8  | 0.28 |
| Flax                          | 0.8  | 0.8  | 0.28 |
| Forage Products, other        | 0.2  | 0.65 | 1    |
| Fruit Fresh, other            | 0.19 | 0.75 | 0.3  |
| Fruit Tropical Fresh, other   | 0.19 | 0.75 | 0.3  |
| Garlic                        | 0.39 | 0.85 | 0.45 |
| Ginger                        | 0.13 | 0.5  | 0.28 |
| Gooseberries                  | 0.11 | 0.75 | 0.3  |
| Grapes                        | 0.19 | 0.75 | 0.3  |
| Grasses, other                | 0.2  | 0.65 | 1    |
| Green beans                   | 0.1  | 0.85 | 0.45 |
| Green corn (maize)            | 0.28 | 0.85 | 0.45 |
| Peas, Green                   | 0.22 | 0.85 | 0.45 |
| Groundnuts in shell           | 0.92 | 0.8  | 0.4  |
| Natural gums                  | 0.35 | 0.5  | 0.28 |
| Hazelnuts                     | 0.8  | 0.75 | 0.28 |
| Hemp fibre and tow            | 0.8  | 0.8  | 0.28 |
| Hempseed                      | 0.95 | 0.8  | 0.52 |
| Hops                          | 0.2  | 0.5  | 0.28 |
| Jute                          | 0.87 | 0.8  | 0.28 |
| Kapok fibre                   | 0.8  | 0.5  | 0.28 |
| Kapokseed                     | 0.8  | 0.5  | 0.28 |
| Karite nuts                   | 0.8  | 0.5  | 0.28 |
| Kiwi                          | 0.13 | 0.75 | 0.3  |
| Kolanuts                      | 0.95 | 0.5  | 0.28 |
| Legumes, other                | 0.2  | 0.65 | 1    |
| Lemons and limes              | 0.13 | 0.75 | 0.3  |
| Lettuce                       | 0.05 | 0.85 | 0.45 |
| Linseed                       | 0.9  | 0.8  | 0.52 |
| Maize for forage and silage   | 0.35 | 0.85 | 1    |
| Mangoes                       | 0.18 | 0.75 | 0.3  |
| Mate                          | 0.9  | 0.5  | 0.28 |
| Melonseed                     | 0.9  | 0.8  | 0.52 |
| Mixed grain                   | 0.88 | 0.8  | 0.4  |
| Mixed grasses                 | 0.2  | 0.65 | 1    |
| Mushrooms                     | 0.1  | 0.85 | 0.45 |
| Mustard seed                  | 0.9  | 0.8  | 0.52 |
| Nutmeg, Mace and              | 0.8  | 0.5  | 0.28 |
| Crop                  | Value 1 | Value 2 | Value 3 |
|-----------------------|---------|---------|---------|
| Cardamons             | 0.8     | 0.75    | 0.28    |
| Nuts, other           | 0.8     | 0.5     | 0.28    |
| Oil palm fruit        | 0.73    | 0.8     | 0.52    |
| Oliseeds, other       | 0.11    | 0.85    | 0.45    |
| Okra                  | 0.4     | 0.5     | 0.28    |
| Olives                | 0.09    | 0.85    | 0.45    |
| Oranges               | 0.14    | 0.5     | 0.3     |
| other crops           | 0.51    | 0.741   | 0.429   |
| Papayas               | 0.11    | 0.75    | 0.3     |
| Peaches and nectarines| 0.11    | 0.75    | 0.3     |
| Pears                 | 0.17    | 0.75    | 0.3     |
| Peppermint            | 0.2     | 0.5     | 0.28    |
| Pepper                | 0.8     | 0.5     | 0.28    |
| Persimmons            | 0.22    | 0.75    | 0.3     |
| Pimento               | 0.8     | 0.8     | 0.28    |
| Pineapples            | 0.15    | 0.75    | 0.3     |
| Pistachios            | 0.947   | 0.75    | 0.28    |
| Plantains             | 0.34    | 0.75    | 0.3     |
| Plums                 | 0.19    | 0.75    | 0.3     |
| Pop corn              | 0.89    | 0.85    | 0.45    |
| Poppy seed            | 0.95    | 0.8     | 0.52    |
| Pulses, other         | 0.9     | 0.85    | 0.49    |
| Pumpkins, Squash, Gourds| 0.09 | 0.85 | 0.45 |
| Pyrethrum, Dried Flowers| 0.95 | 0.5 | 0.28 |
| Quinces               | 0.16    | 0.75    | 0.3     |
| Ramie                 | 0.9     | 0.5     | 0.28    |
| Raspberries           | 0.16    | 0.75    | 0.3     |
| Rice                  | 0.89    | 0.8     | 0.4     |
| Roots and Tubers, other| 0.2     | 0.8     | 0.4     |
| Natural rubber        | 0.35    | 0.5     | 0.28    |
| Rye grass for forage  | 0.2     | 0.65    | 1       |
| Safflower seed        | 0.95    | 0.8     | 0.52    |
| Sesame seed           | 0.94    | 0.8     | 0.52    |
| Sisal                 | 0.92    | 0.5     | 0.28    |
| Sorghum for forage and silage | 0.35 | 0.85 | 1 |
| Sour cherries         | 0.1     | 0.75    | 0.3     |
| Spices, other         | 0.8     | 0.5     | 0.28    |
| Spinach               | 0.1     | 0.85    | 0.45    |
| Strawberries          | 0.1     | 0.75    | 0.3     |
| String                | 0.13    | 0.85    | 0.45    |
| Sugar Crops, other    | 0.56    | 0.85    | 0.28    |
### Table S2: Aggregation of biome classes given by Olson et al. (2001) into five classes used here according to similar biophysical characteristics.

| This study                          | Respective Olson classes                                      |
|-------------------------------------|----------------------------------------------------------------|
| Temperate Forest Biome              | • Temperate Broadleaf and Mixed Forests                       |
|                                     | • Temperate Coniferous Forests                                |
| (Sub-) Trop. Forest Biome           | • Tropical and Subtropical Moist Broadleaf Forests            |
|                                     | • Tropical and Subtropical Dry Broadleaf Forests              |
|                                     | • Tropical and Subtropical Coniferous Forests                 |
| Temperate Grassland Biome           | • Temperate Grasslands, Savannas, and Shrublands              |
|                                     | • Montane Grasslands and Shrublands                           |
| (Sub-) Trop. Grassland Biome        | • Tropical and subtropical grasslands, savannas, and shrublands|
|                                     | • Mediterranean Forests, Woodlands, and Scrub                  |
| Deseret and Xeric Shrub Biome       | • Deserts and Xeric Shrublands                                |

### Table S3: Linear models used for calculating biomass harvest (y) along rising N-inputs (x).

| Biome                           | Linear models          |
|---------------------------------|------------------------|
| Temperate Forest Biome          | $y = 31.962x + 87.17$  |
| (Sub-) Trop. Forest Biome       | $y = 35.273x + 96.089$ |
| Temperate Grassland Biome       | $y = 32.644x + 93.581$ |
| (Sub-) Trop. Grassland Biome    | $y = 16.882x + 158.57$ |
| Global                          | $y = 33.3x + 86.019$   |
Table S4: NPP and N profiles of five global biomes. (1) Cropland area in Million km² (2) potential NPP in gC per m²/yr; (3) average N-inputs.

| Indicator                      | Unit      | Temperate Forest Biome | (Sub-) Trop. Forest Biome | Temperate Grassland Biome | (Sub-) Trop. Grassland Biome | Deserts and Xeric Shrubs Biome² | Global |
|--------------------------------|-----------|------------------------|---------------------------|---------------------------|-----------------------------|---------------------------------|--------|
| (1) Cropland area              | [M km²]   | 3.9                    | 3.6                       | 3.2                       | 2.5                         | 1.3                             | 14.5   |
| (2) NPPₚₑᵗ                     | [gC/m²/yr]| 523.9                 | 748                       | 465.2                     | 471.7                       | 180.2                           | 526.3  |
| (3) Average N fertilization    | [kg/ha/yr]| 84.3                  | 60.5                      | 36.0                      | 21.2                        | 59.4                            | 54.1   |

4. References

Döll, P. & Siebert, S., 2000. A digital global map of irrigated areas. *Icic Journal*, 49(2), pp.55–66.

Fritz, S. et al., 2013. The need for improved maps of global cropland. *Eos, Transactions American Geophysical Union*, 94(3), pp.31–32.

Gerten, D. et al., 2004. Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology*, 286(1), pp.249–270.

Haberl, H. et al., 2007. Quantifying and mapping the human appropriation of net primary production in earth’s terrestrial ecosystems. *Proceedings of the National Academy of Sciences*, 104(31), p.12942.

Hijmans, R.J. et al., 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25, pp.1965–1978.

Kastner, T., 2009. Trajectories in human domination of ecosystems: Human appropriation of net primary production in the Philippines during the 20th century. *Ecological Economics*, 69(2), pp.260–269.

Krausmann, F. et al., 2013. Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences*. Available at: http://www.pnas.org/content/early/2013/05/30/1211349110.short [Accessed June 21, 2013].

Krausmann, F. et al., 2008. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics*, 65(3), pp.471–487.

Lieth, H., 1975. Modeling the primary productivity of the world. In *Primary productivity of the biosphere*. Springer, pp. 237–263. Available at: http://link.springer.com/chapter/10.1007/978-3-642-80913-2_12 [Accessed November 26, 2015].

Monfreda, C., Ramankutty, N. & Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, 22(1), pp.1–19.

Mueller, N.D. et al., 2012. Closing yield gaps through nutrient and water management. *Nature*, 490(7419), pp.254–257.
Niedertscheider, M. et al., 2014. Exploring the effects of drastic institutional and socio-economic changes on land system dynamics in Germany between 1883 and 2007. *Global Environmental Change*, 28, pp.98–108.

Niedertscheider, M. & Erb, K., 2014. Land system change in Italy from 1884 to 2007: Analysing the North–South divergence on the basis of an integrated indicator framework. *Land Use Policy*, 39, pp.366–375.

Niedertscheider, M., Gingrich, S. & Erb, K.-H., 2012. Changes in land use in South Africa between 1961 and 2006: an integrated socio-ecological analysis based on the human appropriation of net primary production framework. *Regional Environmental Change*, 12(4), pp.715–727.

Olson, D.M. et al., 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience*, 51(11), pp.933–938.

Plutzar, C. et al., 2015. Changes in the spatial patterns of human appropriation of net primary production (HANPP) in Europe 1990–2006. *Regional Environmental Change*, pp.1–14.

Ramankutty, N. et al., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles*, 22(1), p.GB1003.

Sitch, S. et al., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, 9(2), pp.161–185.

Thenkabail, P.S. et al., 2010. A holistic view of global croplands and their water use for ensuring global food security in the 21st century through advanced remote sensing and non-remote sensing approaches. *Remote sensing*, 2(1), pp.211–261.