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New anthropogenic land use estimates for the Holocene; HYDE 3.2

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Abstract. This paper presents an update and expansion of the History Database of the Global Environment (HYDE, v 3.2.000). HYDE is and internally consistent combination of updated historical population estimates and enhanced allocation algorithms with weighting maps for land use which are time-dependent. Categories include cropland, with a new distinction into irrigated and rain fed crops (other than rice) and irrigated and rain fed rice. Also grazing lands are provided, divided into more intensively used pasture and less intensively used rangeland. Population is represented by maps of total, urban, rural population and population density as well as built-up area. The period covered is 10 000 BCE to 2015 CE.

We estimate that global population increased from 4.4 million people in 10,000 BCE to 7,310 million in 2015 CE, resulting in a global population density increase of < 0.1 cap km^{-2} to almost 56 cap km^{-2} respectively. The urban built-up area evolved from almost zero to roughly 450 Mha at present, still only less than 0.5% of the total land surface of the globe.

Cropland occupied approximately less than 1% of the global land area for a long time period until 1000 CE, quite similar like the grazing land area. In the next centuries the share of global cropland slowly grew to 2.3% in 1700 CE (ca. 294 Mha), 4.5 % in 1850 CE (580 Mha) and 11% in 2015 CE (ca. 1564 Mha). Cropland can be further divided into rain-fed and irrigated land, and these categories can be further divided into rice and non-rice. Rainfed croplands are much more common with 2.2% in 1700 CE (294 Mha), 4.2% (552 Mha) in 1850 CE and 10% (1298 Mha) in 2015 CE, while irrigated croplands used less than 0.05% (5 Mha), 0.2% (28 Mha) and 2.0% in 2015 CE (266 Mha) resp. We estimate the irrigated rice area (paddy) at 0.02% in 1700 CE (2.7 Mha), 0.1% (127Mha) in 1850 CE and 0.6% in 2015 CE (73 Mha).

The share of grazing land grew from 5.1 % in 1700 CE (668 Mha) to 9.2% in 1850 CE (1200 Mha) and 25.2 % in 2015 CE (3284 Mha). Land used for grazing can be divided into more intensively used pasture and less (or not) managed rangeland.

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Pasture occupied 1.1% in 1700 CE (149 Mha), 2.0 % in 1850 CE (257 Mha) and 6.1 % (800 Mha) in 2015 CE, while rangelands usually occupy more space due to the occurrence in more arid regions and thus lower yields to sustain livestock. We estimate 4% in 1700 CE (519 Mha), 7.2% in 1850 CE (943 Mha) and 19% in 2015 CE (2483 Mha). All data can be downloaded from doi: http://dx.doi.org/10.17026/dans-znk-cfy3

1 Introduction

Humans have emerged as the most important driving force of landscape transformation during the last millennia on Earth (Butzer, 1964; Ellis, 2015; Ellis et al., 2013; Kaplan et al., 2011). The first phase can be characterized as the Paleolithic or Human system, from 2.5 million year ago till 10,000 BCE. Fire was widely used to facilitate easier hunting by opening up landscapes for grazing of wildlife. The second phase, known as the Neolithic or Agricultural system, from 10,000 BCE to 1700 CE, evolved gradually through the conversion, often deforestation, of untouched ecosystems to other types of land use such as cropland, grazing land for livestock and built-up areas. This conversion greatly expanded in the Third phase, which is also known as the Industrial Revolution or the Great Acceleration, when large areas in the so called New World were opened up by European colonization and new types of agriculture were introduced in many parts of the world. All this led to a situation that more than 37% of the ice-free land in the world is currently domesticated; another 30% is more or less under the influence of humans, causing many natural resources to be heavily used or even near depletion (Ellis et al., 2013; Foley et al., 2005).

These historical land use changes have also added substantially to the cumulative increase of greenhouse gases in the atmosphere (Le Quéré et al., 2015). The coupled land-atmosphere system is studied by Earth System Models (ESM's, e.g. see Hazeleger. W. et al (2010)), ESM's of intermediate complexity (EMICs, e.g. see Brovkin *et al* (2006)) or Integrated Assessment Models (IAM's, e.g. see Stehfest et al. (2014)). The advantage of these models over General Circulation Models is that they are able to study in much less time the transient response of the climate system on longer time scales. Studies with historical land use forcing of ESM's suggest that the bio-geophysical response to land use changes are crucial to better understanding of the complex climate system (Davies-Barnard et al., 2014; He et al., 2014; Mahmood et al., 2014). And it turned out that the historical land use distributions itself were one of the major uncertainties (Bertrand and Van Ypersele, 2002; Betts et al., 2007; Brovkin et al., 2006; Chase et al., 2000; Feddema et al., 2005; Findell et al., 2007; Matthews et al., 2003; Matthews et al., 2004; Strassmann et al., 2008; Van Minnen et al., 2009; Vavrus et al., 2008). Also, information about historical land use is important in other disciplines, such as the study of land use systems in the Anthromes – or Anthropogenic Biomes - approach (Ellis et al., 2010), the Global Fire Emissions Database project (Marlon et al., 2008), global biodiversity trends (Gaston, 2006; Gaston et al., 2003), or the impact of humans on various biodiversity matters (Cincotta et al., 2000; Goudie, 2006).

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However, anthropogenic land cover change (ALCC) is still not successfully implemented in much of these models and studies. As a result, climate modelling in paleo-mode or projection mode that tries to take ALCC into account is seriously hindered (Gaillard et al., 2010). The few scenarios of past ALCC that exist, e.g. HYDE (Klein Goldewijk et al. 2011), KK (Kaplan et al. 2009) and few others, show very large differences indeed (Gaillard et al. 2010). Therefore, improved descriptions of past anthropogenic land cover change at the global spatial scale are urgently needed.

The existing global estimates of historical land use are rare and rather uncertain (Klein Goldewijk and Verburg, 2013). This can partly be explained by the sheer lack of reliable data, and hence by the different approaches used to reconstruct the trends, which vary from simple bookkeeping methods, to 'hind-cast' modeling techniques, to simulations of anthropogenic deforestation based on population densities (Houghton et al., 1983; Kaplan et al., 2011; Klein Goldewijk et al., 2011; Pongratz et al., 2008).

This study present a key update and extension of the former HYDE 3.1 historical land use data base (Klein Goldewijk et al., 2010; Klein Goldewijk et al., 2011). This new version HYDE 3.2.000 is an improved and internally consistent combination of new historical population data and land use allocation algorithms which vary over time. Categories include cropland, with a new distinction into irrigated and rain fed crops (other than rice) and irrigated and rain fed rice. Also grazing lands are provided, divided into more intensively used pasture and less intensively used rangeland. Population is also represented by maps of total, urban, rural population and population density as well as built-up area. The period covered now is 10 000 BCE to 2015 CE.

2 Methodology and data

2.1 Input data for population

Population growth is a very important driver of global change over the past millennia. Thus, it is crucial to get a good view of the demographic changes of the past. The basis for our population data are the historical estimates of McEvedy & Jones (1978), Livi-Bacci (2007), and Maddison (2001). We supplemented them with the sub-national population numbers of Populstat (Lahmeyer, 2004) and many other country specific sources (see Suppl. Material Table S1.doc). Time series were constructed for each province or state of every country of the world (Klein Goldewijk et al., 2010). We used the current administrative units and kept them constant over time for simplicity reasons. Other historical sources were adjusted to match the current boundaries of HYDE 3.2 if needed, by taking fractions of those former, often larger, administrative units (e.g. Roman Empire).

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2.2 Spatial coverage for population

For the present, we used the spatial patterns from Landscan (2014) in our weighing maps to allocate our total population for each administrative unit. These patterns are gradually replaced with combined weighing maps based on various proxies such as soil suitability, slope and distance to water when going back in time. See also for a full description of the methodology in Klein Goldewijk et al. (2010) and Supplementary material Box S1.

2.3 Input data for land use

2.3.1 Cropland and grazing land statistics

Starting point are country totals of the FAO categories for ‘Arable land and permanent crops’ and ‘Permanent meadows and pastures’, further referred to here as ‘Cropland’ and ‘Grazing land’ respectively (FAO, 2015). The FAO present data for the post-1960 CE period only, and divided by the country population it yields a per capita land value. For the pre-1960 CE period another method was used. We assumed that the cropland and grazing land per capita values were not constant, but followed a curved trajectory. The curve can differ between countries and often resulted in either a concave shaped curve, Bell shaped or convex shaped curve. The 1960 CE per capita land use value is in general lower than for the present day since population numbers have exploded after World War II. However, when going further back in time, population numbers were often even lower which resulted in higher land use capita numbers again. It was however limited by the lack of technology and this restrained the maximum amount of land that subsistent farmers could handle. We first estimated the land use per capita on a country by country basis, and by multiplying this with the total population we were so able to compute the total areas for cropland and grazing which were then distributed within countries according to spatial allocation rules either by satellite information for the present day, or by specific rules for the deep past.

Further specific input statistics on sub-national level were taken for some of the larger countries in the world, such as the USA (USDA, 2006), Canada (Urquhart and Buckley, 1965) , Mexico (World Atlas of Agriculture, 1969), Argentina (Vazquez-Presedo, 1988), Brazil (pers.comm. Navin Ramankutty), India (Flint and Richards, 1991; Indiastat, 2009), China (China National Bureau of Statistics, 2006a, b; Ge et al., 2008; He et al., 2012; He et al., 2013), Australia (Australian Bureau of Statistics, 2001). Furthermore, other country specific sources were used when available for specific information per country. The methodology has also been described in in detail in Klein Goldewijk et al. (2011), and also see Supplementary material Table S1).

For a spatially explicit depiction of present land cover we use the ESA Land Cover consortium maps (ESA, 2016; Hollman et al., 2013). The consortium produced a time series of three global 300m spatial resolution land cover datasets predominantly based on MERIS satellite data, representative for the 1998-2002 CE, 2003-2007 CE and the 2008 – 2012 CE

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period. To produce the satellite reference map of HYDE 3.2 the most recent epoch has been used, representing 2010 CE. The ESA classes are aggregated to 5 arc-minute grid cell fractions consistent with the HYDE land mask. Cropland and grazing land are allocated to match the FAO categories ‘Arable land and Permanent crops’ and ‘Permanent meadows and pastures’ statistics per country from the FAO (2015) as closely as possible.

Cropland is allocated to all fractions that do not have tree cover. A preferred order of allocation is defined as giving priority to certain land cover types that are considered more likely to have cropland (see table 1). Of the land cover types that consist fully of cropland, grass or shrubs, only 90% can be used. This is to account for small areas of infrastructure, wetlands, unsuitable terrain, steep slopes or small patches of vegetation that are not explicitly identified in the original land cover product. Within the area that can be allocated a preference is given to cropland locations from the unified cropland layer map (Waldner et al., 2016). This is done in order to make use of the high-quality empirical data that is available, and to correct for the characteristic that the ESA cropland land cover types are most likely a mix of cropland and intensive pasture lands in many regions.

A similar approach is used to allocate grazing land in each country, following an almost identical order of allocation (see table 1). Cropland is given priority over pasture, so cropland that was allocated in the previous step is subtracted from the area available for pasture. In addition, various region-specific rules are implemented. First, in Canada, Russia and USA various subnational regions known to have very little to no pasture area are excluded from allocation, e.g. inaccessible tundra areas. Second, in countries with substantial grazing land that can be allocated in large homogeneous areas (e.g. the Sahara) a preference is given to locations in close proximity to previously allocated grazing area.

Insert Table 1. here

The resulting maps for current cropland and grazing land are used as reference maps *Wcrop_satellite and Wgrazing_satellite* in the HYDE allocation procedure.

2.3.2 Rice

Total rice area statistics per country were taken from FAO for the post-1960 CE period. For the pre-1960 CE period data for some rice growing countries were taken from (Mitchell, 2007a, b, c) for the 1890 – 1950 CE period. The rest was hind-casted on a per capita basis for countries were no historical data could be found. Global totals were compared with literature where possible to tune the per capita numbers. A correction was made for harvested area versus actual area. In China, for example this ratio is around 0.6 due to multiple and triple cropping (Frolking et al., 2002). This ratio was also applied to other Asian rice producing countries, the rest of the world is assumed to have a ratio of 1.0. Ricepedia (2015) presents

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estimates for the fraction of rice which is irrigated per country for the present, and an assumption was made for that fraction in the deep past. For the years in between data were linear interpolated towards the 2010 CE value (see Supplement Table S4, 'data' sheet, columns HM:KL). In general, most arid regions were assumed to be irrigated, others rainfed. So, for each time step the total amount of rice could be computed. Rain fed rice was allocated first (most cost effective), irrigated rice second. The reference maps for rice are derived from MAP SPAM You et al. (2014) and are used for the allocation for the present. They gradually change into combined weighing maps of the HYDE rules, see section 3.

2.3.3 Irrigation

The input data for the categories 'Areas equipped for irrigation' for the post-1960 CE period were taken from FAO (2015) and for the 1900 – 1960 CE period from Siebert et al. (2015). For the 1700 – 1900 CE period estimates were taken from Siebert (2008). For the pre-1700 CE period a per capita estimate was used, to match global estimates of irrigated area of found in literature. The statistics for the actual irrigated area for the 1960 – 2010 CE period were derived by multiplying FAO's category 'Area equipped for irrigation' with the fraction 'equipped/actual irrigated area' of the GMIA_v5 database of (Siebert et al., 2015). For many countries this fraction is 1.0, but not for all countries. Therefore, we used the last known ratio and applied this to the complete series of 'area equipped for irrigation' to compute the historical time series of 'actual irrigated area' (see Supplement Table S2). For the spatial representation of current global areas equipped for irrigation and actual irrigated areas we used the MIRCA 2000 CE maps of Siebert et al. (2015).

3 The HYDE allocation of land use

3.1 Non-usable areas

We excluded specific areas from allocation since we assume that in protected areas and in particular non-used areas in central Australia no agricultural activities occur. However, the protected areas were only established relative late in time, so they are only excluded after 1900 CE till present times, which makes them potentially available for agriculture in the past. We derived the areas from the world database of protected areas (WDPA) from UNEP/WCMC (2013) and the 'non-used areas' map of Australia as provided by NLWRA (2001).

3.2 Allocation of land use

The order of allocation is as follows; first we allocate cropland, then rice, then irrigation and finally grazing land.

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3.2.1 Cropland

The method to allocate historical cropland is carried out for each grid cell of 5’ by 5’ grid cell (ca 85 km^2 around the equator). For allocating historical cropland six major assumptions were made: (i) urban builtup areas (*Uarea*) were excluded for allocation; (ii) a population density (*Wpopd*) less than 0.1 cap km^{-2} means no permanent agriculture; (iii) areas with better soil suitability according Global Agro-Ecological Zones map (GAEZ) of FAO-IIASA for this (GAEZ, 2000) are used first (*Wsuit*); (iv) easier accessible areas such as coastlines and river plains derived from Natural Earth (2015) are more promising for early settlement (Wcoast and *Wriver*); (v) inaccessible terrains with steep slopes derived from Etopo_05 (2005) are less promising for settlement (*Wslope*; (vi) below an annual mean temperature of 0 ^{o}C no agriculture is assumed to be possible (*Wtemp_crop*). The temperature map is derived from the CRU database, an average for the 1960-1990 period (New et al., 1997). We normalized all these assumptions between 0 and 1 and multiplied them into a final, unique weighing map for each time step. This methodology is similar as the one already in described (Klein Goldewijk et al., 2011).

The land use statistics are then allocated to grid cells according to a mix of two weighing maps; a satellite map of 2010 CE for cropland ($Wcrop\_satellite_{2010}$), derived from ESA (2016) for the present, and a historical one, which is constructed on the basis of the six rules as described in the former section. The influence of the satellite map increases gradually from the deep past into the present until it fully dominates the rule based weighing map, i.e. when the cropland distribution mimics the satellite map distribution (i.e. the reference map).

Cropland is allocated by combining historical cropland area statistics from HYDE with the various weighing maps:

Current reference map for cropland allocation:

$$Wcrop_{2010} = Wcrop\_satellite_{2010} \quad (1)$$

Historical weighing maps for cropland allocation:

$$Wcrop_t = Wpop_{,t}\ Wsuit\ Wriver\ Wcoast\ Wslope\ Wtemp\_crop \quad (2)$$

where

$$Garea_{max} = [Garea_{cell} - Uarea_t - Parea_t - NLarea_t] \quad (3)$$

$Garea_{max}$ is the total land area left available for allocation of cropland (no ice and snow), $Garea_{cell}$ is the maximum land area of a 5’ grid cell (spherical Earth), $Uarea_t$ is the urban builtup area for year *t*, $Parea_t$ are protected areas, but only valid for the

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post 1900 period (they did not exist before), and NLarea is the no land use area in Central Australia (see Supplementary material Table S3 for the original input data and Figure S1 for the cropland allocation scheme).

3.2.2 Rice

All rice producing area is assumed to fall within the area defined earlier as cropland. For the spatial representation of global rice areas we used IFPRI's Spatial Production Allocation Model (SPAM) maps of You et al. (2014). They present maps of irrigated and rainfed harvested area of rice.

Current reference maps for irrigated and rainfed rice allocation:

$$Wir\_rice_{2010} = Wir\_rice\_satellite_{2010} \quad (4)$$

$$Wrf\_rice_{2010} = Wrf\_rice\_satellite_{2010} \quad (5)$$

Extra weighing for the past is also determined by a historical geography map for rice growing areas for the year 1000 CE (Widgren et al. pers. Comm). Also, the current reference maps for irrigated and rainfed rice remain important for the allocation since the assumption is made that most rice growing areas are very old indeed, implying that current patterns are for a great extent representative for ancient patterns as well. (see Supplement Table S4 for original input data and Figure S1 for the cropland allocation scheme).

Historical weighing maps for rice allocation:

$$Wir\_rice_{t} = Wrice_{1000}\ Wir\_rice_{2010} \quad (6)$$

$$Wrf\_rice_{t} = Wrice_{1000}\ Wrf\_rice_{2010} \quad (7)$$

3.2.3 Irrigated area

The allocation of irrigated areas is comparable with that of cropland. First we use the reference map for 2000 CE for irrigated areas derived from the MIRCA database (Siebert et al., 2015). When hind-casting, we apply the HYDE rules for allocation based on the following assumptions. All irrigated area must fall within the computed cropland area. Next, we check whether there is enough water available to irrigate (Wwav), for which we use as a proxy a discharge map derived from Van Beek and Bierkens (2008). Furthermore, we assume that when the aridity index (Waridity) is low, the need for irrigation is higher. The aridity index is computed as Annual precipitation / Annual evapotranspiration, both derived from

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New et al. (1997). (see Supplementary material Table S5 for original input data and Figure S1 for the cropland allocation scheme).

Current reference map for irrigated land allocation:

$$Wirri_{2010} = Wirri\_satellite_{2010} \tag{8}$$

Historical weighing maps for irrigated land allocation:

$$Wirri_t = Waridity\ Wwav\ Wirri_{2010} \tag{9}$$

3.2.4 Grazing land

The method to allocate historical grazing land (on $Garea_{max}$ minus the allocated cropland) is comparable to the procedure for cropland, except that on top of area and population, other weighing maps were used, such as natural grassland type ecosystems as computed by the BIOME model (Prentice et al., 1992) are more attractive for use of grazing then other types (*Wbiome*); areas with a higher net primary production are also more favorable for grazing (*Wnpp*), and a different temperature map with no grazing assumed below an annual average temperature threshold of -10^{o} C (*Wtemp_grazing*).

Current reference map for grazing land allocation:

$$Wgrazing_{2010} = Wgrazing\_satellite_{2010} \tag{10}$$

Historical weighing maps for grazing land allocation:

$$Wgrazing_t = Wpopd_t\ Wbiome\ Wnpp\ Wtemp\_grazing \tag{11}$$

(see Supplementary material Table S6 for original input data and Figure S2 for the grazing land allocation scheme).

Furthermore, a distinction is made between the more intensively managed, closer to populated areas and wetter grazing lands (pastures) and the less/no managed, drier or arid remote grazing lands (rangelands). We use an aridity-index, defined as annual precipitation divided by annual evapotranspiration and a population density map. When the aridity index of a grid cell defined as grazing land is less than 0.5 then it is defined as rangeland, or when the aridity index is higher than 0.5 but the population density is less than 5 inhabitants km^{-2}.

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4 Results

4.1 Cropland and Grazing land

We have constructed historical land use maps for a 12,000 year period, on a 5 by 5 minute grid resolution. Agriculture developed very slowly at the start of the Holocene after the domestication of plants and animals, in place as well as over time. Population numbers were very low at the start of the Neolithic era. We estimate 4.4 million in 10,000 BCE, which is in line with the literature range of 1-20 million, while most estimates remain below 6 million mark (Klein Goldewijk et al., 2010).

After the early domestication of rice in Eastern China in the Yangtze River valley, agriculture spread quickly into mainland China and to Taiwan and the Philippines, where on the island of Luzon evidence was found dating back to 3700-3500 BCE. In the late 3rd millennium BCE, there was a rapid expansion of rice cultivation into mainland Southeast Asia and westwards across India and Nepal. Rice was a major crop in Sri Lanka as early as 1000 BCE, and was introduced in Europe's Greece around 330 BCE (Ricepedia, 2015).

Because of a better food security the world population slowly increased to 19 million (range 5-24) in 5,000 BCE. We estimate the corresponding global cropland area extent in 5,000 BCE at a very modest 10.4 million ha (range 1 – 19) and grazing land to be around 32 million ha (range 4 – 60). This corresponds with 0.54 ha cropland cap^{-1} (range 0.07 – 1.02) and 1.67 ha cap^{-1} of grazing land (range 0.13 – 1.93). Technology was limited and agriculture was very sensitive to climate for a long time.

Agriculture was more prevalent throughout the Mediterranean, Northern India and in Eastern China during Greek and Roman times, most likely due to the existence of highly developed irrigation schemes. We estimate a global population in 1 CE of 232 million people (range 170-330), and the global cropland area to reach 197 million ha during that time (range 50 – 344). Grazing land is estimated to be 244 million ha (range 61 – 270). This corresponds to 0.85 ha cropland cap^{-1} (range 0.21 – 1.50) and 1.05 ha grazing land cap^{-1} (range 0.22 – 1.54) respectively.

Insert Figure 1 here.

Europe disappeared into the Dark Middle Ages after the breakdown of the Roman Empire, which was accelerated with the invasion of the Huns from the East, and it resulted in the so-called Migration Period. Many tribes and people sought refuse all over Europe so technological developments did not progress much for a long time period. Later, when things calmed

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down a bit, Europe suffered also from great pandemics such as de Black Plague. This decimated population numbers severely, especially in the countryside and led to large scale abandonment of agricultural land followed by a regrowth forest in large parts of Europe (Bork et al., 1998; Bork and Lang, 2003).

In contrast of Europe, Central America was at the peak of their civilization in that time. For example, the Mayan (4000 BCE – 1517 CE, height 200-900 CE), Aztec (1200 – 1521 CE) and Inca empires (1200 – 1572 CE) flourished greatly during European turmoil. Particular Central and South American regions sustained rather high population densities, built upon various agricultural activities and trade routes (Culbert, 1988; Etter and Van Wyngaarden, 2000; Nevle and Bird, 2008). This resulted in good developed agricultural systems with many backcountries whose main role was being supplier to the centers of power (DeMenocal, 2001). Noticeable is the fact that there was no pasture in the Americas before the Colombian Exchange in the late 15th century, since the first colonists were responsible for introducing livestock on the continent.

Agriculture in Africa also developed slowly during pre-industrial times. Crops were already grown in African Ethiopia's Aksum area at least from 500 BCE (Boardman, 1999) and were limited to wheat, barley, flax and tef. Later this range was extended to potential cash crops which indicated the emergence of a market economy (Boardman, 1999). Western Africa was influenced by three powerful states for a long period, e.g. the Kingdom of Ghana (4th – 14th century) was rich in gold, and it became a leading force in the trans-Saharan trade network. Rulers depended heavily on traded crops, salt, grain and cotton cloth. It was followed by a Mali ruling, Mande speaking people (13th -15th century) and later by the Muslim led Songhai (15th 16th century). Further growth of commerce caused Islam to spread in sub-Sahara. Eastern en Southern Africa also depended heavily on trade and traditional beliefs beside pastoralism and small scale farming.

These continental differences led to a global population of 253 million in 500 CE, and 323 million in 1000 CE (literature range 253 – 345). The acceleration in population growth started somewhere after 1700 CE with our estimate of 592 million people (range 410-680), 944 million in 1800 CE (range 890-1000), 1643 million in 1900 CE (range 1571-1710), 2531 million in 1950 CE, 4487 million in 1980 CE, 6113 million in 2000 CE and 7301 million in 2015 CE (see suppl. Material Table S7.xlsx). The world has been a rural place for most of the time since mankind domesticated plants and animals. It took until the year 2009 CE when more people lived in cities and towns than in the countryside. The area occupied by built-up area (housing, building, etc.) is still very modest, compared to the total land surface available, less than 0.10% in 1900 CE and still less than 0.5% in 2015 CE .

The corresponding cropland areas are estimated to be 172 Mha (68-275) in 500 CE, 170 Mha (82-256) in 800 CE, 220 Mha (126-313) in 1100 CE and 227 Mha (150-303) in 1400 CE, which translates globally to 0.68 ha cropland cap^{-1}, 0.59 ha cap^{-1} and 0.51 ha cap^{-1} resp. Our cropland estimate for 800 CE of 170 Mha is somewhat higher than the 136 Mha (range 80 – 220)

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of Pongratz et al (2008), similar for their 197 Mha estimate for 1100 CE but slightly lower than the 233 Mha for 1400 CE (see suppl. Material Table S7.xlsx), and table 2.

Insert Table 2 here.

The Great Colombian Exchange was the onset of a truly globalization process. Shortly after the re-discovery of the Americas, the Industrial Revolution fueled the colonization by Europeans of the Americas, Australia, and later Africa, accompanied by a huge agricultural expansion, in the temperate regions and a bit later in the tropics as well. We estimate the global population in 1800 CE to have passed the 1 billion mark, in 1930 CE the 2 billion mark, and in 1960 CE the 3 billion mark. The great acceleration in population numbers took place after WWII resulting in more than 7 billion people in 2012 CE.

As result of this large population, and technology growth in order to keep up with it, the total global area of cropland doubled at a faster pace since the 16th century from 295 Mha in 1700 CE, to 581 Mha in 1850 CE, 1223 Mha in 1950 CE, 1509 Mha in 2000 CE and 1589 Mha in 2015 CE. The increase in global cropland area appeared to have leveled off during the early 00's but recently we see an increase again. Ramankutty and Foley (1999) and Pongratz (2008) estimated for 1700 CE a value of around 400 Mha. The latter can probably be explained by the fact that their hind-casting starting point in 1990 CE was already higher than the FAO, because they also used non-FAO data (Pongratz et al., 2008).

The area for land used for grazing were higher than for cropland, namely 314 Mha in 800 CE, 450 Mha in 1100 CE and 486 Mha in 1100 CE, which corresponds globally to 1.10 ha of grazing land cap^{-1}, 1.13 ha cap^{-1} and 1.10 ha cap^{-1}. Our grazing land estimates are overall higher than the (Pongratz et al., 2008) estimates; they present 140 Mha for 800 CE (range 80-210), 198 Mha for 1100 CE and 227 Mha for 1400 CE. (see Table 3 and suppl. Material Table S7.xlsx).

We compute a global area used for grazing of 668 Mha in 1700 CE, higher than the 526 Mha of Houghton et al. (1983). The largest differences appear to be in tropical Africa but large differences could be explained to the fact that we distinguish more intensively used or managed pasture and less intensively managed or non-managed at all rangeland. The latter is assumed not to have undergone a conversion from natural ecosystem to grazing land or degradation, which is important for the carbon cycle in ESM's or IAM's. In 1700 CE this would correspond to 149 Mha of pasture and 519 Mha of rangeland. In 1800 CE the area occupied for grazing has grown to 922 Mha (190 Mha pasture and 732 Mha rangeland), in 1900 CE 1664 Mha (356 Mha pasture and 1307 Mha rangeland). The area of grazing land seems to have reached its peak around 2000 CE with over 3300 Mha (780 Mha pasture and more than 2500 Mha rangeland) and is slowly decreasing towards the present day.

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Insert Table 3 here

Globally, the area of cropland per person increased slowly until 3000 CE to a maximum of 1.09 ha cap^{-1}, then it slowly decreased again to 0.44 ha cap^{-1} at the end of the 18th century, with a temporarily small increase to 0.53 ha cap^{-1} in the early 20th century but after 1950 CE it decreased again because of the strong population growth, to 0.22 ha cap^{-1} in 2015 CE. Technology alone apparently could simply not compensate entirely for the explosive population growth after World War II, and since the best soils are already occupied, this trend continues. The same applies for grazing land, with a global low per capita average number of around 1.05 ha cap^{-1} till 1 CE, then a moderate increase to 1.14 ha cap^{-1} towards 1000 CE and then gradually decreasing again to 0.45 ha cap^{-1} in 2015 CE (see suppl. Material Table S7.xlsx). However, regionally there are large differences, sparsely populated countries such as Australia, Botswana, Mauritania, and Namibia have even today more than 40 ha of grazing land per capita available and Mongolia and Western Sahara even around 150 ha cap^{-1}.

4.2 Irrigation

Irrigation played a vital role in the existence and spread of agriculture. In general, irrigation can be defined as applying additional water (apart from natural rainfall) to the soil in order to enhance crop yield. First, surface water was diverted from lakes, streams and rivers to other places in the landscape. Later, various types of pumps were used, either driven by livestock (oxen, mules, horses), manpower, and eventually by machines. The earliest archaeological evidence of irrigation is found about 6000 BCE in Jordan and Egypt (Sojka et al., 2002). In the millennia that followed irrigation was spread in the Levant region and the Mediterranean. At the same time irrigation emerged independently in India, Pakistan and China. Also, in the Americas the Inca, Maya and Aztec already had irrigation schemes in the first millennium. A bit later in time, the Hohokam practiced irrigation in the dry Southwestern USA only to disappear mysteriously in the 14th century (Sojka et al., 2002). We estimate the global irrigated area to be less than 0.2 Mha in 5000 BCE, 3,4 million ha in 1 CE, and very slowly increasing to 4.5 Mha in 1000 CE, to 5.4 Mha in 1500 CE, see table 4 .

Insert Table 4 here.

The 19th century marked a significant change in technology in many areas of science. Ancient irrigation technology worked mostly proper in already favorable environmental conditions (rainfall, terrain, slope), but when population grew and agriculture expanded in areas with less favorable conditions things had to change. Electrical, steam and internal combustion engines became available for pumping water. Even in remote areas from large groundwater reservoirs many meters deep. This enabled farmers to grow crops where never before agriculture was possible, hence the area of irrigation increased largely.

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Insert Figure 2 here.

We estimate the global irrigated area in 1700 CE to be 6.0 Mha, which is in line with the 4.5 Mha estimate of Siebert (2008) and the 5.1 Mha of Freydank and Siebert (2008a), see figure xx. Our estimate for 1800 CE of 9.3 Mha is close to the 10.5 Mha of (Siebert, 2008) and the 10.6 Mha of (Freydank and Siebert, 2008b). Also, our estimate of 48 Mha for 1900 CE in well in the range of literature 40-63 Mha (Framji et al., 1982; Freydank and Siebert, 2008b; Li et al., 2009; Michael, 2008; Siebert, 2008; Siebert et al., 2015). Finally, we estimate the global irrigated area in 2015 CE at 272 Mha, with a large share in China (63 Mha) South Asia (64 Mha), and SE Asia (47 Mha), see figure 2.

4.3 Rice

There are several domestication theories for rice, supported by several archaeological studies. Zheng and Jiang (2007) proposed the origins of rice agriculture to be earlier than 10000 BCE. However, many studies agree that origins of rice agriculture began in the Lower Yangtze River valley in Eastern China (Barker, 2006; Bellwood, 2001; Fuller et al., 2007; Zhang and Wang, 1998). Zheng et al. (2009) also reported on domesticated rice spikelet bases found at a site called Kuahuqiao along the Yangtze River in East China. These findings form the basis for the hypothesis that rice cultivation that led to domestication began in 6000 BCE. During the period between 6000 BCE until around 4000 BCE, systematic cultivation of rice species had become well established (Opferkuch, 2016).

The Han dynasty (202 BCE – 220 CE) already used hydraulic power for a trip hammer to pound and polish grain, they also used chain pumps powered by a waterwheel for irrigation based farming. Political stability in the centuries followed led to a growing labor force and economic growth, e.g. the Silk Road. Agriculture became more intensive and efficient; they started a double cropping scheme for rice, and used cattle for plowing and fertilization. It gradually evolved into a feudal agricultural society during the Tang dynasty (618-907 CE).

We cautiously estimate rice area in China to be less than 1000 ha in 8000 BCE, 4000 ha in 6000 BCE, 26 000 in 4000 BCE, 161 000 ha in 2000 BCE, 1.1 Mha in 1 CE and 0.8 Mha in 1000 CE. However, these numbers are highly uncertain and must be treated with care. Numbers for Southeast and South Asia show a similar pattern but that might be incorrect for the deep past. Fuller and Qin (2011) suggest that rice arrived later in Southeast and South Asia and was fully domesticated around 4000 BCE.

After the early domestication of rice in Eastern China in the Yangtze River valley, agriculture spread quickly into mainland China and to Taiwan and the Philippines, where on the island of Luzon evidence was found dating back to 3700-3500 BCE. In the late 3rd millennium BCE, there was a rapid expansion of rice cultivation into mainland Southeast Asia and westwards

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across India and Nepal. Rice was a major crop in Sri Lanka as early as 1000 BCE, and was introduced in Europe's Greece around 330 BCE (Ricepedia, 2015).

Local rice cultivars have been cultivated in western Africa around 1500 – 800 BCE along the Niger River delta (Ricepedia, 2015) and later on into Senegal. Asian rice species were introduced in the Common Era in Eastern Africa and spread later on westwards. Currently, it is predominantly grown in Madagascar. Rice was introduced in Spain and Sicily in the 10th century by the Moors. Later on in the 15th century, it spread throughout Italy and France and was introduced in the New world ever since (Ricepedia, 2015).

Insert Figure 3 here.

To summarize, we estimate a global rice area of 0.10 Mha in 4000 BCE, 0.20 Mha in 3000 BCE, 0.42 Mha in 2000 BCE, 0.76 Mha in 1000 BCE, 2.30 Mha in 1 CE and 3.2 Mha in 1000 CE. This is in good agreement with the study of Fuller et al. (2011) who estimated 0.05 Mha wet rice (0.10 total rice), 0.20 Mha w (0.20 t), 0.40 Mha w (0.50 t), 0.70 Mha w (0.80 t), 2.30 Mha w (2.50 t) and 5.0 Mha wet rice (5.3 total rice) resp. See figure 3.

We did not find any global rice area estimates for the 1000 CE 1900 CE period in literature. Barker et al. (1985) estimated 81.3 Mha for 1930 CE, similar to the HYDE 3.2 estimate. Our estimates for 1940 CE of 55.2 Mha, 60.5 Mha for 1950 CE and 77.0 Mha for 1960 CE are lower than the Barker et al. (1985) estimates; 90.0 Mha, 108.5 Mha and 124 Mha resp. See table 5 for regional estimates of rice area.

Insert table 5 here.

4.4 Summary

We have estimated population and specific land use categories for the Holocene. Population has grown exponentially but only during the last century. Grazing land and cropland also increased but at a slower rate. The majority of cropland is rainfed. The irrigated croplands and rice areas are relatively small, compared to the total agricultural area, but have been a very important factor in the increase in yield/production, which enabled the world yet still to feed its self (table 6 and 7, Figure3).

Insert Figure 3 here.

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The total amount of agricultural area is significant smaller than the estimate of Kaplan et al. (2011). This can largely be explained by differences in methodology; Kaplan et al (2011) used a correlation between deforestation and population density, varying over time with changes in technology and development. Since HYDE 3.2 does not estimate anthropogenic activities such as deforestation, wood harvesting or shifting cultivation it will be on the lower side, apparently a factor 2 to 3 compared to Kaplan et al (2011), see table 6.

Insert Table 6 here.

Table 7 summarizes our estimates for population and land use for the Holocene. Agricultural land occupied less than 0.5% of the total land area in 5000 BCE, 3.4% in 1 CE, 13.6 % in 1850 CE and 37.4% in 2015 CE.

Insert Table 7 here.

4.5 Uncertainties

We are fully aware that there are large and many uncertainties attached to hind-cast methods applied in this study. We start with good and reliable data from the United Nations World Population Prospects for the post-1950 period, but there is a strong dependency on a few historical population sources such as McEvedy and Jones (1978), Madisson (2001) and Livi-Bacci (2007), which are for some regions and time periods not undisputed and probably on the low side (Klein Goldewijk and Verburg, 2013). So, especially for the deeper past (pre-1500 CE) the numbers must be treated with caution. However, as already stated in Klein Goldewijk and Verburg (2013), the resulting demographic growth rates seem not to be unfair and rather acceptable for the purpose of this study.

A similar statement can be made for the different land use estimates. The FAO data for the post-1960 are quite reliable, although for some countries they can be questioned, even for the present. Also, the hindcasting approach of using land use per capita is a pragmatic approach, but very sensitive to the shape of the curve into the past. The range in magnitude per curve is very uncertain and differs substantially per country and in time. The study of Klein Goldewijk and Verburg (2013) clearly showed that the shape of the per capita curve profoundly determines the total agricultural area, especially in the pre-industrial era.
Basic assumptions are that it is not zero and that there is a maximum area per person which can be regarded as being feasible of what one could do without any technology in a day's hard work (Williams, 2000).

We have estimated on top on the 'baseline' cropland and pasture per capita estimates also a lower and upper land use scenario on the basis of an uncertainty range. These uncertainty ranges were based on literature and to a great deal on our

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own expert judgement, and should be treated with care. The uncertainty range A is cautiously estimated at 5% in 2000 CE, 10% in 1900 CE, 25% in 1800 CE, 50% in 1 CE and 75% in 10k BCE. The uncertainty range B is twice the uncertainty range of A, and should be considered as that in our opinion it is highly unlikely that areas of cropland or grazing land have been outside this range in the past. The years in between were linear interpolated (the method is similar as described in Klein Goldewijk et al. 2010), and the resulting ranges are depicted in Figure 5. A regional summary of cropland, pasture, population, per capita cropland area and per capita pasture area is presented in supplementary material Table S7.xlsx.

Insert Figure 5 here.

The estimates for HYDE 3.2.000 are in general higher than the older estimates of HYDE 3.1. This is partly because of the use of new (census) data sources as result of cooperation with the Humanities (see CLIO-INFRA project, https://www.clio-infra.eu/), and partly of new insights, see also Klein Goldewijk et al. (2016). Especially grazing land has now been estimated quite a lot higher than before, to acknowledge that livestock grazing has been a long term and widespread activity indeed.

Another issue is that by absence of transient Holocene climate and vegetation maps we simplified things by using weighing maps for current climate and biome over the whole time period. Although the climate in 10,000 BCE differs from the present day (Armesto et al., 2009; Bertrand and Van Ypersele, 2002; Kropelin et al., 2008; Tett et al., 2005; Verschuren et al., 2002), we believe that the lower temperature thresholds we used are still valid, and since they are just one of the factors involved, not the only one. The same applies the biome map. The Sahara desert was more like a grassland/savanna type during the pre-5,000 BCE period (Verschuren et al., 2000), and changed into the current desert state later on, but it has been hardly populated (ample agriculture), so we decided to keep our allocation procedure remained unchanged during that era.

We have experimented with a different choice for the cropland and grazing land reference maps, to see whether it would influence, and if so, to what extent, the spatial patterns of land use. In other words, how important is it to use the most recent satellite information for input land use data series for integrated global modelling exercises. Therefore, we took the old HYDE 3.1 reference maps of DISCover/GLC2000 (Loveland and Belward, 1997; Loveland et al., 2000) valid for the reference year 2000, the IIASA/IFPRI cropland map (Fritz et al., 2015) valid for the reference year 2005, and the 2010 reference map (ESA, 2016).
Next, we ran a fuzzy numerical kappa analysis with the software from the Map Comparison Kit (Visser and de Nijs, 2006). The fuzzy numerical Kappa analysis between the 2000 reference map (DISCover/GLC2000) compared with 2010 reference map (ESA) yielded a substantial degree of agreement of 0.744 (1.00 = very high degree of agreement, 0.00 = very low). The comparison of the 2000 reference map (DISCover/GLC2000) with the 2005 reference map (IIASA/IFPRI) gave a fuzzy numerical Kappa of 0.727. And the comparison between the 2005 reference map (IIASA/IFPRI) and the 2010 reference map

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(ESA) yielded a fuzzy numerical kappa of 0.810. This means that there is overall a substantial agreement (or in other words relative little difference) between the three reference maps for cropland.

The Fuzzy numerical Kappa analysis between the 2000 reference map (DISCover/GLC2000) compared with 2010 reference map (ESA)was 0.635. The comparison between the 2005 reference map (IIASA/IFPRI) and the 2010 reference map (ESA) yielded a Kappa fuzzy numerical of 0.643. There is no grazing land map of 2005 from IIASA/IFPRI.

All this is in agreement with a study of 43 simulations from 11 global-scale LULC change models of Prestele et al. (2016), that cropland is more consistent among the different reference starting conditions than grazing land. However, differences do exist, usually at the local scale. First, the original satellite input is different between the three datasets, with different sensors. Second, different algorithms were used to classify the land cover classes which lead to different results as well. Third, when time progresses, the absolute areas of cropland sometimes has changed over time, either by expansion of abandonment, leading to different maps. We believe that for this hindcasting study it does not play an important role which reference map we used, but it can be important for future modeling studies.

Finally, an important point to be made is that in this HYDE 3.2.000 version no empirical data is systematically used (yet) to improve the historical land use reconstructions. All allocation in in the deep past is done by general, globally applicable HYDE allocation rules. As Morrison (2015) rightly pointed out, these rules are often made with a Euro-centric point of view. We fully acknowledge this, since these rules were used as a first simple attempt to allocate land use in the deep past. We are aware that there is a need for a much more regionalized approach. Very promising work is underway in the Past Global Change (PAGES, http://www.pages-igbp.org/) LandCover6K working group initiative, where archaeologists, historians, geographers, paleo-ecologists and land use re-constructors for the first time join efforts to collect and provide the rich data from all the different disciplines in order to improve the ALCC time series. This, in return is beneficial for several Model Intercomparison Projects such as the Coupled Model Intercomparions Project (CMIP), and the Land Use Model Intercomparison Project (LUMIP), who aim to further advance understanding of the impacts of land-use and land-cover change on climate (Lawrence et al., 2016).

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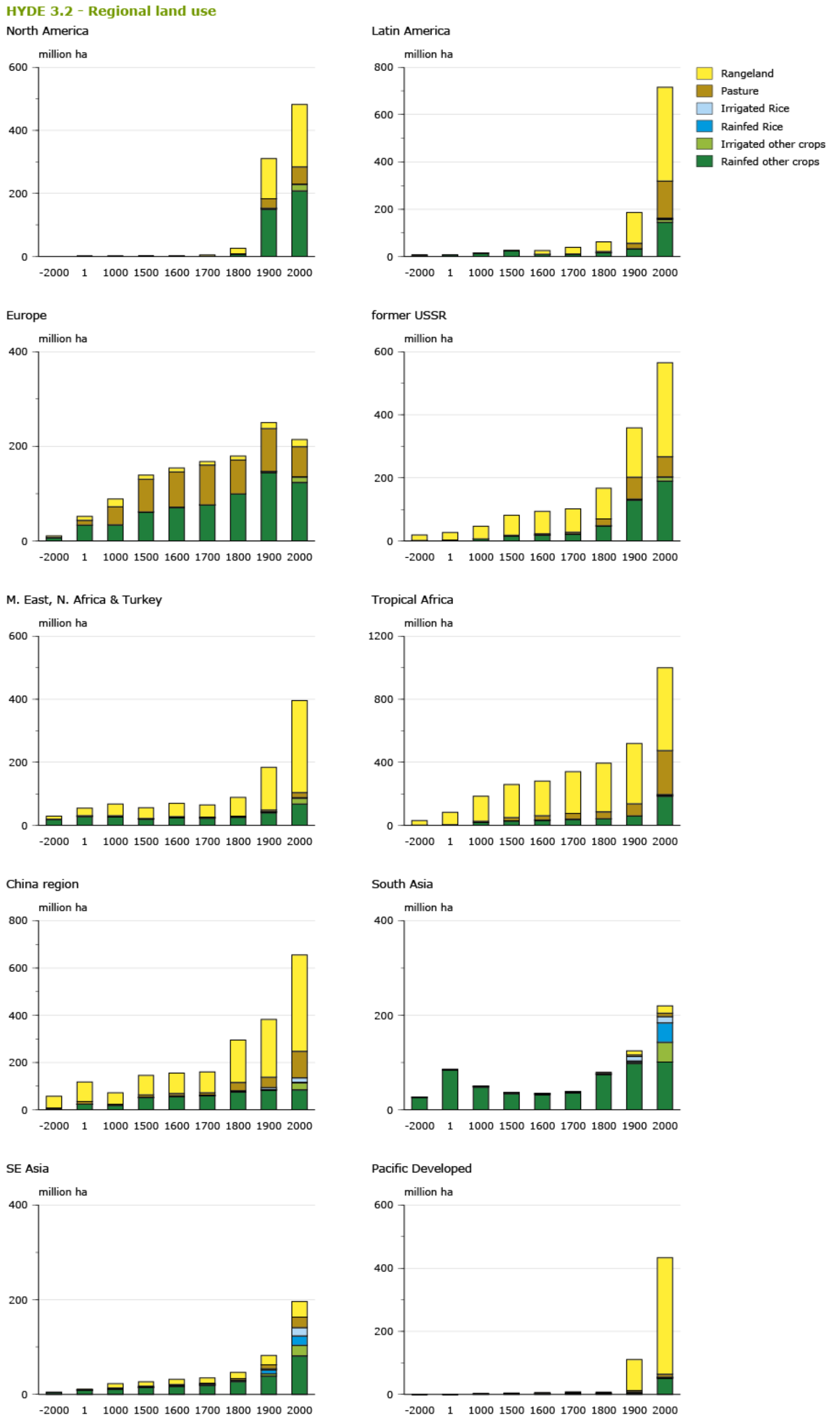

Figure 1. Regional estimates of cropland and grazing land

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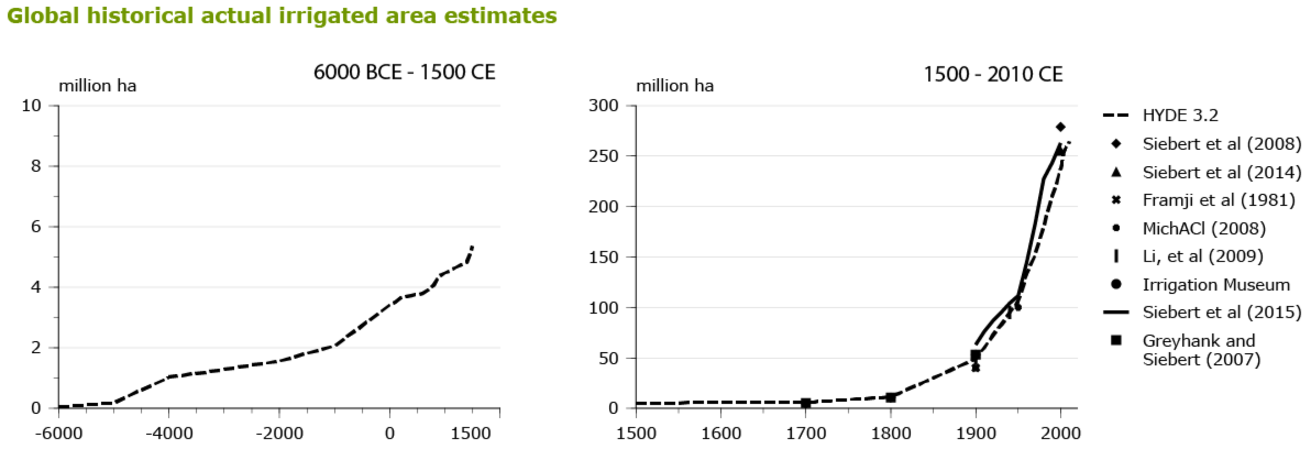

Figure 2. Comparison of HYDE 3.2 and literature for total irrigated area. See also suppl. Material Table S5.

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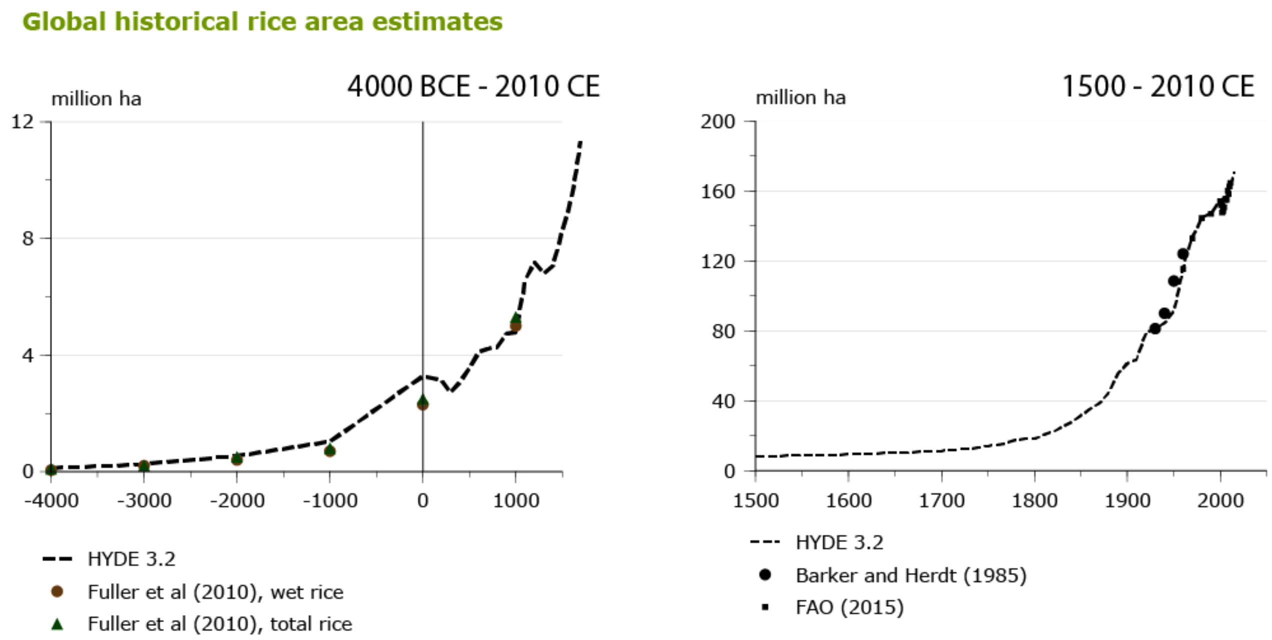

Figure 3. Historical rice area estimates. See also suppl. Table S4.

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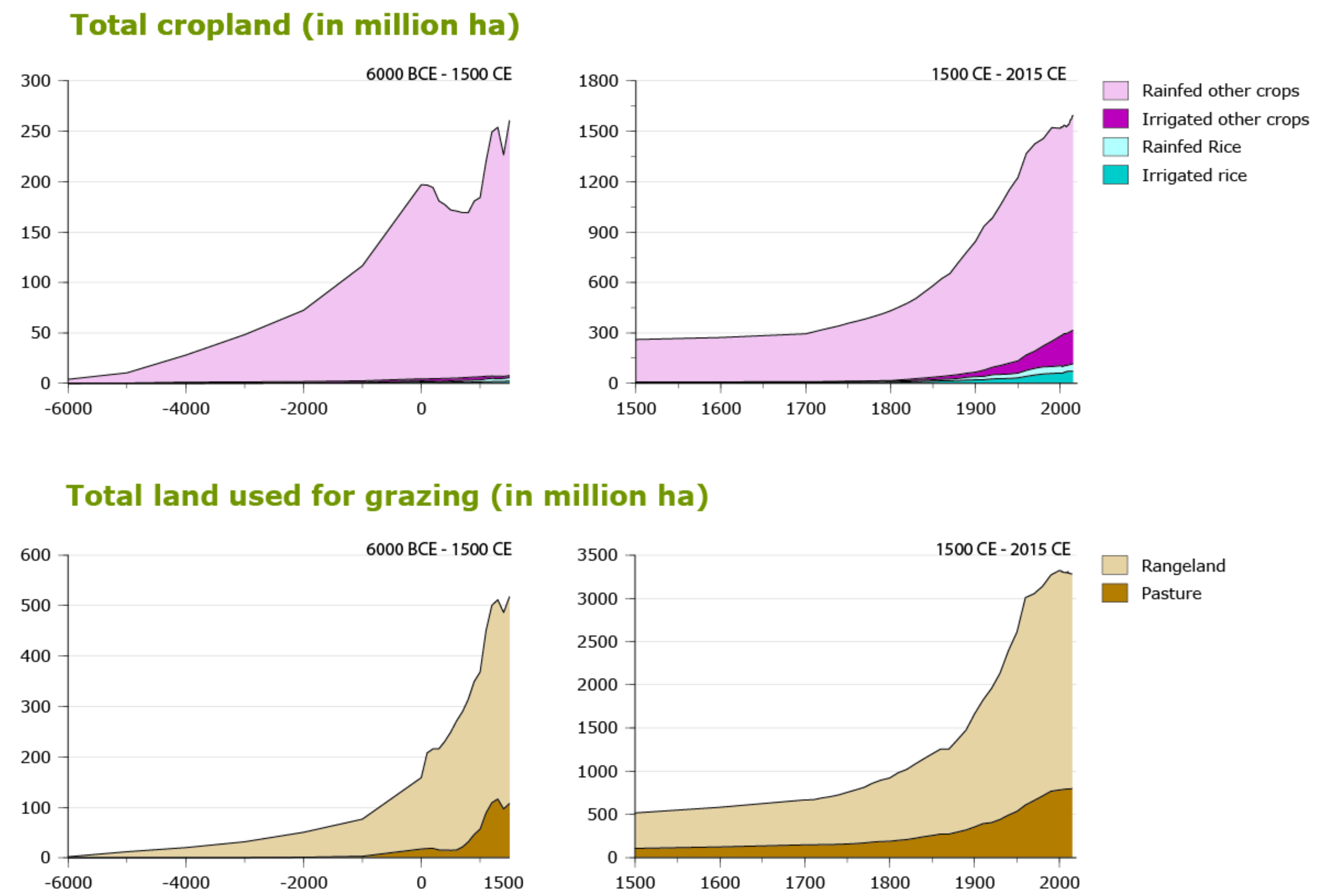

Figure 4. Summary of historical cropland and grazing land estimates.

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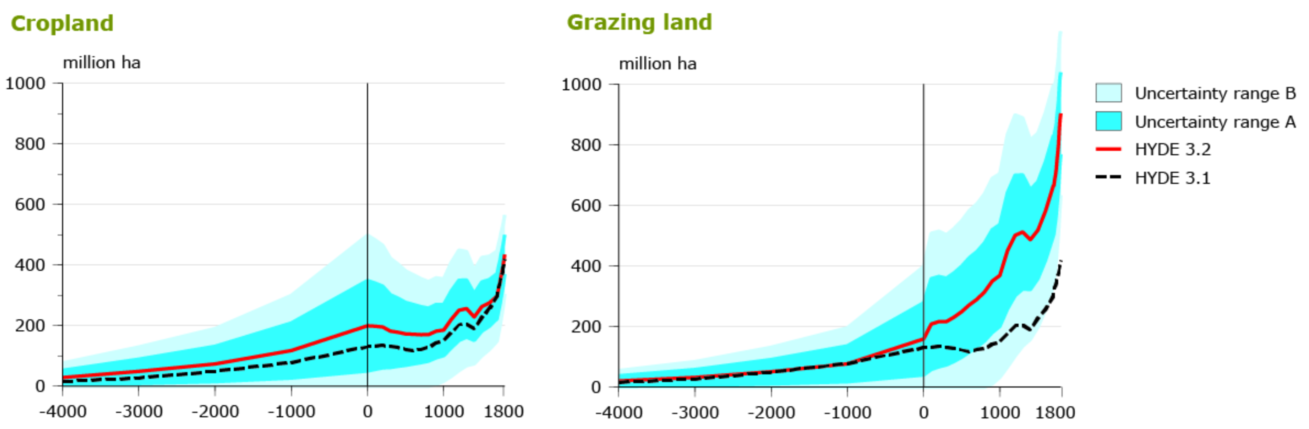

Figure 5. Cropland and grazing land estimates with their uncertainty bands.

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Table 1: Percentages of cropland and grazing land allocated in four steps from the original ESA-CCI land cover classes (between 0 and 100%).

LCCS	UNLCCS Land Cover Class Description	Cropland				Grazing land			
class	*allocation priority*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*
10	Cropland, rainfed	90	0	0	0	90	0	0	0
11	Herbaceous cover	90	0	0	0	90	0	0	0
12	Tree or shrub cover	90	0	0	0	90	0	0	0
20	Cropland, irrigated or post-flooding	90	0	0	0	90	0	0	0
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous)	60	0	0	0	60	0	0	0
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) /	40	0	0	0	40	0	0	0
50	Tree cover, broadleaved, evergreen, closed to open (>15%)	0	0	0	0	0	0	0	0
60	Tree cover, broadleaved, deciduous, closed to open (>15%)	0	0	0	0	0	0	0	0
61	Tree cover, broadleaved, deciduous, closed (>40%)	0	0	0	0	0	0	0	0
62	Tree cover, broadleaved, deciduous, open (15-40%)	0	30	0	0	0	30	0	0
70	Tree cover, needleleaved, evergreen, closed to open (>15%)	0	0	0	0	0	0	0	0
71	Tree cover, needleleaved, evergreen, closed (>40%)	0	0	0	0	0	0	0	0
72	Tree cover, needleleaved, evergreen, open (15-40%)	0	30	0	0	0	30	0	0
80	Tree cover, needleleaved, deciduous, closed to open (>15%)	0	0	0	0	0	0	0	0
81	Tree cover, needleleaved, deciduous, closed (>40%)	0	0	0	0	0	0	0	0
82	Tree cover, needleleaved, deciduous, open (15-40%)	0	30	0	0	0	30	0	0
90	Tree cover, mixed leaf type (broadleaved and needleleaved)	0	0	0	0	0	0	0	0
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	0	40	0	0	0	40	0	0
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	0	60	0	0	0	60	0	0
120	Shrubland	0	90	0	0	0	90	0	0

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121	Evergreen shrubland	0	90	0	0	0	90	0	0
122	Deciduous shrubland	0	90	0	0	0	90	0	0
130	Grassland	0	90	0	0	90	0	0	0
140	Lichens and mosses	0	0	0	0	0	0	0	0
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	0	0	90	0	0	0	90	0
152	Sparse shrub (<15%)	0	0	90	0	0	0	90	0
153	Sparse herbaceous cover (<15%)	0	0	90	0	0	0	90	0
160	Tree cover, flooded, fresh or brakish water	0	0	0	0	0	0	0	0
170	Tree cover, flooded, saline water	0	0	0	0	0	0	0	0
180	Shrub or herbaceous cover, flooded, fresh/saline/brakish water	0	0	0	0	0	0	90	0
190	Urban areas	0	0	0	0	0	0	0	0
200	Bare areas	0	0	0	90	0	0	0	90
201	Consolidated bare areas	0	0	0	90	0	0	0	90
202	Unconsolidated bare areas	0	0	0	90	0	0	0	90
210	Water bodies	0	0	0	0	0	0	0	0
220	Permanent snow and ice	0	0	0	0	0	0	0	0

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Table 2. Regional cropland area estimates (million ha).

	4k BCE	3k BCE	2k BCE	1k BCE	1 CE	800 CE	1100 CE	1400 CE
North America	0.0	0.0	0.0	0.2	0.4	0.6	0.8	1.1
Latin America	1.1	3.8	5.4	6.3	7.3	11.6	16.1	20.8
Europe	1.0	3.3	7.2	14.4	33.4	25.9	41.8	49.2
USSR	0.5	1.4	1.6	2.9	3.2	5.5	8.6	12.4
N.Africa_M.East	14.3	17.6	19.1	23.8	29.1	26.7	23.9	20.4
Tropical Africa	0.3	1.2	1.8	2.8	4.3	13.7	19.4	26.9
China	1.4	3.1	6.3	12.4	24.5	17.5	49.0	41.9
South Asia	8.3	14.8	26.6	47.7	85.4	55.8	46.4	38.2
SE Asia	1.1	3.0	4.2	6.0	9.3	11.2	12.7	14.3
Pacific Dev.	0.0	0.0	0.0	0.0	0.1	0.8	1.0	1.1
World	28.0	48.3	72.4	116.5	196.9	169.3	219.6	226.5
Other global estimates								
Houghton et al (1983)								
Esser (1991)								
Richards (1990)								
Ramankutty and Foley (1999)								
Klein Goldewijk [2001], HYDE 2.0								
Pongratz et al (2008)						136	197	233
Klein Goldewijk (2011), HYDE 3.1					130			
FAO (2015)								

Table 2, cont'd

	1700 CE	1800 CE	1850 CE	1900 CE	1920 CE	1950 CE	1960 CE	2000 CE	2015 CE
North America	0.8	8.3	44	153	199	232	237	230	199
Latin America	9.3	16.5	21	33	52	83	103	162	205
Europe	76.2	99.4	122	147	151	155	156	136	124
USSR	22.3	48.3	72	133	156	196	234	203	197
N.Africa_M.East	24.0	26.6	34	43	48	64	78	88	87

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Tropical Africa	38.9	42.0	48	61	70	113	146	195	262
China	62.3	80.7	89	94	103	110	110	135	127
South Asia	37.2	76.8	110	119	122	148	157	168	169
SE Asia	21.1	30.0	36	54	69	92	105	137	163
Pacific Dev.	2.6	2.5	3	8	14	30	40	55	56
World	294	431	585	844	987	1223	1366	1509	1589
Other global estimates									
Houghton et al (1983)	264								
Esser (1991)				1390	1570	1910			
Richards (1990)	265		537		913	1170			
Ramankutty and Foley (1999)	405	678	821	1144	1301	1528	1688		
Klein Goldewijk [2001], HYDE 2.0	266	402	537	813	944	1230			
Pongratz et al (2008)	401								
Klein Goldewijk (2011), HYDE 3.1	300	418	562	849	995	1214		1531	
FAO (2015)							1372	1519	1591

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Table 3. Regional grazing land area estimates (million ha).

	4k BCE	3k BCE	2k BCE	1k BCE	1 CE	800 CE	1100 CE	1400 CE
North America	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latin America	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Europe	0.8	1.7	3.7	7.4	18.4	31.9	81.2	77.5
USSR	12.6	14.7	17.5	20.6	24.0	38.5	47.2	58.6
N.Africa_M.East	4.3	6.6	10.4	15.8	26.1	38.1	36.8	33.3
Tropical Africa	10.0	17.2	29.4	51.6	79.0	147.2	180.1	222.4
China	20.2	32.2	51.7	55.3	93.5	45.2	90.1	80.0
South Asia	0.0	0.1	0.2	0.3	0.7	1.8	2.0	2.2
SE Asia	0.2	0.2	0.6	1.0	1.8	10.3	11.0	10.3
Pacific Dev.	0.0	0.0	0.0	0.1	0.1	1.3	1.3	1.8
World	48	73	113	152	244	314	450	486
Other global estimates								
Houghton et al (1983)								
Pongratz et al (2008)						144	198	227
Klein Goldewijk [2001], HYDE 2.0								
Klein Goldewijk (2011), HYDE 3.1					106			
FAO (2015)								

Table 3, cont'd

	1700 CE	1800 CE	1850 CE	1900 CE	1920 CE	1950 CE	1960 CE	2000 CE	2015 CE
North America	4.2	18.2	36.1	158.0	181.3	278.1	280.8	251.8	266.7
Latin America	29.5	45.4	73.1	152.7	216.7	370.7	457.2	553.5	561.2
Europe	91.8	80.2	94.3	103.0	103.5	100.0	90.7	78.7	72.3
USSR	79.8	118.9	148.5	225.7	263.3	274.0	301.0	361.7	362.3
N.Africa_M.East	41.0	62.2	107.9	140.9	156.2	196.0	250.6	307.8	293.0
Tropical Africa	301.8	352.6	400.9	458.5	500.1	697.0	799.6	804.9	811.3

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China	98.5	214.5	298.0	288.1	317.0	311.4	367.2	519.9	506.1
South Asia	2.9	3.5	4.1	5.0	4.6	6.7	13.9	10.8	10.2
SE Asia	13.7	16.4	19.4	28.5	34.8	46.3	53.9	55.1	55.5
Pacific Dev.	4.9	4.8	15.0	102.6	179.7	332.1	394.6	378.7	344.6
World	668	917	1197	1663	1957	2612	3010	3323	3283
Other global estimates									
Houghton et al (1983)	526								
Pongratz et al (2008)	370								
Klein Goldewijk [2001], HYDE 2.0	524	942	1310	1955	2282	2930			
Klein Goldewijk (2011), HYDE 3.1	324	513	721	1294	1769	2464		3429	
FAO (2015)							3095	3424	3359

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Table 4. Regional net irrigated area estimates.

	4k BCE	3k BCE	2k BCE	1k BCE	1 CE	1000 CE	1500 CE
North America	0.00	0.00	0.00	0.03	0.11	0.25	0.38
Europe	0.00	0.00	0.00	0.00	0.04	0.08	0.13
USSR	0.00	0.00	0.00	0.00	0.05	0.12	0.19
Pacific Dev.	0.84	0.97	1.03	1.12	1.28	1.91	1.05
China	0.00	0.00	0.00	0.00	0.01	0.03	0.06
Latin America	0.03	0.08	0.15	0.30	0.91	1.21	1.69
N.Africa_M.East	0.04	0.08	0.14	0.25	0.44	0.26	0.19
Tropical Africa	0.10	0.16	0.24	0.36	0.55	0.50	0.44
South Asia	0.00	0.00	0.00	0.00	0.00	0.11	0.15
SE Asia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
World	1.02	1.28	1.56	2.06	3.41	4.5	4.3
Siebert et al (2008)							
Siebert et al (2014)							
Framji et al (1981)							
Michael, A. (2008)							
Li, et al (2009)							
Siebert et al (2015)							
Freydank and Siebert (2008)							

table 4, cont'd

	1700 CE	1800 CE	1900 CE	1960 CE	2000 CE	2015 CE
North America	0.13	0.34	2.19	5.75	14.06	18.46
Europe	0.17	0.34	2.90	6.90	11.91	11.63
USSR	0.25	0.67	3.24	6.38	13.08	13.14
Pacific Dev.	0.93	0.92	2.75	10.13	20.78	23.18
China	0.09	0.20	0.78	2.43	5.42	5.71
Latin America	1.81	4.07	11.41	40.01	48.98	62.12
N.Africa_M.East	0.19	0.75	11.83	24.36	56.74	63.77
Tropical Africa	0.58	1.44	6.67	18.35	39.68	47.08

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South Asia	0.29	0.57	2.61	3.44	4.21	4.45
SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
World	4.5	9.3	44.4	117.7	214.9	249.5
Siebert et al (2008)	4.5	10.5	53.2		278.9	
Siebert et al (2014)					255.2	
Framji et al (1981)			40.0			
Michael, A. (2008)			40.0			
Li, et al (2009)			50.0			
Siebert et al (2015)			63.0	144.5	262.9	
Freydank and Siebert (2008)	5.1	10.6	53.2			

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Table 5. Regional Rice area estimates.

	4k BCE	3k BCE	2k BCE	1k BCE	1 CE	1000 CE
North America	0.03	0.06	0.13	0.18	1.14	0.78
Latin America	0.05	0.10	0.19	0.35	0.67	0.96
Europe	0.02	0.04	0.09	0.19	0.42	0.81
USSR	0.00	0.00	0.01	0.02	0.03	0.52
N.Africa_M.East	0.00	0.00	0.00	0.00	0.00	0.00
Tropical Africa	0.10	0.20	0.42	0.76	2.30	3.23
China	0.00	0.00	0.00	0.00	0.00	0.00
South Asia	0.05	0.20	0.40	0.70	2.30	0.00
SE Asia	0.10	0.20	0.50	0.80	2.50	0.00
Pacific Dev.	0.00	0.00	0.00	0.00	0.00	0.00
World	0.35	0.80	1.73	3.00	9.36	6.3
Fuller et al (2010), wet rice	0.05	0.20	0.40	0.70	2.30	
Fuller et al (2010), total rice	0.10	0.20	0.50	0.80	2.50	
Barker and Herdt (1985)						
FAO (2015)						

table 5, cont'd

	1500 CE	1850 CE	1900 CE	1930 CE	1960 CE	2000 CE
North America	1.82	8.33	7.78	12.54	18.79	20.64
Latin America	1.10	5.82	17.93	18.11	22.21	28.57
Europe	1.40	3.85	9.94	16.36	25.12	37.15
USSR	0.83	1.37	1.80	2.07	2.15	1.27
N.Africa_M.East	0.00	0.00	0.00	0.00	0.00	0.00
Tropical Africa	5.63	20.81	39.63	52.88	77.00	104.40
China	0.00	0.00	0.00	0.00	0.00	0.00
South Asia	0.00	0.00	0.00	0.00	0.00	0.00
SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
Pacific Dev.	0.00	0.00	0.00	81.25	0.00	0.00

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World	10.8	40.2	77.1	183.2	145.3	192.0
Fuller et al (2010), wet rice						
Fuller et al (2010), total rice						
Barker and Herdt (1985)				81.3		
FAO (2015)					115.4	154.5

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Table 6. Comparison total agricultural land estimates, HYDE 3.2 and Kaplan et al (2011)

	4000 BCE	1000 BCE	1 CE	100 CE	500 CE	1000 CE	1500 CE	1600 CE	1850 CE
HYDE 3.2	76	269	440	405	421	552	779	856	1778
Kaplan et al (2010)	186	871	1360	1440	1530	1800	2300	2160	2940

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Table 7. Summary of global population and land use estimates.

	5k BCE	1 CE	500 CE	1000 CE	1500 CE	1700 CE	1850 CE	2015 CE
Population	19.0	232	253	323	503	592	1271	7301
Cropland	10.4	197	172	184	261	294	580	1589
Rainfed area	10.2	194	168	180	256	290	552	1317
Net irrigated area	0.2	3	4	4	4	4	28	271
Net rice area	0.1	2	2	3	6	8	21	116
Paddy rice	0.0	1	1	1	2	3	13	73
Rainfed rice	0.1	1	1	2	3	5	8	44
Grazing	31.8	244	249	368	518	668	1197	3283
Pasture	12.0	79	71	142	222	286	487	1153
Rangeland	19.8	165	178	227	296	382	710	2130
% agric /total land area	0.3%	3.4%	3.2%	4.2%	6.0%	7.4%	13.6%	37.4%