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To cite this article: Kees Klein Goldewijk, Stefan C. Dekker & Jan Luiten van Zanden (2017) Per-capita estimations of long-term historical land use and the consequences for global change research, Journal of Land Use Science, 12:5, 313-337, DOI: [10.1080/1747423X.2017.1354938](https://doi.org/10.1080/1747423X.2017.1354938)

To link to this article: <http://dx.doi.org/10.1080/1747423X.2017.1354938>



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Accepted author version posted online: 11 Jul 2017.  
Published online: 31 Aug 2017.



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# Per-capita estimations of long-term historical land use and the consequences for global change research

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## ABSTRACT

Changes in land use and land cover are important in global climate change, but the many uncertainties in historical estimates seriously hamper climate modelling. We collected new data on estimated per capita land use over the last two millennia, using new data sources from the Humanities. In general, and in agreement with literature, we found that per capita land use indeed has not been constant in the past, but differ per region and over time. Land use in the distant past was mostly less than 1 ha/cap. However, the recently colonised regions show much higher values and have experienced a much higher per capita land use for the recent past. Most known trajectories follow a concave or bell-shaped curve towards the present.

## ARTICLE HISTORY

Received 15 December 2016  
Accepted 6 July 2017

## KEYWORDS

Historical land use; cropland; pasture; agriculture; global climate change; land use per capita

## Introduction

As long as humans have walked the Earth, they have been altering the global landscape (Kaplan et al., 2011; Ruddiman, 2003). These historical changes in land use culminated primarily in the conversion of undisturbed ecosystems (mainly forests) into other forms of land use – mainly cropland, pastures and, to a lesser extent, built-up area (Kaplan et al., 2011; Kaplan, Krunhardt, & Zimmermann, 2009). Already more than one third of the world's land surface is at present under agricultural cultivation, while another 30% is being affected by agriculture to a greater or lesser degree (Ellis, Klein Goldewijk, Siebert, Lightman, & Ramankutty, 2010). All these activities have led to anthropogenic greenhouse gas emissions that have subsequently influenced global climate change. However, at which point in time this influence began is highly uncertain, as is its extent.

Historical land-use information is frequently used in integrated assessments and global change studies (Hurt et al., 2011; Kaplan et al., 2011; Klein Goldewijk, Beusen, van Drecht, & de Vos, 2011), but they are still subject to major uncertainties which are not often addressed. In general, these databases are constructed from the relationship between land use and population size. Uncertainties not only arise due to large temporal and spatial variations in historical population data, but also and especially relate to the assumptions that are made about the relationship between population and land use.

Therefore, it is crucial to have a better understanding of the relationship between population and land use and how it has changed over time, in order to improve our past trajectories of land use. This study aims to present new empirical land-use data and to show how these new estimates

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 The supplemental material for this article can be accessed [here](#).

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change those of overall historical land use of the History Database of the Global Environment (HYDE) (Klein Goldewijk, 2013; Klein Goldewijk, Beusen, & Janssen, 2010; Klein Goldewijk et al., 2011). HYDE is widely used as a reference database in many studies on global climate change (e.g. Hurtt et al., 2011; Kaplan et al., 2011; Lawrence et al., 2016; Le Quééré et al., 2015). However, anthropogenic land-cover change (ALCC) has still not been implemented successfully in the models used in those studies due to the uncertainties in the per capita land use. As a result, climate modelling in paleo-lithic mode or projection mode that tries to take ALCC into account is seriously hampered (Strandberg et al., 2014). Thus, more accurate descriptions of historical ALCC on a global spatial scale are needed. In this study, we mainly used new information from the CLIO-INFRA project, the main purpose of which was to create a database with numerous socio-economic indicators as well as other environmental data, in order to address inequality between countries, over time (e.g. see <http://www.clio-infra.eu>).

Not all countries in the world have experienced the same land-use trajectory over time.

Boserup (1965) proposed a population-driven sequence of technological stages in agricultural development from hunter-gatherers, pastoralism, fallow (forest), bush fallow, short fallow with domestic animals, annual cropping with intensive animal husbandry and multi-cropping with little animal food. She presented evidence from many field studies to underpin her theory that land use intensifies with increasing population: population density determines agricultural methods, rather than agricultural technology determining population, a process which is still ongoing in many regions of the world. Ruddiman and Ellis (2009) elaborated on Boserup's theory and applied it to (paleo)history. They argue that 'average land use per capita appears to have fallen from several ha per person in the middle Holocene to just tenth on one ha near the start of the industrial era' (p. 3), which is consistent with Boserup. However, they do not know the exact shape of the land use per capita curve, nor the timing of the process.

In this study, we aim to reduce uncertainties in historical land-use data by identifying several groups of countries with comparable land-use change trajectories and by using information from different literature sources. Finding the information needed proved not to be a straightforward effort. HYDE uses information from the Food and Agricultural Organization (FAO) of the United Nations as a starting point for back-casting. The FAO is a globally recognised authority when it comes to agricultural statistics, and provides country data on the post-1960 period. However, for the pre-1960 period, data sources are severely limited. This paper describes our search for more empirical data on historical land use, in collaboration with the discipline of economic history, and puts the findings into the perspective of the global change modelling community. It is merely an effort to bridge the gap with data sources from other disciplines such as the Humanities and setting up networks and cooperation with scientists from that side.

## Material and methods

### *Data, selection and division*

To find better empirical evidence of historical land use, we used as search criteria the following keywords: (historical) land use, cropland, cultivated land, irrigation, rice, pasture, grazing land. Search platforms used were Scopus, Web of Science, Google Scholar and the library at Utrecht University, The Netherlands. We aggregated our data into two categories: (1) cropland and (2) pasture, as they have a totally different relationship between land use and population, due to different land-use intensities. In principle, we follow the definition of FAO for cropland and pasture. Cropland is defined by FAO as 'the sum of Arable land and land under Permanent crops. Arable land is defined as land under temporary crops, temporary meadows for mowing or pasture, land under market and kitchen gardens, and land temporarily fallow (less than five years)'. Pasture is defined by FAO as 'Permanent meadows and pastures; the land used permanently (five years or

more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land)'.

A problem with many historical sources is that often the exact definition is not given of the land use described. Many times they refer to 'cropland', 'cropped land', 'arable land', 'farmland', 'cultivated land' or 'pasture', 'fallow', 'meadows' only. We assumed that the FAO definition was valid for that time period. Sometimes, examples were given of a 'typical household with x persons, needing y ha of cropland to sustain them selves', so we had to convert the numbers into hectares per person ourselves. By varying the number of people in a household and area needed to sustain a family, we tried to compute a reasonable minimum and maximum range of the numbers (marked with a \* in Tables 1 and 2). This is always done by our own expert judgement basis. We are fully aware that this might introduce more uncertainty, but most of the historical evidence simply does not give more exact information. With the uncertainty bands, we think that the order of magnitude obtained in this way is sufficient enough for the scientific modelling community which uses these numbers as input. It is in our view that the best result at this moment is achieved, and, since a lot of new historical information is now being used, a major advancement has been made over previous estimates.

We subsequently ordered our data according to geographical regions, namely North America, Latin America, Europe (incl. fUSSR), Northern Africa and Middle East, Sub-Saharan Africa, Asia and Oceania (for a detailed description of the countries and regions see the supplementary material 'Regional\_breakdown.xlsx').

Following the HYDE approach (Klein Goldewijk et al., 2011), we estimate per capita values of land use, defined as a certain area in hectares of cropland or pasture used per person per year. Population estimates refer to the total population of a country or region and not to the agricultural population only. Since population data are probably more accurate and more widely available than absolute land-use data, we preferred to use population data as starting point. We adapted the ideas of Ruddiman and Ellis (2009) and experimented with different shapes of a per capita land-use curve per country (convex, concave, S-shape), which are then used to compute total land-use numbers over time. We hope by finding more empirical evidence that we can define these curves with more certainty, so we can improve the historical land-use trajectories, and reduce the uncertainties attached.

We were able to update the information on the relationship between population and land use in 55 of the total of 238 countries, which covered 23% of the world's countries. We found that the temporal spread of the data from the sources on empirical historical land use differed quite considerably between countries. Therefore, as a first approach, we selected the countries for which there was a reasonable historical data source, and considered them 'representative' of the neighbouring countries, assuming that the entire region had evolved in a similar way. From here, we estimated the most plausible trajectories to present conditions, usually following a concave or bell-shaped curve (see the supplementary material). See also Supplementary material Figures SF1 and SF2 for a spatial explicit representation of countries where data was found for the pre-1960 FAO period.

## Results

### Cropland

#### North America

**Agriculture in North America before the Columbian exchange.** North America saw rather substantial agricultural activity well before the arrival of European settlers (Iseminger, 2010; Mann, 2005; Nevle, Bird, Ruddiman, & Dull, 2011). A relatively well-known example is that of the city state of Cahokia, located in the American Bottom floodplain in south-western Illinois, across the Mississippi River, between approximately 650 and 1400 CE. It had its high point in around 1000 CE, with an estimated 10,000 to 20,000 people living there, who had to be sustained with elaborate, intensive agriculture.



Table 1. Selected historical cropland estimates (in ha cropland per capita).

Region	Representative country	Earliest estimate	Timing earliest estimate	Maximum historical value estimate found (range)	Timing max value	1960 value of FAO	2000 value of FAO	Sources	Countries and regions assumed with similar trajectories
<b>North America</b>									
	Canada	0.72	1852 CE	4.74	1921 CE	2.95	1.70	Urquhart and Buckley (1965), Statcan (2015)	-
	U.S.A	<1.0*	Pre 1500 CE	2.00	1880 CE	1.00	0.62	US Bureau of Census (1975), Vale (2002), Hurt (2002)	-
<b>Latin America</b>									
	Mexico	<1.0*	Pre 1500 CE	0.9 (0.6–1.0)*	Pre 1500 CE	0.63	0.28	Cowgill (1962), Puleston (1982), Reina (1967), Vale (2002)	Rest of Central America
	Antigua	0.61	1833 CE	0.61	1833 CE	0.15	0.12	HCCP (2005)	Caribbean
	Bermuda	0.02	1831 CE	0.10	1960 CE	0.10	0.02	HCCP (2005)	
	Jamaica	0.10	1900 CE	2.57	2000 CE	0.17	2.57	HCCP (2005)	
	Grenada	0.18	1831 CE	0.22	1970 CE	0.21	0.11	HCCP (2005)	
	Trinidad	0.60	1832 CE	0.60	1832 CE	0.12	0.09	HCCP (2005)	
	Colombia	1.50*	1500 CE	5.10	1800 CE	0.31	0.11	Etter and Van Wyngaarden (2000), (2006), 2008)	Ecuador, Peru, Bolivia
	Guyana	0.11	1831 CE	0.63	1960 CE	0.63	0.63	HCCP (2005)	Demerara and Essequibo, Berice. Later a.k.a. Br. Guiana
	Brazil	0.21	1920 CE	0.45	1940 CE	0.39	0.24	Fundacao Instituto Brasileiro de Geografia e Estatistica (1996), Reis (1997)	Venezuela, Surinam, Guyana, Fr. Guiana
<b>Europe and fUSSR</b>									
	Argentina	0.69	1900 CE	1.79	1930 CE	0.95	0.78	Vazquez-Preseado (1988)	Uruguay, Paraguay, Chile
	Ireland	0.26	1840 CE	0.56	1960 CE	0.56	0.28	O'Rourke (1991)	
	England/United Kingdom	0.94	1086 CE	0.94	1086 CE	0.14	0.10	Campbell (2007), Van Zanden (2009)	Scotland, Wales, Is. of Man
	Sweden	1.01	1000 CE	1.01	1000 CE	0.48	0.31	Myrdal and Morell (2011), Van Zanden (2009)	Iceland, Norway, Finland
	Denmark	2.94*	1870 CE	2.94*	1870 CE	0.615	0.429	Van Zanden (2009), Jakobsen (2005)	
	Germany	0.27	600 CE	1.75	1200 CE	0.17	0.17	Bork and Lang (2003), Van Zanden (2009)	Rest of Europe, except Mediterranean region
	The Netherlands	0.88*	700 CE	2.63*	1000 CE	0.09	0.06	Van Zanden (2009), Van Bavel (2010), CBS (2009)	Low countries
	Belgium	0.34*	1870 CE	0.34*	1870 CE	0.106	0.087	Van Zanden (2009), Mitchell (2007)	
	France	0.96*	1870 CE	0.96	1870 CE	0.47	0.33	Van Zanden (2009)	
	Austria	0.67	1830 CE	0.67	1830 CE	0.25	0.18	Van Zanden (2009), Krausmann (2001)	Switzerland, Liechtenstein
	Italy	1.59*	1 CE	1.59 (1.27–2.12)	1 CE	0.32	0.20	Van Zanden (2009)	Portugal, Spain, Malta

(Continued)

Table 1. (Continued).

Region	Representative country	Earliest estimate	Timing earliest estimate	Maximum historical value estimate found (range)	Timing max value	1960 value of FAO	2000 value of FAO	Sources	Countries and regions assumed with similar trajectories
	Greece	0.36–0.73*	1 CE	0.87	1842 CE	0.44	0.35	Jameson et al. (1934), Kizos and Koulouri (2006), Sallares (1991), Foldvart and van Leeuwen (2012)	Turkey, Cyprus, Albania
<b>Northern Africa and Middle East</b>	Russia	1.25*	1890 CE	1.39*	1910 CE	1.13	0.72	Mitchell (2007)	Former USSR
	Egypt	4.60	4000 BCE	4.60	4000 BCE	0.09	0.05	Butzer (1976)	Morocco, Algeria, Tunisia, Libya, Israel, Jordan, Syria, Iraq, Iran
<b>Sub-Saharan Africa</b>	Sierra Leone	0.42	1831 CE	0.42	1831 CE	0.18	0.13	HCCP (2005)	Sub-Saharan Africa except southern Africa
	South Africa	0.72	1831 CE	0.72 (0.60–0.74)		0.74	0.36	Biggs and Scholes (2002), Van Zanden and Fourie (2013), HCCP (2005)	Namibia, Botswana, Zimbabwe, Swaziland, Lesotho
<b>Asia</b>	India	0.40	1595 CE	0.47	1920 CE	0.36	0.16	Moosvi (1987), Flint and Richards (1991)	Pakistan, Nepal, Bhutan
	Bangladesh	0.31	1880 CE	0.31	1880 CE	0.20	0.18	Flint and Richards (1991)	
	Sri Lanka	0.16	1831 CE	0.27	1909 CE	0.15	0.10	HCCP (2005), Flint and Richards (1991)	
	Laos	0.15	1880 CE	0.31	1960 CE	0.31	0.18	Flint and Richards (1991)	
	Malaysia	0.32	1880 CE	0.56	1920 CE	0.49	0.32	Flint and Richards (1991)	
	Myanmar	0.38	1880 CE	0.57	1920 CE	0.48	0.23	Flint and Richards (1991)	
	Cambodia	0.20	1880 CE	0.54	1960 CE	0.54	0.31	Flint and Richards (1991)	
	Philippines	0.40	1880 CE	0.40	1880 CE	0.26	0.13	Flint and Richards (1991)	
	Thailand	0.31	1880 CE	0.42	1950 CE	0.41	0.30	Flint and Richards (1991)	
	Vietnam	0.49	1880 CE	0.59	1920 CE	0.18	0.10	Flint and Richards (1991)	
	China	0.66*	1 CE	0.66*	145 CE	0.16	0.12	Fuller et al. (2011), Chao (1986)	Dem. Korea, Rep. Of Korea, Taiwan
	Indonesia	0.16	1820 CE	0.28	1850 CE	0.21	0.17	Boomgaard and van Zanden (1990), Flint and Richards (1991), Van Zanden (2009)	Brunei dar el Salam, Singapore
<b>Oceania</b>	Japan	0.14	730 CE	0.16	1150 CE	0.06	0.04	Bassino et al. (2011)	
	Australia	0.90	1831 CE	3.25	1970 CE	2.89	2.40	Australian Bureau of Statistics (2001), HCCP (2005)	1831 value for van Diemensland (Tasmania)
	New Zealand	0.12	1860 CE	1.48	1960 CE	1.48	0.28	HCCP (2005)	

\*Computed, inferred and constructed from (sometimes qualitative) descriptions in literature.



**Table 2.** Selected historical pasture estimates (in ha pasture per capita).

Region	Representative country	Earliest estimate	Timing earliest estimate	Maximum historical value estimate (range)	Timing max value	1960 value of FAO	2000 value of FAO	Source	Countries and regions assumed with similar trajectories	
<b>North America</b>	Canada	0.47	1852 CE	1.35	1941 CE	0.95	0.50	Urquhart and Buckley (1965), Statcan (2015)	-	
	U.S.A	4.49	1700 CE	4.49	1700 CE	1.42	1.20	US Bureau of Census (1975), Vale (2002), Hurt (2002)	-	
<b>Latin America</b>	Mexico	n/a	n/a	n/a	n/a	1.97	0.80	FAO (2015)		
	Bahamas	0.24	1832 CE	0.24	1832 CE	0.01	0.01	HCCP (2005)		
	Bermuda	0.11	1831 CE	0.23	1832 CE	0.01	0.01	HCCP (2005)		
	Jamaica	0.28	1900 CE	0.16	1960 CE	0.16	0.09	HCCP (2005)		
	Grenada	0.06	1831 CE	0.06	1831 CE	0.03	0.01	HCCP (2005)		
	Trinidad	0.10	1831 CE	0.10	1831 CE	0.01	0.01	HCCP (2005)		
	Colombia	0.38*	1500 CE	2.94*	1850 CE	2.19	2.10	Etter & Van Wyngaarden, 2000; Etter et al., 2006, 2008	Ecuador, Peru, Bolivia	
	Argentina	2.30*	1881 CE	5.72	1960 CE	5.72	2.7	Viglizzo (2001), La Pampa region only	Uruguay, Paraguay, Chile	
<b>Europe and fUSSR</b>	Brazil	1.55*	1920 CE	2.10	1950 CE	1.68	1.13	Fundacao Instituto Brasileiro de Geografia e Estatistica (1996), Reis (1997)		
	Guyana	0.10	1831 CE	1.76	1960 CE	1.76	1.63	HCCP (2005)		
	England/United Kingdom	0.16*	1250 CE	0.18*	1400 CE	0.24	0.21	Campbell (2007), FAO (2015)	Scotland, Wales, Isl. of Man	
	Ireland	0.70	1840 CE	1.43	1960 CE	1.43	0.88	O'Rourke (1991)		
	Germany	0.54	600 CE	3.22	1100 CE	0.09	0.07	Bork and Lang (2003), Van Zanden (2009)	Remaining countries of Europe, except	
	The Netherlands	0.54*	700 CE	1.60*	1000 CE	0.112	0.064	Van Zanden (2009), Van Bavel (2010), CBS (2009)	Mediterranean region	
	Italy	n/a	n/a	n/a	n/a	n/a	0.103	0.076	FAO	Belgium, Luxembourg
	Greece	0.039*	1831 CE	0.625	1960 CE	0.625	0.427	Jameson et al. (1934), Kizos and Koulouri (2006), Sallares (1991), Foldvarir and van Leeuwen (2010)	Portugal, Spain, Malta, Balkan states, Albania	
	Russia	n/a	n/a	n/a	n/a	n/a	0.64	0.73	FAO (2015)	Turkey, Cyprus
	Kazakhstan	n/a	n/a	n/a	n/a	n/a	15.50	15.90	FAO (2015)	Turkmenistan
<b>Northern Africa and Middle East</b>	Kyrgyzstan	n/a	n/a	n/a	n/a	2.20	2.04	FAO (2015)	Uzbekistan, Tajikistan	
	Iraq	n/a	n/a	n/a	n/a	0.55	0.16	FAO (2015)	Kuwait, Jordan, Lebanon, Syria	

(Continued)

Table 2. (Continued).

Region	Representative country	Earliest estimate	Timing earliest estimate	Maximum historical value estimate (range)	Timing max value	1960 value of FAO	2000 value of FAO	Source	Countries and regions assumed with similar trajectories
<b>Sub-Saharan Africa</b>	Iran	n/a	n/a	n/a	n/a	2.03	0.70	FAO (2015)	northern Africa
	Saudi Arabia	n/a	n/a	n.a.	n/a	20.86	36.69	FAO (2015)	Qatar, Oman, Yemen, UAE
	Western Sahara	n/a	n/a	n/a	n/a	152.42	98.16	FAO (2015)	Western Sahara
	Namibia	n/a	n/a	n/a	n/a	63.08	55.69	FAO (2015)	-
	Botswana	n/a	n/a	n/a	n/a	48.87	42.98	FAO (2015)	-
	Chad	n/a	n/a	n/a	n/a	15.17	13.61	FAO (2015)	Somalia, Angola, Djibouti, Gabon
	Cape of Good hope	60.27	1831 CE	60.27	1831 CE	n/a	n/a	HCCP (2005)	-
<b>Asia</b>	South Africa	9*	1831 CE	9*	1831 CE	5.13	4.35	HCCP (2005)	-
	India	n/a	n/a	n/a	n/a	0.031	0.022	FAO (2015)	Bangladesh, Pakistan, Nepal, Bhutan
	Sri Lanka	0.03	1831 CE	0.07	1860 CE	0.05	0.02	HCCP (2005)	-
	China	n/a	n/a	n/a	n/a	0.38	0.58	-	Dem. Korea, Rep. Of Korea, Taiwan, Hong Kong, Macau
<b>Oceania</b>	Mongolia	n/a	n/a	n/a	n/a	146.00	121.00	FAO (2015)	-
	Indonesia	n/a	n/a	n/a	n/a	0.135	0.11	FAO (2015)	-
	Japan	n/a	n/a	n/a	n/a	0.012	0.004	FAO (2015)	-
	Australia	0.11	1831 CE	41.96	1960 CE	41.96	36.19	Australian Bureau of Statistics (2001), HCCP (2005)	1831 value for van Diemensland (Tasmania)
	New Zealand	0.28	1860 CE	5.80	1900 CE	5.38	5.28	HCCP (2005)	-

\*Computed, inferred or constructed from (sometimes qualitative) descriptions in literature.

More towards the south-west of the United States, for example, the Hohokam (seventh century to fourteenth century), the Anasazi, and the Mogollon cultures were thriving (Mann, 2005). Vale (2002) estimated that dryland farming required around 1.0 ha/cap, with irrigation reducing the field size to 0.6 ha/cap. Also along the western US coastline of California and along riverbanks such as those of the Klamath, many small settlements have been found, probably with similar features (Hurt, 2002). Along the eastern coast, the first settlements were of woodland tribes. These people were hunters and gatherers, who later evolved to living in villages, supplementing their diet with cultivated crops (Hurt, 2002).

**The post-colonisation era.** European settlers, who initially established themselves along North America's eastern coastline, cleared quite extensive areas of forest for timber exploitation, cultivation and grazing purposes (Williams, 2003). In the subsequent decades, this led to a rapid increase in settlements on government land. Wheat cultivation shifted towards the west, due to land-price increases and encroaching corn cultivation. In the 1860s, the Corn Belt moved westward, and in the 1870s and 1880s, agricultural settlements within the Great Plains region increased substantially. Dryland farming in the semi-arid regions of the Midwest began in the 1880s (Mather, 1990). Some states had very low population densities (US Bureau of Census, 1975) and reached up to 20 ha/cap in North Dakota, 13 ha/cap in South Dakota and 10 ha/cap in both Montana and Nebraska, by the end of the twentieth century. However, in many states, the amount of cropland per capita was much lower, leading to an average of 1.74 ha/cap of cropland for the U.S.A in 1850 CE, peaking at 2.01 ha/cap in 1880–90 CE, and slowly declining to 0.63 ha/cap in 2000 CE (Table 1, Figure 1(a)).

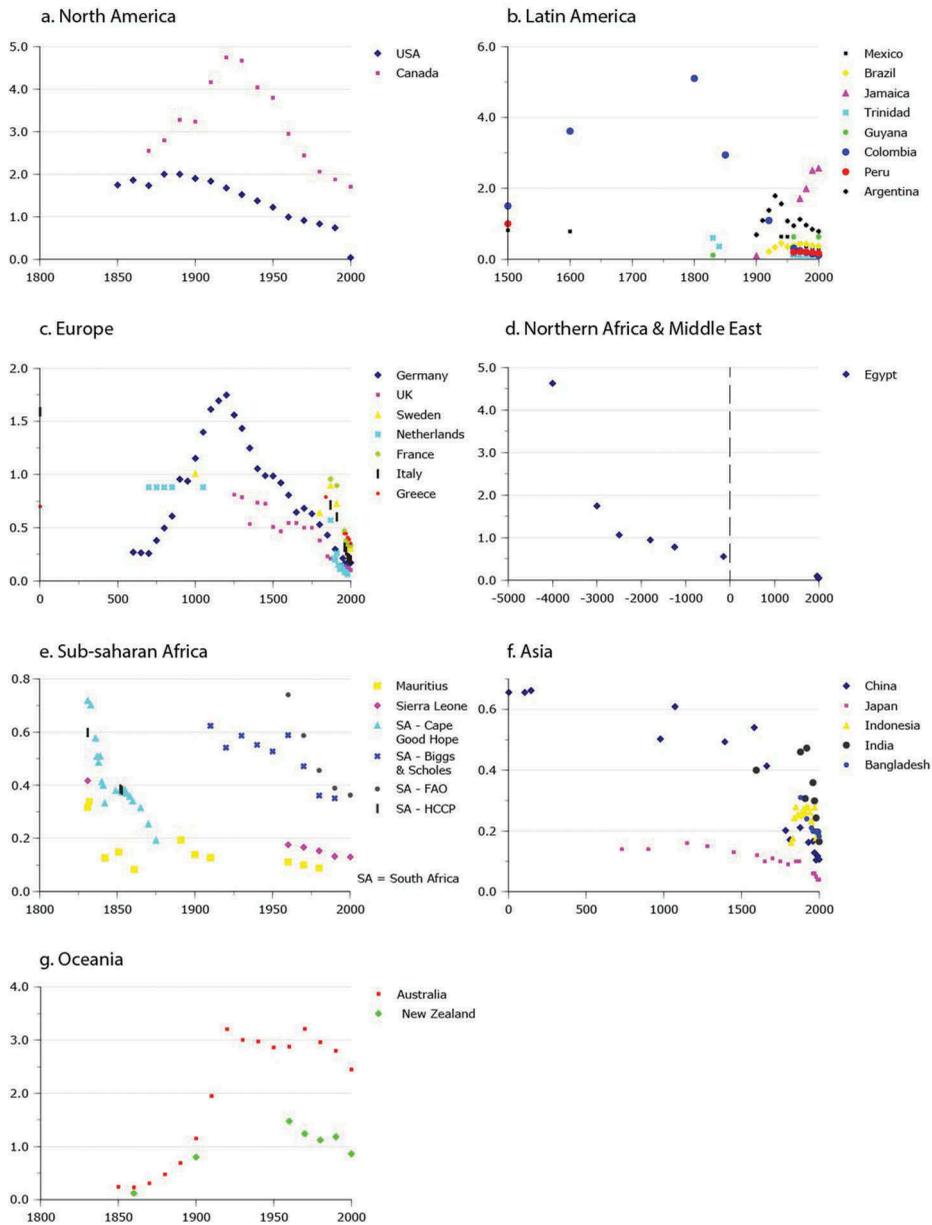
In what is now Canada, the Prairie provinces had almost no crop cover in 1900 CE, but were agriculturally developed by 1930 CE (Lower, 1973, as cited by Mather, 1990). The first-known census data on Canada are from 1871 CE and it appears that the per capita amount of cropland in Canada never exceeded 5 ha/cap and peaked in the first half of the twentieth century. We estimate 0.74 ha/cap in 1852 CE (HCCP, 2005), a peak at 4.74 in 1921 CE and a slowly decline to 1.70 in 2000 CE (Urquhart & Buckley, 1965) (Table 1, Figure 1(a)).

### **Latin America**

**Before the Columbian exchange.** The Maya civilisation began roughly around 2000 BCE, stretching all over lowland Yucatan (Mexico), Guatemala and Belize. Most famous is the Classic period from 200 to 900 CE, when large societies evolved, pyramids were built and agriculture was highly developed and intensive. Many studies have estimates for this agricultural period before the Columbian Exchange around 1500 CE (Cowgill, 1962; Puleston, 1982; Reina, 1967). All studies report that an average of less than 1.0 ha/cap of cropland was needed, with Cowgill (1962) stating the highest at 0.9 ha/cap, followed by Puleston (1982) at 0.83 ha/cap and Reina (1967) at 0.78 ha/cap. The first official census estimate on cropland for Mexico was for 1940 CE (see also Table 1 and Figure 1(b)).

The Aztecs lived in large parts of central Mexico, roughly from the fourteenth to the sixteenth century and were already quite advanced in agriculture (Cartwright, 2014; Morehart & Frederick, 2014). They used artificial islands to grow their crops, which were called floating gardens or 'Chinampas', thus using water very efficiently. Because of the abundance of water and the favourable climatic conditions, up to 7 harvests per year could be achieved. They also practiced terracing to create more usable land. Favoured crops were maize, squash and beans, also known as the 'Three Sisters' (Mann, 2005). These three crops were planted together, because they kept the nutrients in the soil; thus ensuring crops would grow well and provide sufficient food for the human population. The Aztecs also grew, for example, avocados, tomatoes and guavas as food sources, and used cotton plants and rubber trees to create products they needed, such as clothing and latex balls (Mann, 2005).

The Incas lived on the north-western coast and in the Andes region of South America (Peru, Bolivia) from 1450 to 1535 CE. They had an advanced agricultural system, which allowed them to



**Figure 1.** Selected historical cropland per capita estimates per world region. (a) North America; (b) Latin America; (c) Europe; (d) North Africa and Middle East; (e) Sub-Saharan African; (f) Asia; (d) Oceania.

grow copious amounts of food and to specialise (D’Altroy, 2015; Kelly, 2010). They would carve terraces out of a hillside to grow vegetables there, such as corn, beans and squash. They also had an advanced irrigation system that consisted of canals and streams to help water these terraces. The estimated maximum land use per capita is 1 ha.

**Rest of South America.** Before the Columbian Exchange (fifteenth century to sixteenth century), large parts of the Amazon basin were populated by many small households scattered along the Amazon riverbanks and its tributaries. They created so-called Terra Preta plots, or black soils, which

were completely man-made and made it possible to sustain relatively good harvests for a long period of time (Mann, 2005; Morton et al., 2008). Things changed dramatically when the Europeans arrived in Latin America.

During the nineteenth century, three million hectares of forest were converted into coffee plantations (Williams, 2003). Half of the original forest area that was dominated by hardwood trees, such as *Nothofagus pumilio*, was simply burned down to make way for sheep and cattle ranching. Historical statistics yield an average cropland per capita for Brazil of 0.21 ha/cap in 1920 CE, peaking at 0.40 ha/cap in 1980 CE and declining again to 0.24 ha/cap in 2000 CE (see also Table 1 and Figure 1(b)) (Fundacao Instituto Brasileiro de Geografia e Estatistica, 1996; Reis, 1997).

Grigg (1987) presented figures on the expansion of cropland in Argentina: 6 million ha in 1900 CE, 24 million ha in 1930 CE and 22 million ha in 1960 CE. These figures are much higher than estimates by Vazquez-Presedo (1988), who estimated 3.4 million ha for 1900 CE, 20 million ha for 1930 CE and 19 million ha for 1960 CE, which is close to the FAO value for 1960 CE. Therefore we use Vazquez-Presedo (1988), and estimate a value of 0.69 ha/cap for 1900 CE, peaking in 1930 CE with 1.79 ha/cap and slowly decreasing again to 0.95 ha/cap in 1960 CE and 0.78 ha/cap in 2000 CE. Etter and Van Wyngaarden (2000), Etter, McAlpine, Wilson, Phinn, & Possingham (2006), Etter, McAlpine, & Possingham (2008) report historical patterns for Colombia for 1500 CE, 1600 CE, 1800 CE, 1850 CE, 1920 CE and 1970 CE but this mainly concerned cleared areas, instead of giving total cropland areas (Etter & Van Wyngaarden, 2000; Etter et al., 2006, 2008). He estimated 7500 ha of cleared land in 1500 CE, of which 80% was used for agriculture and 20% for grazing. Combined with population data from HYDE, and adjusted to match FAO data in 1970, we estimate 1.50 ha cropland per capita around 1500 CE, 1.60 ha/cap in 1600 CE, peaking at 5.10 ha/cap in 1800 CE, 2.94 ha/cap in 1890 CE, and slowly decreasing to 2.19 ha/cap in 1960 CE and 1.01 ha/cap in 2000 CE (Table 1 and Figure 1(b)).

### Europe

Jameson, Runnels, and Van Andel (1934) made a rough estimation of the amount of arable land per capita in Ancient Greece, which they compared to the size of allotments allocated to families in Ancient Greece (40–60 plethra, equalling 3.6–5.4 ha). Assuming an average household size of 5–8 persons, this would roughly correspond to a range of 0.56 to 0.90 ha of cultivated land, per capita (average of 0.7 ha/cap). This is of the same order of magnitude as data by Kizos and Koulouri (2006), who reported 0.61 ha/cap for the island of Lesbos, from the sixteenth century onwards. Sallares (1991) presents estimates for ancient Attica. With an area of ca. 2400 km<sup>2</sup>, of which 15% was cultivated, and with three different population densities (52, 43, 35 inhabitants per km<sup>2</sup>) based on various carrying capacity assumptions, this would yield a range of 0.28 ha/cap to 0.43 ha/cap, with an average of 0.36 ha/cap. We assumed the same relations for Turkey and Cyprus. See Table 1 and Figure 1(c) for selected cropland per capita estimates.

In the fifth century BCE, farms in Rome were small and family-owned. Farm sizes in Rome, in those days, could be divided into three categories. Small farms were between 5 and 28 ha; medium-sized farms were between 21 and 130 ha and large estates (called *latifundia*) were over 130 ha). Cato the Elder described a typical farm, representing with an average of 25.5 ha for 16 people = 1.59 ha/cap. Lower and upper bounds for 12 and 20 people represent a respective 1.27 ha/cap and 2.12 ha/cap (Cato the Elder, 160 BCE). According to Van Zanden (2009), the amount of cultivated land in Italy decreased to 0.71 ha/cap by 1870 CE, 0.60 ha/cap by 1910 CE, 0.32 ha/cap by 1960 CE and 0.20 ha/cap by 2000 CE.

Myrdal and Morell (2011) give lower and upper estimates for Swedish farm sizes, depending on the cropping system, for the period around 1000 CE. Combined with household sizes varying from 5 to 8 people, this yields roughly 1.01 ha/cap for Sweden in 1000 CE. Supplemented with estimates by Van Zanden (2009) for 1870 and 1910, we assumed these per capita figures also to be valid for other Nordic countries such as Iceland, Norway and Finland. Jakobsen (2005) published a historical-geographical survey of Danish agriculture and settlement conditions of ca. 1000–1688 CE. He

suggested several farm sizes, ranging from 46.4 to 81.1 ha. Combined with lower and upper bounds for household sizes (5–10 people), this yields an average range of 3.1–5.5 ha/cap. These figures seem rather high. Adjusted to the total population, meaning including people living in cities and towns, we assume that less than 2.9 ha/cap would be more realistic; FAO data on the period after 1960 CE show 0.62 ha/cap, and 0.43 ha/cap for 2000 CE (Table 1, Figure 1(c)).

There is a very good time series (per year) on cropland in the United Kingdom for the period 1250–1870 CE (Campbell, 2007). It is a very precise body of data on pre-modern grain harvests, with information from thousands of precisely dated manorial accounts from England. For cultivated land, this yields a range of 0.10–0.81 ha/cap for the United Kingdom and 0.21–1.07 ha/cap for England only. We estimate an earliest average value of 0.94 ha/cap for 1086 CE. O'Rourke (1991) presented data on Ireland's agricultural extent before and after the Great Famine (1845–1849 CE), with 0.26 ha/cap for 1840 and 0.22 ha/cap for 1850 CE. In subsequent years, population numbers fell dramatically due to starvation and emigration, from 8 million to less than 3 million in one century. Therefore, FAO data on cropland, per capita, for 1960 CE were higher again, with 0.56 ha/cap (Table 1)

Bork and Lang (2003) presented a quantification of changes in land and the resulting soil erosion in Germany from the sixth century until the present. Changes in forest, pasture and cropland area were estimated, and extreme events (e.g. severe weather, wars and pandemics such as the Black Plague) left clear traces on the landscape. This same pattern is also reflected in the data on per capita land use from Bork and Lang (2003); starting at very low values of around 0.20 ha/cap in 600 CE, then rapidly increasing towards a peak of 1.75 ha/cap around 1200 CE as a result of better techniques and different rotation schemes, followed by an almost linear decrease to 1.05 ha/cap in 1400 CE, 0.68 ha/cap in 1700, and then returning to the 600 CE level of ca. 0.21 ha/cap in 1950 CE. The values provided by Van Zanden (2009) of 0.90 ha/cap for 1870 CE and 0.55 ha/cap for 1820 CE seem to be either on the high side or at a too late point in time. Van Zanden (2009) reports similar values for France: 0.96 ha/cap for 1870 CE and 0.90 ha/cap for 1910 CE. The FAO provides a value of 0.47 ha/cap for 1960 CE and 0.33 ha/cap for 2000 CE. For the earlier period, France is assumed to have had a per capita cropland use similar to that of Germany (Table 1, Figure 1(c)).

Other European countries do not show (or to a much lesser extent) this 'peak' in cropland per capita. In the Low Countries, which were far more densely populated, this was probably due to the fact that they were not as severely affected by the Black Death. For the Netherlands, estimates from Statistics Netherlands (2009) and Van Bavel (2010) were used to determine land use per capita for the period from 700 CE to 2000 CE. This led to an estimate of around 0.88 ha/cap for the seventh and eighth century, slowly decreasing to 0.57 ha/cap in 1870 CE (Van Zanden, 2009), and finally arriving at a very low 0.08 ha/cap in 1960 CE, due to high population numbers. Ranges for Belgium and Austria are similar, with 0.34 ha/cap in 1870 CE and 0.1 ha/cap in 1960 CE for Belgium, and 0.67 ha/cap in 1830 CE and 0.47 ha/cap in 1960 CE for Austria (Mitchell, 2007; Van Zanden, 2009). Russia had 1.25 ha/cap in 1890 CE and 1.13 ha/cap in 1960 CE (Mitchell, 2007; Van Zanden, 2009). Table 1 summarises the maximum numbers and also shows which countries are believed to have followed a similar pattern. In general, we can see that the more southern based European countries already were at a maximum around 1 CE at 1.0 ha/cap and then show a decline to the current lower FAO values. Some northern European countries show a peak in the middle Ages (1000–1200 CE) and then a decrease towards current low values (see also Table 1 and Figure 1).

### **North Africa, Middle East**

Foldvari and van Leeuwen (2010) estimate the size of the area that needed to be cultivated to support one person in an Ancient Mediterranean society at between 0.5 and 1.0 ha. This corresponds well with later estimates by Butzer (1976) for Egypt. He presented figures on land use in Egypt for 4000 BCE (4.6 ha/cap), 3000 BCE (1.7 ha/cap), 2500 BCE (1.1 ha/cap), 1800 BCE (0.9 ha/cap), 1250 BCE (0.8 ha/cap) and 150 BCE (0.6 ha/cap) (Table 1, Figure 1(d)). From 150 BCE onwards,

the numbers remain low and we interpolated them towards the FAO value for 1960 CE. We assumed these numbers to also be representative of northern Africa and the Middle East (Morocco, Algeria, Tunisia, Libya, Egypt, Turkey, Cyprus, Israel, Jordan, Syria, Iraq and Iran).

### *Sub-Saharan Africa*

There is not as much information on land use on the African continent as there is on other parts of the world. One of the first sub-Saharan regions with permanent agriculture and for which there are sound historical records was the Cape of Good Hope area in South Africa. Between 1650 and 1800, the colonists expanded towards the Orange River, into large coastal areas and the Karoo (Dean & Milton, 1999). With this expansion, agriculture spread as well, with many small farms and large estates becoming established, with a moving settlement frontier into the hinterland that was mainly based on pastoral activities, thus slowly pushing the indigenous KhoiKhoi herding people out of the area. Until about 1870, the economy of the region was almost entirely based on agriculture.

Van Zanden and Fourie (2013) presented land-use data for South Africa reaching 0.72 ha/cap in 1831 CE, then quickly decreasing to 0.58 ha/cap in 1840 CE, 0.40 ha/cap in 1852 CE, 0.32 ha/cap in 1865 CE and 0.19 ha/cap in 1875 CE. The South African House of Commons Parliamentary Papers (HCCP, 2005) are in good agreement with Van Zanden, and present 0.60 ha/cap for 1831 CE and 0.38 ha/cap for 1852 CE. For the whole of South Africa, over the 1911–1993 period, Biggs and Scholes (2002) present figures in the range of 0.62 ha/cap for 1911 CE, 0.59 ha/cap for 1960 CE and 0.35 ha/cap for 1990 CE. The FAO (2015) value for 1960 CE is 0.74 ha/cap (Table 1, Figure 1(e)). We could only find in the House of Commons Parliamentary Papers one other estimate for an African country; Sierra Leone with 0.43 ha/cap for 1831 CE (HCCP, 2005).

### *Asia*

According to Fuller and Qin (2001) and Fuller et al. (2011), early rice cultivation, before 4000 BCE, in the Yangtze region and southern China was based on wet, paddy-field systems. Northern India and Thailand cultivated predominantly dry rice in 2000 BCE, with a documented transition towards flooded rice systems in India around 1000 BCE. China and Japan are two of the few countries with long records of cropland farming. In China, we estimate cropland cultivation at 0.7 ha/cap in 1 CE, and steadily decreasing to less than 0.1 ha/cap by 1950 CE (Chao, 1986). After 1950 CE, because of the enormous population explosion, it decreased further and more rapidly, to very low per capita numbers indeed. In 730 CE, Japan already had very modest cropland use per capita, with 0.14 ha/cap (Bassino, Broadberry, Fukao, Gupta, & Takashima, 2011). Here, numbers also steadily decreased further, to 0.06 by 1960 CE (FAO, 2015) (see Table 1 and Figure 1(f)).

The Mughal Empire was the dominant power on the Indian sub-continent, between the mid-sixteenth century and the early eighteenth century (Moosvi, 1987). Agriculture was the most important source of income for the majority of people. The use of irrigation was not widespread, although some areas did have access to canals. Moosvi (1987) reports data on India for 1595 CE, where the amount of cropland per capita was only very modest, with 0.4 ha/cap, and steadily decreased even further towards modern times, to 0.36 ha/cap in 1960 CE, and, because of the population growth after the Second World War, to 0.16 ha/cap in 2000 CE.

Many other Asian countries, such as Indonesia (Van Zanden & Marks, 2012) and other parts of Southeast Asia (Flint & Richards, 1991), were found to follow a similar pattern, starting with very few hectares per capita, followed by a small increase when cropland areas expanded, but then a gradually decreasing trend again to even smaller numbers, due to population pressure. An elaborate research on land-use changes in South and Southeast Asia is available on the period between 1880 CE and 1980 CE (Richards & Flint, 1994). That study covered an area of 8 million km<sup>2</sup> in 13 countries (India, Sri Lanka, Bangladesh, Myanmar, Thailand, Laos, Cambodia, Vietnam, Malaysia, Brunei, Singapore, Indonesia and the Philippines). Throughout this whole area, forests, woodlands and wetlands declined by 47% (131 million ha), at the costs from cultivated area that

increased by 106 million ha, which is nearly a doubling since 1880 CE. All cropland per capita estimates for these countries were well below 1 ha/cap in 1880 CE (Flint & Richards, 1991) (see Table 1 and Figure 1(f)).

Indonesia first went from 0.16 ha/cap in 1820 CE to a maximum of 0.28 ha/cap in 1850 CE, and again returned back to 0.16 ha/cap by 2000 CE (Boomgaard & van Zanden, 1990; Flint & Richards, 1991; Van Zanden, 2009). Sri Lanka was found to have a similar history of cropland per capita. Starting in 1830 CE with only 0.15 ha/cap, then increasing to a peak of 0.25 ha/cap around 1900 CE, followed by a steady decrease to less than 0.10 ha/cap, in the present (HCCP, 2005) (see Table 1 and Figure 1(f)).

In conclusion, we observed clear differences between countries, with China having maximum values and Bangladesh the lowest (Figure 1(f)). Interesting in this is that highest values of the rice-based economy fairly are close to the lowest values of the irrigated regions (Egypt).

### **Oceania**

Australia and New Zealand experienced similar patterns of colonisation. The first European settlers arrived in south-eastern Australia around 1788 CE and it took a while before the expansion of agricultural land was noticeable. Expansion took place mostly in the fertile and rain-fed regions of the south-eastern part of the country, a bit to the north-east and in the south-western Perth area. So, the relatively late arrival of settlers by the end of the eighteenth century, followed by a rapid expansion of cropland and, later on, by an increase in population, led first to a sharp increase in hectares per capita and to a decrease later on. Australian values start at 0.90 ha/cap in 1831 CE, peaking at 3.25 ha/cap in 1970 CE and 2.40 ha/cap in 2000 CE (Australian Bureau of Statistics, 2001). Based on HCCP (2005), we estimate for New Zealand 0.12 ha/cap in 1860 CE, a maximum of 1.48 ha/cap in 1960 CE and 0.28 ha/cap in 2000 CE (Table 1, Figure 1(g)).

### **Pasture or grazing land**

Much less is known about pastures. A prominent difficulty is that many ecosystems or land-cover classifications are used to indicate pasture, but are not converted and thus less visible for recording, which is especially seen for the ancient past. This is in contrast to modern Brazil, where large areas of rainforest are being deforested and completely converted into pastures. Another problem is the use of, and the lack of reporting on, other types of land use, which are often closely associated with livestock, such as meadows (for hay), fallow land, rotational pastures (summer and winter, low lying and seasonal high-altitude pastures), temporarily abandoned land and shifting cultivation. All this makes it very hard to determine the 'real' amount of pasture area – for the present, but even more so for the past.

### **North America**

The same census data as those reported earlier for cropland, also provides information on pastureland for Canada from 1871 CE onwards (Urquhart & Buckley, 1965), and for the United States for 1850 CE (US Bureau of Census, 1976). In contrast to the conditions in Asia, these new colonies were rapidly discovered to be very suitable for large-scale cattle ranching. In North America, cattle ranching really took off when, in the nineteenth century, an elaborate countrywide railway system was developed, enabling relatively fast and easy transportation of meat. These census data show that the per capita amount of pasture in Canada gradually increased towards the FAO value of 0.95 ha/cap for 1960 CE, and slowly decreased towards the present. Again, for the United States, the differences between states were considerable. Many states had very low population densities at the end of the eighteenth century when pasture area expanded quite substantially. This led to staggering numbers, such as 180–220 ha/cap by the end of the nineteenth century for Nebraska and Wyoming, and 100–150 ha/cap for Montana and Colorado. But, for many states, considerably lower per capita numbers were found for pasture (US Bureau of Census, 1975, 1976) because of less

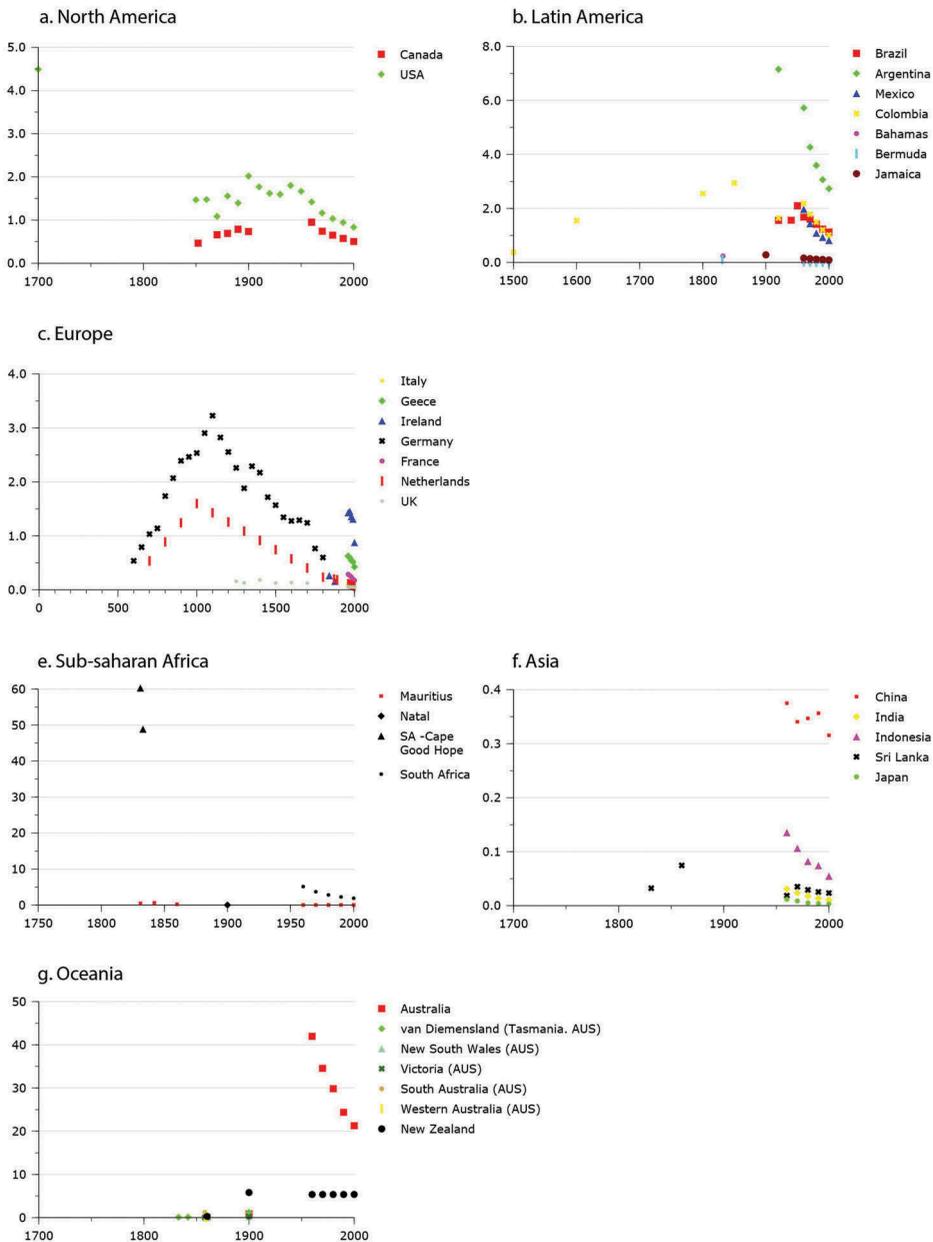
favourable pasture conditions and higher population densities, leading to a modest national maximum of 4.49 ha/cap around 1700 CE, which slowly decreased again to 1.2 ha/cap by 2000 CE. Census estimates for Canada yield 0.47 ha/cap in 1852 CE, a maximum of 1.35 ha/cap in 1941 CE and 0.50 ha/cap in 2000 CE (Urquhart & Buckley, 1965) (See Table 2, Figure 2(a)).

### Latin America

In general, we assumed that before the European settlers arrived, there were no pastures in the Americas. We disregarded the grazing land used by species such as alpacas and llamas. For the post-Columbian era, we clearly found land conversions to pasture. Most Latin American countries were struggling to recover from European conquests. It took some time before population numbers in Mexico peaked, in the 1960s; with a national average of 1.97 ha pasture per capita (FAO). Pasture was, and is, not evenly distributed within Mexico, regions with relatively high pasture area in 1960 were Chihuahua with 9.45 ha/cap, Sonora with 8.57 ha/cap, Durango with 5.75 ha/cap, Coahuila with 5.44 ha/cap and Zacatecas with 3.74 ha/cap (FAO).

The study by Etter *et al.* (2008) presents land-use data for Colombia, starting in 1500 CE. The authors describe different stages, which all had their influence on natural ecosystems. First was the Pre-Spanish period (before 1500), which was marked by a modest forest clearance for the cultivation of crops, irrigation and raised field techniques, but also some areas experienced population collapses with partial land abandonment, such as the disappearance of the Zenú 'amphibian culture' around 1300 CE. The use of fire was an important method of landscape management. The second period is known as the Conquest (1500–1600 CE). It was marked by a rapid and substantial decline in the indigenous population. The introduction of cattle, horses and sheep was very important. The third is known as the Colonial period (1600–1800 CE). In this period, population numbers stabilised, recovering the demographic collapse of the Conquest period, also because many slaves were being imported. It was characterised by open-range grazing on natural grasslands (savanna) (the Orinoco and the Caribbean), or on semi-natural grasslands and secondary regrowth (Interandean Valles and the Caribbean). In the Andean highlands, cattle were part of a land use mixed with crops such as wheat, maize and potatoes. The fourth period is the Independence (1800–1850 CE). Political turmoil, population growth and the land for grazing became larger than cropland, and thus becoming a major source of land control and political power, and thereby strongly shaping the landscape. The fifth period is the Andean re-colonisation (1850–1920 CE). It was characterised by active reoccupation of the Andean slopes and parts of the lowlands, boosted by population growth, railway development, market globalisation and the increased availability of large areas of public lands. The sixth period is that of the early twentieth century (1920–1970 CE), with exponential population growth, technological changes in the agricultural sector, strong dependence on coffee, oil and the use of fertiliser. The seventh period, the late twentieth century (from 1970 CE onwards), saw continued, strong exponential population growth, ongoing urbanisation and industrialisation, as well as the establishment of National Parks to preserve natural resources. We assumed the trend in Colombia to be somewhat representative of that in Central America and the Andean region countries of South America. We estimate based on the work of Etter *et al.* a number of 0.38 ha/cap around 1500 CE, peaking at 2.94 ha/cap in 1850 CE, and then declining to 2.19 ha/cap in 1960 CE and 2.10 ha/cap in 2000 CE (Etter & Van Wyngaarden, 2000; Etter *et al.*, 2006, 2008; FAO, 2015) (See Table 2 and Figure 2(b)).

Massive conversion of land for large-scale cattle ranching occurred especially during the last decades of the twentieth century, also in Latin America (e.g. Argentina, Brazil). In addition, large-scale infrastructural projects such as the Trans-Amazonian Highway opened up pristine tropical forest areas, often followed by the spread of settlements. Between 1850 and 1985 CE, an amount of 370 million ha in forest, in Latin America, was converted for other land uses (this equalled 28% of the area in 1850 CE; different assumptions on definitions and classifications gave a range of 25–30%). Most of this reduction in forest area was due to the expansion of pasture; for cattle ranching (44% of the reduction), croplands (25%), degraded lands (20%) and shifting cultivation



**Figure 2.** Selected historical pasture per capita estimates per world region. (a) North America; (b) Latin America; (c) Europe; (d) North Africa and Middle East; (e) Sub-Saharan African; (f) Asia; (d) Oceania.

(10%) (Williams, 1990, 2000, 2003, 2008). Based on Viglizzo (2001), we estimate a number of 2.30 ha/cap in 1881 CE, a peak of 5.72 ha/cap in 1960 CE and 2.70 ha/cap in 2000 CE (Table 2, Figure 2(b)).

Brazil experienced a steep and large increase in pasture expansion, starting in the early twentieth century. Census data go back as far as 1920 CE, and the country's average was estimated at 1.55 ha/cap then, and reached its highest point in 1950 CE, with 2.10 ha pasture per capita (Fundacao Instituto Brasileiro de Geografia e Estatistica, 1996; Reis, 1997). Again, large differences were found between regions. Mato Grosso do Sul peaked in 1950 with 40.80 ha/cap, Mato Grosso

with 34.00 ha/cap, Roraima with 27.10 ha/cap and Goias with 16.59 ha/cap (Table 2, Figure 2(b)). The other regions hardly exceeded 3 ha/cap. Later on, deforestation rates increased the total pasture area, also at an enormous rate, but per capita numbers decreased due to population growth.

### Europe

The Mediterranean region has seen a long period of pastoralism. Many arid and semi-arid regions were not suitable for agriculture and were used for herding sheep and goats. This was not always done in a sustainable way. For example, both Plato and Aristotle already mentioned the widespread soil erosion and deterioration of the hills and mountains of Greece, mostly due to overgrazing. Around 2400 years ago, Plato (424–328 BCE) wrote: ‘...what now remains...is like the skeleton of a sick man, all the fat and soft earth having wasted away, and only the bare framework of the land is being left’ (Hughes, 1994; Plato, 360 BCE; Runnels, 1995). Despite the qualitative reports about overgrazing, it is still very hard to find quantitative estimates on pasture use. Numbers as low as 0.036 ha/cap for the Ionian Islands in 1831 CE and 0.106 ha/cap in 1840 CE were reported by HCCP (2005) (see Table 2). This seems in line with the FAO data, but there are other stories, such as by Kizos and Koulouri (2006), who computed an estimate of roughly 0.91 ha/cap for the Isle of Lesbos. To compare with other arid regions, Egypt, according to FAO classification, has no pasture at all, and is therefore not representative for the arid regions in the Middle East. Remarkable are the high numbers for Saudi Arabia, where, according to the FAO, very large areas of desert and semi-desert are used for grazing animals. Since very few historical estimates have been found, we show in Table 2 several countries with FAO estimates for 1960 CE and 2000 CE only to demonstrate the large differences in pasture area per capita between countries even within regions. Where possible, we have tried to add a more historical estimate.

Williams (2000), citing Gregg (1988), estimated that a typical European Neolithic (early Holocene) settlement of 6 households comprising 30 people would have needed to plant 13.2 ha of wheat and to run a 40-head herd of cattle with 40 sheep or goats. The settlement would require 4.5 ha for houses, outbuildings and garden plots, a woodlot of 52.8 ha with a further 4.8 ha for timber for construction purposes. The livestock would require 18.2 ha of pastureland (perhaps cleared forest), 19.7 ha of natural meadows and 2.6 km<sup>2</sup> for forest browsing which could be doubled to guard against overgrazing the forest resource. Thus, each group of 30 people needed a little over 6 km<sup>2</sup> of woodland to survive, a staggering 20 ha per person. This seems a really high number indeed, but it is very sensitive to the definition and classification of the purposes described, and covers all activities. Questions remain what is permanent and what is temporary pasture? Does one have to take into account the natural meadows or the extra space needed to guard against overgrazing? Per household the total pasture area needed was 18.2 ha, yielding a modest 0.6 ha/cap, a number not far from the estimates we arrive for other European countries after 700 CE.

The study by Bork and Lang (2003) not only quantified cropland changes in Germany between the sixth century and the present-day, but also included grassland areas. Starting at very low values of around 0.54 ha/cap for 600 CE, it yielded a total grassland area of 1.6 million ha. The pasture use increased up to a peak of 3.2 ha/cap around 1100 CE (12.9 million ha), then decreasing almost linearly to 1.9 ha/cap in 1400 CE (14.1 million ha), but increasing again to 2.2 ha/cap in 1450 CE, due to the Black Plague. Then, slowly but steadily, decreasing towards the FAO value of 0.09 ha/cap in 1960 CE. We assumed the per capita values for Germany, between 600 and 1900 CE, to be more or less representative for most northern and Central European countries (Figure 2(c)). Table 2 summarises the few estimates for Europe.

### North Africa, Middle East

Pastureland has existed for very long time periods in the Middle East (Butzer, 1961, 1964). Since the beginning of the domestication of animals, around 10,000–8000 BCE, nomadic herdsmen have

been exploiting the extensive pasturelands. Many of the large and fertile mountain valleys were used for growing crops, but theoretically these were also suitable for pastoral use. Most of the steep slopes and hard-to-reach plateaus were in fact used for herding grazing animals, also because terracing and converting these areas into cropland was impossible, in most cases, due to a lack of topsoil. We could not find any data for these regions.

### *Sub-Saharan Africa*

The main forage resource for livestock in Africa is rangeland grazing. For these systems, rainfall is the primary determinant of forage production. A twofold distinction can be made here, arid and semi-arid regions with lots of space and low population densities (Sahel region, dry southern Africa) and other, wetter regions (eastern Africa, Rift valley, Congo).

One of the first and most significant impacts from early colonists on grassland and savanna biomes, albeit indirectly, was the decimation of indigenous herbivore populations, replacing them with only a few domesticated species (Danell, Bergstroem, Duncan, & Pastor, 2006). This led to a gradual decrease in the area of grassland savanna and to encroachment of unsuitable forest and other types of vegetation. Furthermore, large semi-arid, arid and hyper-arid regions were overgrazed to such an extent that severe soil degradation occurred. The HCCP (2005) present a value of 60.27 ha pasture per capita for Cape of Good Hope as early as 1831 CE, and already rapidly decreasing to 48.85 ha/cap in 1833 CE. This trend continues to 1960 CE at 5.13 ha/cap and 1.87 ha/cap in 2000 CE (FAO). From our literature research, no data could be extracted on historical pasture use, per capita, in Africa, and therefore the relations rely on the FAO estimates for 1960 CE and 2000 CE (see Table 2 and Figure 2(e)).

### *Asia*

Pasture does not play an important role in large parts of East and South eastern Asia, nor did it so in the past. Cattle are not considered an important food staple, for both dietary and religious reasons. Therefore, it uses relatively little pasture space. In central Asia, however, livestock herding is still a main activity. According to the FAO (2012b), traditional forms of nomadic pastoralism were widely practiced in Buryat, Kazakhstan, Kalmyk and Kyrgyzstan until the 1930s, and in Mongolia up to the 1960s. Arid to semi-arid climatic conditions favoured nomadism. However, during the 1930s, agricultural development changed in most Central Asian countries under the Soviet regime. Mass collectivisation took place, and the economic systems became based on public and collective ownership of productive resources, including all industrial plants, land and the majority of the livestock population. Members of agricultural cooperatives and employees of state farms were allowed private ownership of only a very restricted number of animals. During the collectivisation process, nomadic pastoralists were forcibly moved to permanent settlements, which brought traditional nomadism to an end. In only five years, between 1930 and 1935 CE, all of the nomads in Kazakhstan converted to a life of sedentism (FAO, 2012b).

During our study, we found only one recorded estimation for Asia on pasture land use per capita, predating 1960, Sri Lanka (0.03 ha/cap for 1831 CE, Table 2). The FAO data for 1960 CE show very large differences between countries, from 146 ha/cap in Mongolia to 0.012 ha/cap in Japan. Based on geographical and climatological equalities between countries, we made a scale-up for countries that we assumed to behave in a similar fashion when sharing similar conditions (see Table 2 and Figure 2(f)).

### *Oceania*

In Australia, British immigrants explored and occupied rural areas, in the early nineteenth century, partially dislocating the native population and disturbing local grazing wildlife (kangaroos) by introducing sheep and cattle on large scale (FAO, 2012a). During the first century of exploration and exploitation, the expanding herds of grazing livestock were sustained through many activities, such as tree clearing, regular burning regimes, the granting of grazing rights and eventual land tenure,

fencing and fenced-in yards, and the provision of reliable water supplies, improved breeding technology and husbandry skills, better monetary services after the discovery of gold in the 1850s, and the start of the Australian railway after 1855 CE (Shaw, 1990). By 1891 CE, when most of the railway system was in place, more sheep were grazing the Australian landscape than there are today. However, the numbers of sheep and cattle were reduced during the subsequent decade, as the result economic depression and by the 'Federation drought', which began around the mid-1890s and peaked in the early twentieth century (FAO, 2012a). There was a rapid expansion in improved pastures between 1950 (5 million ha of improved pastures) and 1975 CE (>20 million ha), based on prior investments in agricultural research. To summarise, for Australia, we estimated per capita pasture numbers of around 15 ha/cap for 1860 CE, 25 ha/cap for 1900 CE, and increases to 40.9 ha/cap by 1960 CE (Australian Bureau of Statistics, 2001; HCCP, 2005) (see Table 2 and Figure 2(g)).

McWethy et al. (2010) show that fires which occurred shortly after the Polynesian (Māori) colonisation around 1280 CE transformed 40% of the original forest cover of the island to grassland and scrubland. The transformation of scrubland to grassland at the hands of Europeans in the mid-nineteenth century triggered further, sometimes severe, watershed changes, through fires, erosion and the introduction of non-native plant species. The native grasslands of New Zealand that covered much of the hills and plains to the east of the Southern Alps contained many palatable grasses and herbs and were rapidly stocked with sheep, with little effort apart from fencing. On much of the more easily accessible land, the tussock grassland was ploughed to grow crops, and was then sown in pasture. In the North Island, grassland development was quite different. Except for the stretches of tussock grassland of the Central Plateau, the land was covered with forests, ferns and scrubs. Grassland farming, therefore, had to be preceded by the removal of the original vegetation. After this was cut and burned, grass seeds were sown, by hand, on the ash among the logs and stumps (McLintock, 1966). From HCCP (2005), we concluded that the amount of pasture land per capita was 0.28 ha/cap in 1860 CE, peaked around the start of the twentieth century, with almost 6 ha/cap, then declined again to 0.39 in 1960 (see Table 2 and Figure 2(g)).

## Discussion

### *Implications for modelling*

Although many uncertainties remain, some conclusions can be drawn. For some countries and/or regions, fairly good data exist; for example, for the rice-based civilisations of China, Japan and Indonesia, for the irrigation or hydraulic civilisations such as Egypt, Greece and Italy and for the more recently colonised parts of the world, such as Canada, the United States, Australia and New Zealand. In general, the trend appears to be that indeed, the ancient agricultural land use per capita was higher than at present ('the present time' here defined as that of the first FAO value for 1960 CE. After 1950 CE, the world population exploded, so nearly all per capita numbers very rapidly decreased even further, up to 2000 CE). However, taking 1 CE as the benchmark, there is no convincing evidence that per capita land use anywhere was much higher than 2.0 ha/cap, in many cases, it was even less than 1.0 ha/cap; see, for example, all the work on cropland agriculture in the Americas before the Columbian Exchange, (Cartwright, 2014; Cowgill, 1962; Morehart & Frederick, 2014; Puleston, 1982). Does that mean that Ruddiman and Ellis (2009) overestimated their historical 4 ha/cap land use? Not necessarily, because Butzer (1976) showed indeed that in Egypt a number of 4.7 ha/cap could have been realistic, albeit that the number was valid for 4000 BCE. It seems that the timeframe for such numbers is crucial for estimating acceptable total agricultural areas in the ancient past, to be used for integrated assessments.

It is also crucial to define exactly what form of agriculture is reported on in detailed case studies. Other land uses, such as pasture/grazing land, or land used for browsing, shifting cultivation and fuelwood, are also very important, and often are mixed into the total estimates.

This can be illustrated by the following example. We took the minimum and maximum estimates of Boserup (Table 1 from Ruddiman & Ellis, 2009) and multiplied them with the HYDE population density maps for the years 1000 CE, 1500 CE, 1700 CE, 1900 CE, 1950 CE and 2000 CE. When there was no population, there was also no value computed for cropland. Then, we computed the global average percentage cropland of all 5' grid cells for each given year. The results are shown in Figure 3.

It shows that in the period 1850 CD–2000 CE, the HYDE estimates are well in range of the Boserup's values. Before that period they are lower, exactly following the argument that HYDE at this moment only estimates real cropland only, while the estimates of Boserup and Ruddiman and Ellis also took into account 'land clearance for purposes other than growing crops (pasture, woodlots, dwellings and other structures)'.

This type of research is still very much in its infancy. We have just begun to explore data sources from other disciplines, and many regions in Asia, Africa and Latin America have started to make their sources available in English and on the Internet. There will probably always be gaps in our knowledge because of lacking data, but we can decrease the uncertainty in some parts by combining data and expert knowledge from all disciplines concerned with land-use data, as much as possible.

### Consequences for global change research

#### Total land use estimates

**Cropland.** Table 3 presents an overview of different global estimates of historical agricultural areas, for the period from 6000 BCE to the present. Klein Goldewijk and Verburg (2013) describe the uncertainties attached to backcasting techniques for estimating land use. Most of the backcasting is done by using historical land use per capita, and they argue that the choice of the land use, per capita curve is crucial for the resulting estimations on total agricultural area. In the present study, we also estimated a lower and upper land-use scenario, on the basis of an uncertainty range applied on top of the 'baseline' cropland and pasture per capita estimates. The uncertainty ranges were based on literature and own judgement, and should be treated with care. The uncertainty range A is roughly estimated at 5% for 2000 CE, 10% for 1900 CE, 25% for 1800 CE, 50% for 1 CE and 75% for 10,000 BCE (see also Klein Goldewijk et al. (2010)). The uncertainty range B is twice as high as with A, and, in our opinion, it is highly unlikely that areas of cropland or grazing land were outside this range in the past. The years in between were linearly interpolated (the method used is similar to that described by Klein Goldewijk et al. (2010)). Apart from these various uncertainties in

#### Agricultural land use intensity Boserup versus HYDE

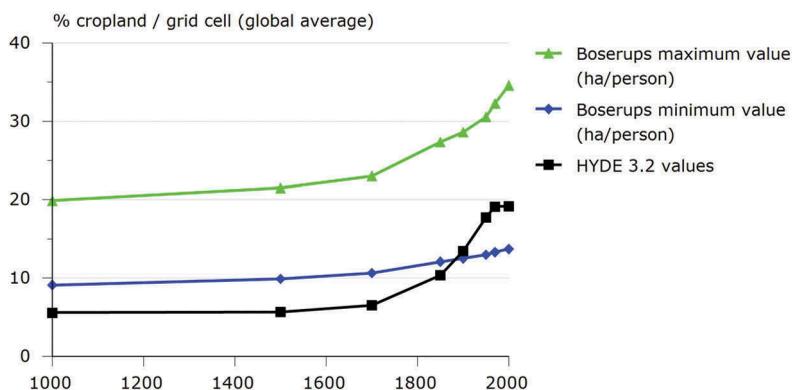


Figure 3. Comparison of Boserup minimum and maximum land use values with HYDE.

**Table 3.** Global historical estimates on total cropland area, different backcasting scenarios (in million km<sup>2</sup>), for a number of selected years.

	6000 BCE	1000 BCE	500 1 CE	800 CE	1000 CE	1100 CE	1400 CE	1500 CE	2000 CE
HYDE 3.1 (baseline)	0.02	0.79	1.31	1.24	1.30	1.53	2.06	1.95	2.32
HYDE 3.1 1st lower	0.00	0.18	0.33	0.49	0.63	0.83	1.25	1.29	1.61
HYDE 3.1 1st upper	0.03	1.40	2.30	1.99	1.97	2.23	2.88	2.61	3.05
HYDE 3.1 2nd lower	0.00	0.00	0.00	0.00	0.00	0.14	0.43	0.63	0.89
HYDE 3.1 2nd upper	0.05	2.01	3.29	2.74	2.64	2.93	3.70	3.27	3.76
HYDE 3.1 (constant)	0.06	0.47	0.76	0.85	0.99	1.19	1.50	1.59	1.82
Linear	0.33	1.50	1.87	1.78	1.83	2.04	2.41	2.24	2.46
S-curve	0.46	1.16	1.12	1.07	1.16	1.34	1.65	1.71	1.94
Concave-curve	0.40	2.91	4.15	4.22	4.48	5.16	6.36	5.74	6.38
Convex-curve	0.24	0.88	1.15	1.16	1.27	1.46	1.78	1.79	2.01
<b>This study</b>	<b>0.01</b>	<b>1.05</b>	<b>1.48</b>	<b>1.45</b>	<b>1.54</b>	<b>1.89</b>	<b>2.58</b>	<b>2.35</b>	<b>2.75</b>
min	0.00	0.00	0.00	0.00	0.00	0.14	0.43	0.63	0.89
avg	0.13	1.04	1.50	1.45	1.53	1.79	2.29	2.19	2.52
max	0.46	2.91	4.15	4.22	4.48	5.16	6.36	5.74	6.38
Pongratz, Reick, Raddatz, and Claussen (2008)					1.36			2.33	
Kaplan et al (2011)*	1.86	6.10	9.50	10.70		12.60			16.10

\*Kaplan et al.'s KK10 scenario is the total of cropland and pasture added together; 1st lower and upper, 2nd lower and upper refer to uncertainty bands around the baseline. Linear, S-curve, concave curve and convex curve refer to different shapes of the per capita land-use curve.

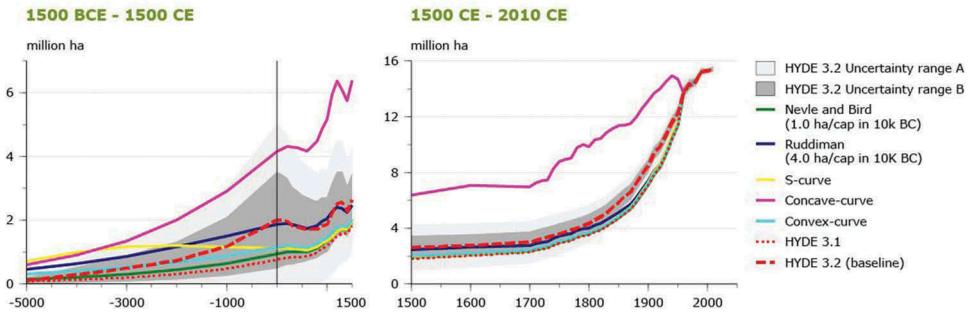
the underlying data, the range is quite large, depending on the shape of the curve (S-curve, linear, concave, convex). This study represents a 'best educated guess, based on the aforementioned literature study, with empirical census data on 55 countries, and is used as a basis for the new HYDE 3.2 database' (Klein Goldewijk, Beusen, Doelman, & Stehfest, 2016). It appears that total cropland areas are consistently higher than those in the original baseline by Klein Goldewijk et al. (2011), but very close to the Pongratz et al. (2008) estimate. The new estimates, based on the 55 countries, increase the global land use in 1 CE with 13%, in 800 CE with 18%, in 1000 CE with 24% and in 1500 CE with 19%.

Table 3 shows that the update for 55 countries does result in a different total estimate of total historical cropland, compared with the baseline by Klein Goldewijk et al. (2011). Figure 4 shows that our new best estimate (coarse dotted line) is higher than that in the baseline in Klein Goldewijk et al. (Klein Goldewijk et al., 2011) (thin dotted line), especially for the pre-1500 period. The estimates are up to twice as high.

**Pasture.** Table 4 presents estimates on the total amount of pasture area for various backcasting scenarios and other literature studies. It shows clearly that the assumption about the historical trajectory of the per capita area of pasture is crucial for the global total area. Compared with the baseline (and its uncertainty ranges), in this study, the figures tend to be adjusted to higher values on average, indicating that apparently people used larger areas for grazing than previously thought.

### Per capita land use estimates

**Cropland per capita.** Here we see quite different patterns, over time. For many 'Irrigation or hydraulic' civilisations in North Africa and the Middle East, land use per capita was found to be rather high in the early stages of development (Butzer, 1976). This in contrast to the more temperate regions, for which Gregg (1988) assumed a modest land use of less than 1 ha/cap for Neolithic farmers. Other regions with long-term agricultural activities, such as Turkey and India, might have had somewhat higher values. Mexico and the Rest of South America experienced an increase after colonisation (albeit centuries later) due to large expansions of cropland (e.g.



**Figure 4.** Cropland and grazing land estimates from the new HYDE 3.2 and the old HYDE 3.1 with their uncertainty bands and estimates based on different per capita land-use assumptions.

plantations). The same happened in the nineteenth century in the United States, and a bit later in Central Asia, and more recently and to a larger extent also in Canada and Oceania (Australia) (Figure 5).

**Pasture per capita.** Pasture estimates are much more uncertain than cropland estimates. Partly due to the former’s unclear definition in many countries, often historical census reports simply do not list areal numbers for pasture. Nevertheless, some patterns can be seen to emerge. Especially in the more recently colonised regions, such as Australia, South America and Central Asia, the pasture per capita curves show a sudden increase in the twentieth century, while regions such as eastern Africa and Central Asia experienced higher per capita trends, probably due to much earlier livestock domestication combined with low population numbers. In all cases, the per capita numbers decreased again due to the worldwide, enormous population explosion following the Second World War (Figure 6).

Little is known about past land use. Some history books and papers do describe agricultural development and patterns, but almost always in a qualitative rather than quantitative manner. In this study, we tried to fill some of the gaps and explored possible ways of dealing with the ‘no data’ phenomenon. By doing so, we fully acknowledge that, in many cases, the estimates are merely educated guesses, rather than being based sound, empirical data. However, new research was developed. In 2014, the LandCover6K working group of Past Global Changes (PAGES, see [www.pages.org](http://www.pages.org)) was established. It brings together paleo-ecologists, historians, archaeologists, geographers

**Table 4.** Global historical estimates of total pasture area, different backcasting scenarios (in million km<sup>2</sup>), selected years.

	6000 BCE	1000 BCE	1 CE	500 CE	800 CE	1000 CE	1100 CE	1400 CE	1500 CE	2000 CE
HYDE 3.1 (baseline)	0.00	0.63	1.06	1.08	1.19	1.43	1.88	1.93	2.24	34.29
HYDE 3.1 1st lower	0.00	0.91	1.65	1.56	1.93	2.48	3.33	3.13	3.31	34.04
HYDE 3.1 1st upper	0.00	0.14	0.27	0.43	0.58	0.78	1.13	1.28	1.55	34.53
HYDE 3.1 2nd lower	0.00	1.61	2.65	2.39	2.42	2.73	3.37	3.24	3.62	33.80
HYDE 3.1 2nd upper	0.00	0.00	0.00	0.16	0.28	0.42	0.66	0.80	0.99	34.78
HYDE 3.1 (constant)	0.16	1.66	2.51	3.10	3.56	3.96	5.06	5.07	5.53	34.29
Linear	0.02	1.19	1.91	2.36	2.70	3.06	3.75	4.04	4.51	34.29
S-curve	0.02	1.54	2.41	2.98	3.45	3.88	4.99	5.02	5.50	34.29
Concave-curve	0.10	2.39	3.33	3.75	4.15	4.59	5.74	5.57	6.03	34.29
Convex-curve	0.23	1.83	2.58	3.13	3.58	3.98	5.08	5.08	5.55	34.29
<b>This study</b>	<b>0.10</b>	<b>3.75</b>	<b>5.45</b>	<b>5.99</b>	<b>6.59</b>	<b>7.47</b>	<b>9.42</b>	<b>8.85</b>	<b>9.74</b>	<b>34.29</b>
min	0.00	0.00	0.00	0.16	0.28	0.42	0.66	0.80	0.99	33.80
avg	0.06	1.37	2.10	2.37	2.70	3.10	3.98	3.95	4.35	34.29
max	0.23	3.75	5.45	5.99	6.59	7.47	9.42	8.85	9.74	34.78
Pongratz et al. (2008)					1.44	*1.97		2.27		

\*1100 value.

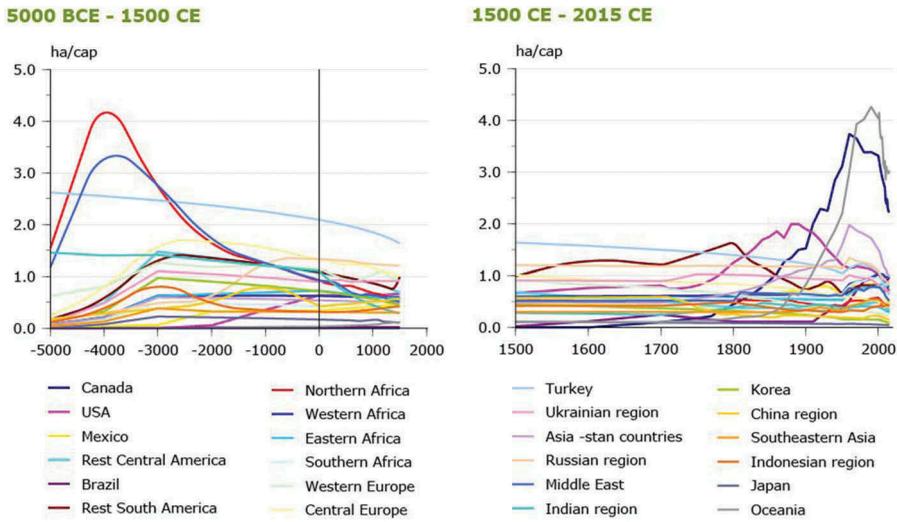


Figure 5. Computed regional cropland per capita estimates.

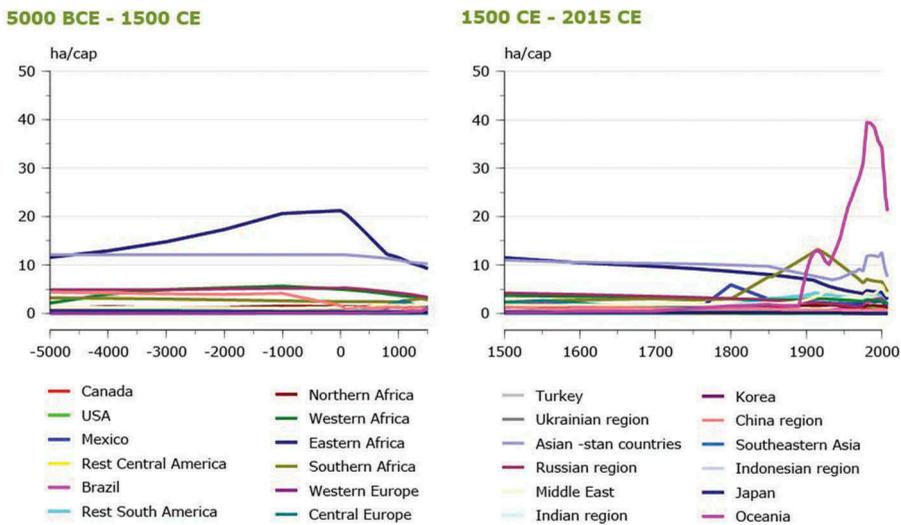


Figure 6. Computed regional pasture per capita trajectories.

and modellers, to explore and provide new empirical information about ALCC, and with the intention to create new products for climate modellers and subsequently, policymakers. We hope that studies such as this one will fuel the research and debate about improving historical land-use reconstructions.

### Acknowledgements

This work was supported by the Netherlands Organisation for Scientific Research (NWO) under VENI grant [no. 016.158.021], and through NWO's granted Clio Infra project (<https://www.clio-infra.eu/>). It is endorsed by the PAGES LandCover6k working group (<http://www.pages-igbp.org/ini/wg/landcover6k/intro>).

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This work was supported by the Netherlands Organisation for Scientific Research (NWO) under VENI grant [no. 016.158.021], and through NWO's granted Clio Infra project (<https://www.clio-infra.eu/>).

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