Supporting information

Land management: data availability and process understanding for global change studies

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Table S1. Selected management activities. The review focusses on the individual management activities in the flagged ecosystem types.

Management activity	Definition	Closed forest	Open woodlands	Grazing land	Cropland	Wetlands
Forestry harvest	Extraction of woody biomass (mainly boles, but also bark and branches), by means of clear cutting or selective cutting	x	x			
Tree species selection	Selection of tree species by means of planting of tree seedlings	x				
Grazing and mowing harvest	Herbaceous biomass extraction, mainly by roaming ruminant livestock, or by mowing appliances		x	x		
Crop harvest and crop residue management	Biomass extraction of primary (e.g. grain) and secondary biomass products (e.g. straw), post-harvest management of residues (e.g. leaving on field, ploughing in, removing)				x	
Crop species selection	Selection of crop species by means of planting or herbicides				x	
N-fertilization	Application of N-containing substances (of natural or synthetic origin) to soils in order to sustain plant growth			x	x	
Tillage	Mechanical preparation of soils, including digging, stirring, hoeing, raking, overturning, etc., by use of machinery or muscle power				x	
Irrigation	Artificial application of water to ecosystems, at least once a year				x	
Artificial drainage of wetlands	Removing water from a wetlands for the purpose of agriculture, recreation or housing					x
Fire as management tool	Ignition of controlled fires to reduce biomass stocks, e.g. for opening vegetation in order to facilitate hunting or livestock grazing, to improve plant growth, or to reduce the threat of lightning fires. Includes also fire prevention in naturally fire-prone ecosystems	x	x	x	x	

Summary of data status, underlying Table 1

1. Forestry harvest

Overall, largest data gaps exist for the sparsely forested regions in the northern hemisphere and the arid regions between the tropics and the temperate zone, regions in which definitorial ambiguities as well as data uncertainties prevail. In general terms, data on wood harvest is surprisingly limited in the light of the importance of forests for understanding many aspects of the Earth system. For example, forest contain the vast majority of the global standing biomass (Pan *et al.*, 2013). However, spatially explicit data on recent forest harvest volumes are becoming available (Plutzar *et al.*, 2015; Levers *et al.*, 2014) for the continental scale, i.e. Europe. A global forest harvest map is provided by Haberl et al. (2007), following a top-down system approach that allocates harvest over the entire used forest area and not to the actually harvested gridcells. A global map that discerns used from unsued forest is currently not available, but maps discerning fragmented from intact forests are available which can serve as proxies (Potapov *et al.*, 2008), as well as the reconnaissance-level inventory maps used for wilderness mapping (McCloskey & Spalding, 1989; Sanderson *et al.*, 2002). This lack of data, exacerbated by the absence of a commonly agreed definition for the extent of forest (Sasaki & Putz, 2009; Hansen *et al.*, 2014; Tropek *et al.*, 2014) results in large uncertainties for estimates of used vs unused forests and for timber harvest intensity.

Global time series on roundwood harvest, discerning coniferous and deciduous wood, has been compiled by the FAO since 1961 at the national level. Uncertainty related to wood harvest is large (a possible underreporting by FAO of >30% is estimated;(Krausmann *et al.*, 2008); (Bais *et al.*, 2015)), mainly due to massive uncertainties (factor two) related to the use of woodfuel. Longer time series have been reconstructed, for harvest volumes as well as areas under harvest (e.g. (Hurtt *et al.*, 2011; Krausmann *et al.*, 2013)). These reconstructions come with considerable uncertainties (Erb *et al.*, 2013; Birdsey & Pan, 2015) as they are based on extrapolations of per-capita wood demand, human population change and on standing biomass simulations from simple vegetation models.

Another valuable data source for forest harvesting data are forest inventories, often available at considerable spatial resolution and, in some exceptional cases, for time series that go back to 1948 (Tomppo *et al.*, 2010). The readily available global summary by the Forest Resource Assessment is also available at the national level and goes back to 1948 (see e.g. http://www.fao.org/forestry/fra/52045/en/), but is prone to data gaps and to large uncertainties, in particular for the Southern hemisphere (Houghton, 2005; Pan *et al.*, 2011; Mitchard *et al.*, 2013, 2014; Avitabile *et al.*, 2016).

2. Tree species selection

Data on tree species composition and changes therein is generally scarce, especially at fine spatial resolutions. Main tree species classes are captured by global-scale, country-level databases such as the FAO's Forest Resource Assessment (FAO, 2010), but suffer from the same problems as data for wood harvest, in terms of data consistency in space and time and data robustness. Similarly, forest inventory data provide important information on tree species composition, but are typically not freely available across larger areas. A few studies have recently attempted to map tree species composition at fine spatial resolution, using downscaling techniques from census data. Brus et al. map the spatial distribution of twenty tree species, including some plantation species, across Europe at a 1-km (Brus *et al.*, 2011). These data were used to map forest management types across Europe (Hengeveld *et al.*, 2012), information that could be used to reconstruct the impact of land management on tree species distribution. Advances in remote sensing data availability and processing capabilities open up new avenues for high-resolution mapping of forest types and tree species across larger areas (e.g. (Thompson *et al.*, 2015). Notably, some studies have also demonstrated the capability of satellite sensors to separate plantation forest from primary forest (Margono *et al.*, 2014), information lacking so far at the global scale.

3. Grazing and mowing harvest

Mapping the spatial extent of grazing land is challenging, due to terminological difficulties, due to problems to apply remote sensing (but see (Rufin *et al.*, 2015) as well as due to the fact that grazing activities are not ore only partly reported in census statistics (Erb *et al.*, 2007). As a result, maps of grazing extent are generally scarce and uncertain (Erb *et al.*, 2007; Kuemmerle *et al.*, 2013). The most prominent data source on the extent of grazing is the national level inventory provided by FAOSTAT (2014) which started in 1961 and contains on a subset of grazing areas, i.e., permanent pastures. For other types of grazing, such rangeland grazing, sporadic grazing land, or forest grazing, no statistical database is currently available. Spatially explicit time series on the extent of grazing land are based on the FAO database (Ellis *et al.*, 2010; Hurtt *et al.*, 2011; Klein Goldewijk *et al.*, 2011) and are thus prone to large uncertainties. Likewise, data on carbon flows due to grazing or grazing intensity (expressed either as animals per unit area or the share of net primary production grazed) is model derived. Global assessments of the biomass flow through grazing usually rely on reconstructions based on the so-called grazing gap approach, with calculates the amount of grazed biomass as the difference between feed demand (extrapolated by using livestock number data and feed requirement information) and feed supply from known sources, e.g., market feed from commodity balances (Wirsenius, 2003; Bouwman *et al.*, 2005; Krausmann *et al.*, 2008; Herrero *et al.*, 2013), also for time-series analyses (Krausmann *et al.*, 2013). Downscaling these country-level data to a global grid (e.g. 5 arc min resolution) often relies on the gridded livestock of the world database (Wint & Robinson, 2007); see, for example (Herrero *et al.*, 2013; Petz *et al.*, 2014), or on assumptions of grazing suitability (Haberl *et al.*, 2007) and refers to the year 2000 only.

4. Crop harvest and residue management

The spatial extent of cropland is probably the best-described land-use feature at the global scale (see e.g., (Erb *et al.*, 2007; Klein Goldewijk *et al.*, 2007; Ramankutty *et al.*, 2008; Fritz *et al.*, 2013; You *et al.*, 2014; See *et al.*, 2015), even covering centennial time scales (Ramankutty & Foley, 1999; Ellis *et al.*, 2010) or millennium time scales (Pongratz *et al.*, 2008; Ruddiman & Ellis, 2009; Kaplan *et al.*, 2010; Klein Goldewijk *et al.*, 2011; Goldewijk & Verburg, 2013). However, uncertainty related to cropland extent is high (e.g. (Fritz *et al.*, 2011; Anderson *et al.*, 2015)), and errors propagate into estimates of cropland harvest flows and harvest intensity. Particular knowledge gaps refer to cropland in small-scale and subsistence farming (Fritz *et al.*, 2013), in shifting cultivation systems (van Vliet *et al.*, 2012), to changes in cropland rotation or abandonment (Munroe *et al.*, 2013; Ray & Foley, 2013; Estel *et al.*, 2015), but also the discrepancy between harvested cropland and physical cropland (Erb *et al.*, 2007; Siebert *et al.*, 2010). Likewise, massive uncertainties relate to particular world regions like sub-Saharan Africa. (See *et al.*, 2015), but also China (Liu *et al.*, 2005). See et al. (2015) identify the top 10 high priority countries, namely Chad, Liberia, Ethiopia, Angola, Guinea-Bissau, Mozambique, Lao PDR, Mongolia, Namibia and Tajikistan, in which land-use information is still derived from land-cover maps.

Only a few estimates on the amount of biomass harvested annually exist for the global scale. For the year 2000, (Monfreda *et al.*, 2008) provided a global map of cropland harvest, discerning 175 cultivars at the resolution of 5 arc min (approximately 10 x 10 km at the equator), consistent with a global spatially explicit account of the extent of cropland (Ramankutty *et al.*, 2008). Other maps are available for a selection of 20 major crops (You *et al.*, 2014). Time-series of harvested biomass are mainly available at the national level (FAOSTAT, 2014), while gridded data cover usually refer to a single year only (but see (Plutzar *et al.*, 2015) for Europe). From the year 1961 onwards, FAO reports annual primary cropland harvests in fresh weight units, as well as harvest yields (i.e. yield per unit area and harvest event (FAOSTAT, 2014) at the national level. At the subnational level gridded yield data for the four major crops (corn, soybean, rice and wheat) are available for the years 1981-2010 based on a combination of remote sensing of NPP, national crop yield data and information on crop planting and harvesting dates (Iizumi *et al.*, 2014; Iizumi & Ramankutty, 2016). In addition, historical yield data for the same crops for the period 1961-2008 is available at the scale of ca. 13,500 political units based on historic census statistics (Ray *et al.*, 2012). However, no statistical data are available for secondary products at the global level, i.e., the harvest of straw or other plant components, e.g., for livestock management. Krausmann et al. (2013) reconstructed national-level primary and secondary biomass harvest from historic statistics for cropland back to 1910. For the year 2000, Wirsenius (2003) and Krausmann (2008) provided consistent, reconciled accounts of crop harvest, in energy content and dry matter units , available at the national level, discerning primary (grain, oil seeds, etc.) and secondary products (leaves, straw). The proportion of biomass killed but not harvested (also denoted as "unused harvest" or "backflows to nature") is estimated on basis of crude, region-specific factors and therefore characterized by substantial uncertainties. Uncertainty, however, in particular of species-specific datasets is large, due to annual variation owing to crop rotation and the fact that multi-cropping or the extent of fallows is not systematically included in most of these assessments (Erb *et al.*, 2007; Portmann *et al.*, 2010; Siebert *et al.*, 2010).

5. Crop species selection

Spatially explicit data on the distribution of individual cultivars are available, closely linking to data on crop harvest. The dataset by (Leff *et al.*, 2004), has been widely used in global modelling efforts, and so has the species-specific data on cropland harvest (section 1.4; (Monfreda *et al.*, 2008; Mueller *et al.*, 2012; You *et al.*, 2014). Species selection, however, is extremely dynamic and can change on a yearly basis, due to decision making at the farm level, but also due to constraints of plant growth that entails crop rotation systems. Thus, uncertainty is huge, and aggravated by the fact that – as with cropland harvest – multi-cropping or fallow areas is not systematically included (Erb et al., 2007; Portmann et al., 2010; Siebert et al., 2010). Spatially explicit data or information on rotational systems at the global scale are lacking, as are data at the subspecies level, which is, however, decisive for factors such as water use efficiency or evapotranspiration of cropland (Anda & Løke, 2005; Yoo *et al.*, 2009).

6. N-Fertilisation

Annual global data for annual flows of NPK fertilizers are provided at the national scale by (FAOSTAT, 2014), from 1961 onwards and from by the International Fertilizer Industry Association (IFA, 2015). This data has been combined with available subnational statistics to create spatially explicit (5 arc min resolution) global maps of the magnitude of N fertilizer application (Potter *et al.*, 2010; Mueller *et al.*, 2012). These datasets are all available for the year 2000, including mineral fertilizer as well as manure flows for 2000. Spatially explicit estimates of manure and nitrogen in manure production at the global level is available from SEDAC-CIESIN (Potter *et al.*, 2010) and from Herrero et al. (2013). The Potter et al. dataset is based on estimates of on animal density (Wint & Robinson, 2007) and pasture area (Ramankutty *et al.*, 2008) and represents downscaled national level data, but ignore local livestock system and applied management practices. Herrero et al. follow an enhanced approach by considering specific manure management practices for livestock species, 8 livestock production systems (Robinson et al. 2011) and 28 world-regions.

Besides the good availability of estimates on manure and related nitrogen, data on the application of artificial fertilizers on grasslands is almost inexistent at the global level. Even in countries like New Zealand where fertilization of grasslands plays an essential role, data on fertilizer application are not available (Fetzel *et al.*, 2014). IFA statistics report grassland fertilizer application under the category "other crops" which is a heterogeneous group including grasslands, pulses, nut trees, rubber, cocoa, coffee, tea, tobacco, etc (IFA, 2015). In consequence to this data structure, large uncertainties prevail (Lassaletta *et al.*, 2014). Cropland fertilization, furthermore, suffers from the uncertainty related to cropland maps (see above). Based on statistical data and a spatial allocation model, N-input-output ratios have been mapped at the global scale (Liu *et al.*, 2010). No spatially explicit time series on patterns and intensity of fertilizer application is available.

7. Tillage

Surprisingly, no comprehensive information such as continental or global data on the area and distribution of tillage croplands exists. Also, spatially explicit information of no-tillage agriculture is not available. (Derpsch *et al.*, 2010) present an estimate of extent of no-till agriculture at the national level, partly in short (decadal) time series.

8. Crop irrigation

Data on the spatial extent of area equipped for irrigation in 2000 (Döll & Siebert, 2002; Portmann *et al.*, 2010) as well as for actually irrigated areas (Salmon et al., 2015) are available, with a resolution between 5 min and 500m. National time series going back to 1961 are archived by the FAO (FAOSTAT, 2014) as part of the agricultural input statistics, although data is sparse before 1980 (Freydank & Siebert, 2008). Uncertainties of the spatial pattern as well as of the global extent of irrigated areas or areas equipped with irrigation facilities are large, owing to the dynamics of agricultural management, the uncertainties related to mapping cropland, and the existence of heterogeneous definitions (Salmon *et al.*, 2015). In particular, the reporting framework is not sufficiently harmonized and some countries report the extent of irrigated area, whereas most report the area equipped for irrigation in a given year or time period. The area equipped with irrigation facilities is mapped by Freydank and Siebert (2008; see also (Siebert *et al.*, 2015) for the period between 1900 and 2003. The actually irrigated area is intricate to map due to the impacts of meteorological and climatological variations on the demand for irrigation (Wisser *et al.*, 2008). Such a map, based on remote sensing, climate and census data, is provided by Salmon et al. (2015). Data on input intensity of irrigation (i.e., water volume used per unit area) is not readily available at the global scale. World-regional data exist, in particular for rice cultivation (e.g. Frolking *et al.*, 2006) provide a remote sensing derived, spatially explicit estimate of the extent of paddy rice and annual water consumption at the district level).

9. Wetland drainage

Data on drainage is scarce, however. A spatially explicit map on drainage of agricultural soils is presented by (Feick *et al.*, 2005), but uncertainties and data gaps reported in this source are large. Data for artificial wetland drainage is not existing at the global scale.

10. Fire management

Data on the extent of fires are available from remote sensing, .e.g. on active fires (Alonso-Canas & Chuvieco, 2015), fire radiative power (Kaiser *et al.*, 2012) and burned area (Giglio *et al.*, 2013), but these do not discern between human-induced and natural fires. Some countries also provide more detailed national statistics on number of fires and fire extent (Stocks *et al.*, 2002; Mouillot & Field, 2005). The GFED estimates of fire emissions, covering the timeperiod 1997-2011 (van der Werf *et al.*, 2008; Van der Werf *et al.*, 2009) and is the only product that distinguishes between deforestation, savanna, forest, agricultural, and peat fire carbon emissions. Small agricultural maintenance fires are typically not detected from space. Spatially explicit information on fire management, i.e. human-induced fires, as well as on fire prevention and its effects is lacking altogether.

Method for assessing the extent of management activities, underlying Figure 2a

First, for each land management type, the total area potentially affected by this form of management was assessed. For forest species selection and forestry harvests, this was the total forested area. For grassland and shrubland grazing (and mowing) harvest, this was the total area of pasture lands and other non-forest, productive lands. For management activities in cropland, this was the total cropland area. Then, these areas were separated into different levels of intensity for each land management type, with a gradient of high intensity (HI), medium intensity (MI), low intensity (LI). Values are generally for around the year 2000.

The levels of intensity are defined as follows:

Forestry: HI: Area of planted forests, thus affected by species selection and harvests, MI: Area of naturally regenerated forest affected by forestry use, LI: Area under other use (which may include illegal or informal logging and fuelwood collection), NO: Wilderness forest. Sources: (Luyssaert *et al.*, 2014), S.I.

Grazing and mowing harvest: HI: pasture land with >100 animals/km2, MI: Total pasture minus area of HI, LI: Other unforested, productive land affected by management or human activities, NO: Wilderness, productive and unforested. Animals are defined as cattle head plus 1/7 of small ruminants heads. Sources: FAO (2007) and Luyssaert et al. (2014).

Crop harvest and crop species selection: HI: Cropland area with Cropping Intensity excluding fallow lands (CI_{NF}) > 1.1, MI: Cropland area with CI_{NF} < 1.1, LI: temporary or young fallows. Following Siebert et al. (2010), CI_{NF} is calculated as (AH/MMGA) with AH = Total harvested crop area and MMGA = maximum monthly growing area, computed by adding together the growing areas of all irrigated and rainfed crops for each of the 12 months and by afterward selecting the maximum of the 12 total monthly growing areas. Data source: (Portmann *et al.*, 2010). CI_{NF} > 1.1 corresponds to areas with on average more than one harvest per year.

Crop irrigation: HI: paddy rice irrigation, MI: other cropland equipped for irrigation, LI: other cropland. Sources: (Portmann *et al.*, 2010; Siebert *et al.*, 2015)Portmann et al. (2010).

Fertilization: HI: cropland and pasture area >100 kg/ha of N fertilization, MI: cropland and pasture area with 50-100 kg/ha/yr, LI: cropland and pasture area with 5-50 kg/ha/yr, NO: cropland and pasture area <5 kg/ha/yr. 59% of global cropland show fertilization rates below 50kg/h/yr, close to 25% less than 10kgN/ha/yr. Sources: (Potter *et al.*, 2010; Mueller *et al.*, 2012), for fertilizers use, (Ramankutty *et al.*, 2008), for agricultural land area, (Niedertscheider *et al.*, 2016) for an intersection of the two.

Tillage: HI: Tilled cropland, calculated as the residual of the other categories, LI: no-till cropland and temporary and young fallows. Sources: (Derpsch *et al.*, 2010; Siebert *et al.*, 2010).

Artificial drainage of wetlands: no intensity levels discerned

Fire: Data from (Lauk & Erb, 2009) for human-induced fires, not further differentiated. Contains also fires that are used for land clearings.

Table S2. Estimates of management intensities

Forest harvest & species selection		
High intensity	2.2	7%
Medium intensity	19.1	65%
Low intensity	8.1	28%
Total	**29.4**	
Grazing and mowing harvest		
High intensity	2.58	6%
Medium intensity	31.52	67%
Low intensity	12.8	27%
Total	**46.90**	
Cropland harvest and species selection		
High intensity	3.64	24%
Medium intensity	7.94	52%
Low intensity	3.62	24%
Total	**15.20**	
Fertilization		
High intensity	1.66	14%
Medium intensity	3.34	28%
Low intensity	7.12	59%
Total	**12.12**	
Tillage		
High intensity	7.43	
Low intensity	4.73	4.73
Total	**12.16**	
Crop irrigation		
High intensity	1.00	32%
Medium intensity	0.63	20%
Low intensity	2.33	74%
Total	**3.15**	
Artificial wetland drainage	0.18	
Fire management	4.0	
Total forestry, grazing, cropland		
High intensity	**8.37**	**9%**
Medium intensity	**58.60**	**64%**
Low intensity	**24.54**	**27%**

Estimate of biogeochemical and biophysical impacts, underlying Figure 2b

For Figure 3 in the main text, the importance of the biogeochemical and biophysical effects of each management activity is estimated based on expert judgment as recorded in table S3. For each management activity, the impact is extiamted on basis of a comparison with a unmanaged reference ecosystem

Table S3 Evaluation of the biophysical and biogeochemical effects of each of the reviewed management activities with the reference ecosystem considered and the processes taken into account for the evaluation.

Ecosystem	Management type	Extent (Mkm2)	Reference ecosystem	Biophysical effects		Biogeochemical effects	
				Rationale for the evaluation	Score	Rationale for the evaluation	Score
Forest	Harvest	40.81	Unmanaged forest	Stand destruction modifies albedo, roughness length and evapotranspiration	High	Stand destruction leads to considerable carbon fluxes	High
Forest	Species selection	40.81	Managed forests under other species	Different functional groups lead to large changes in albedo and roughness length	High	Changes in carbon allocation but similar NPP	Low
Grassland	Grazing & mowing harvest	53.9	Unmanaged grassland (natural herbivory)	Small changes in vegetation cover	Low	Stand destruction has high impacts on soil carbon and GHG fluxes	High
Crop	Harvest	11.58	Unmanaged grassland (natural herbivory)	Large effects of stand destruction on albedo, roughness length and evapotranspiration	High	Stand destruction leads to large exports of carbon and GHG	High
Crop	Residue management	11.58	Cropland without residue management	Effects last only for a couple of days	Low	Soil carbon depletion and soil erosion	Medi um
Crop-/grazing land	Fertilization	15.27	Unfertilized ecosystem	Small change in vegetation cover	Low	GHG emissions	High
Crop	Tillage	15.2	No-tillage cropping	Effects lasts only couple of days to weeks	Low	Effects on soil carbon	High
Crop	Irrigation	15.2	Same land without irrigation	Plant growth and ecosystem conditions, soil reflectance, water cycle are largely affected	High	Production is increased as well as GHG emissions	High
Crop	Wetland drainage	4	Natural wetland	Changes in evapotranspiration	Medi um	Soil emissions of GHG	High
Crop	Species selection	15.2	Cropland with another species	no difference in functional groups despite non-negligible changes in albedo	Low	Similar NPP and high legacy effects	Low
Crop	Fire	0.94	Forest without fire	Vegetation regrows quickly	Low	Stand destruction	High

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