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Dataset of cropland cover from 1690 to 2015 in Scandinavia

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Abstract

High-resolution historical land cover datasets are essential not only for simulations of climate and environmental dynamics, but also for projections of future land use, food security, climate and biodiversity. However, widely used global datasets are developed for continental-to-global scale analysis and simulations and the accuracy of global datasets depends on the verification of more regional reconstruction results. In this study, based on the collected statistics of cropland area of each administrative unit (Parish/ Municipality/ County/ Province) in Scandinavia from 1690 to 2015, the cropland area at the administrative unit level was allocated into 30-arc second grid cells. The results indicated that the cropland area increased from 1.81 million ha in 1690 to 7.10 million ha in 1950, then decreased to 6.02 million ha in 2015. Before 1810, cropland cover expanded in southern Scandinavia and remained stable in northern. From 1810 to 1910, northern Scandinavia experienced slight expansion and the cropland area increased rapidly in the southern part of the study area. Then, cropland area changed gently. After 1950, cropland area began to decrease in most regions, especially in the east of Scandinavia. When comparing HYDE3.2 with this study, differences

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in cropland distribution over the past 300 years are mainly observed in regions which were highly cultivated. Our dataset can be used by future environment and climate models in Scandinavia. The dataset can be downloaded from https://doi.pangaea.de/10.1594/PANGAEA.919929 (Wei et al., 2020).

1 Introduction

Anthropocene was defined as a new epoch of geologic time, partly because human influenced land is a major component of anthropogenic global changes in the earth system, since 2000 (Lewis and Maslin, 2015; Crutzen and Stoermer, 2000; Verburg et al., 2016). During AD 800 ~ AD 1700, according to Pongratz et al. (2008), 5% of the area covered by natural vegetation brought under human land use, compared to 44% in the following 300 years. The decrease of natural vegetation is accompanied by an increase in cropland area. From AD 1000 to AD 1700, global cropland grew slightly from 1% to 2.3% of the global land area, then it occupied 4.5% and 11% in AD 1850 and AD 2015, respectively (Klein Goldewijk et al., 2017). Anthropogenic land cover change (ALCC) may have caused feedbacks to the climate system through modifying the surface roughness, surface albedo, latent heat flux and river runoff, and changing atmospheric CO_2 concentration (Foley et al., 2005; Kaplan et al., 2017; Pongratz et al., 2009b; Pongratz et al., 2010; Houghton et al., 2012; Yang et al., 2015; Liu et al., 2016). For example, land use change likely led to an increase of the Earth albedo with a radiative forcing of -0.15 ± 0.10 W m^{-2} since 1850 (Myhre et al., 2013). Over the years 1980-2005, changes from mid-latitude natural forests to cropland and pastures were accompanied by a reduction of latent heat flux and an increase of sensible heat flux in summertime (Findell et al., 2017). The atmospheric CO_2 increase above pre-industrial levels was mainly caused by the release of carbon from ALCC and net emissions from land cover change were greater than 50% of the total before 1940 (Ciais et al., 2013; Le Quéré et al., 2018; Houghton, 2018). The above conclusions of climate and environmental dynamics were all made by using high-resolution historical land cover datasets. Historical land cover change information is also essential as baseline analysis for projections of future land use, food security, climate and biodiversity (Hurtt et al., 2011; Foley et al., 2011; Ellis et al., 2012; Brovkin et al., 2013; Mehrabi et al., 2018; Fuchs et al., 2015). Precise information on land cover is required for

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running earth system models.

Satellite data can provide information on changes in land cover with high-resolution, however, it is impossible to map land cover earlier than the mid-1970s (Liu and Tian, 2010; Roy et al., 2014; Moulds et al., 2018). Therefore, satellite data was combined with historical statistics and inventory data in order to produce spatially explicit land cover datasets which cover longer time periods. Using combined sources and hindcasting methods, Center for Sustainability and the Global Environment (SAGE) (Ramankutty and Foley, 1999) and History Database of the Global Environment (HYDE) (Klein Goldewijk, 2001) was produced as two representative datasets of global land use/cover. SAGE covers the period between 1700 and 1992 with a 0.5°×0.5° resolution, including cropland, pasture and forestland (Ramankutty and Foley, 2010). The latest version of HYDE (HYDE 3.2) has a 5′×5′ resolution, covers the period 10000BC - AD2015 and consists of cropland, pasture and built-up land (Klein Goldewijk et al., 2017). Based on SAGE and historical population data, PJ dataset was produced, which covers the period AD 800 - AD 1700 (Pongratz et al., 2008). Subsequently, anthropogenic land cover change from 8000BP to AD1850 (KK10) was reconstructed (Kaplan et al., 2009; Kaplan et al., 2010). These global datasets were widely used by simulation on global and regional climate change or carbon budget because of their high spatial resolutions and long-term coverages (Foley et al., 2005; Olofsson and Hickler, 2007; Strassmann et al., 2008; Pongratz et al., 2009b; Van Minnen et al., 2009; Arora and Boer, 2010; Kaplan et al., 2010; Pongratz et al., 2010; Hurtt et al., 2011; Brovkin et al., 2013; Yan et al., 2017; Zhang et al., 2017; Le Quéré et al., 2018).

However, global datasets were developed for continental-to-global scale studies (Klein Goldewijk, 2001; Ramankutty and Foley, 2010; Pongratz et al., 2009a). Assuming near-constant cropland per capita and using population data to estimate historical land use induced large uncertainties and limitations in presenting the details at the regional scale (Klein Goldewijk and Verburg, 2013). Many regional land use reconstructions illustrated that global datasets had unneglectable discrepancies in reflecting the spatial patterns of land use at the regional scale over history, especially for cropland. Historical document-based reconstructions concluded that SAGE, HYDE, and PJ had drawbacks to capture the spatial

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distribution of the historical cropland change in China (Li et al., 2010; Zhang et al., 2013; Li et al., 2015; Wei et al., 2019; Li et al., 2019). In the US, the HYDE maps greatly underestimate crop density in high cropland coverage regions but overestimate it in low-density regions during 1850-2016 (Yu and Lu, 2018). Neither KK10 nor HYDE captures the fine-scale spatial pattern of open land as inferred from the pollen-based land cover reconstructions in Europe for four preindustrial time windows (Kaplan et al., 2017). Uncertainties in global datasets could be transferred into higher uncertainties in quantifying climate and environmental effects of ALCC at both local and regional scales (Yang et al., 2018; Lejeune et al., 2018; Yu et al., 2019). Therefore, the PAGES LandCover6k and related projects aim to improve ALCC history at both regional and global scales based on empirical data (Gaillard et al., 2015a; Widgren, 2018a). Errors can be assessed or corrected by using the regional quantitative reconstructed land cover data and regional agrarian history maps (Widgren, 2018b; Fang et al., 2020).

In Scandinavia, the pollen-based reconstructions indicated that the cover percentage of cereals was very high in southern Sweden and Denmark (Nielsen et al., 2012; Gaillard et al., 2015b). The comparison of the pollen-based reconstructions with historical map-based estimates of land use history in the South Swedish Uplands over the past 200 years showed that the pollen-based estimates overestimated the cropland and grassland cover in some sites (Mazier et al., 2015). To facilitate simulation studies with high-precision regional input data, the dataset of cropland cover change from 1875 to 1999 in Sweden and Norway was developed (Li et al., 2013). Materials from mainly two sources were collected, including the data of Sweden from the official agricultural statistics and the data from Norwegian Social Science Data Services (NSD). To access orderly time intervals, 6 time slices were chosen. Methods of seed-cropland conversion, data interpolation and allocation, and data gridding were used to produce the cropland dataset on the spatial resolution of 0.5 degrees.

The main objective of this study is to provide a cropland cover dataset with high precision and spatial resolution in Scandinavia (includes Sweden, Norway and Denmark) over the past 300 years. In this paper, on the basis of the cropland datasets in Scandinavian Peninsula from 1875 to 1999 (Li et al., 2013), we extended the period to 1690-2015 and added Denmark to

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the study area through validating and integrating data from multi-sources. The spatial resolution of our dataset was improved to 30-arc second. Our newly developed dataset of cropland cover would give more detailed information on temporal and spatial patterns of cropland change in Scandinavia.

2 Data sources

Data sources in this study are shown in Table 1. Besides the cropland data of the Scandinavian Peninsula (Sweden and Norway) after 1875 processed by Li et al. (Li et al., 2013), the cropland data were from different sources. For Sweden, all the data before 1875 were from the *Svensk Nationell Datatjänst* (Swedish National Data Service, termed SND, https://snd.gu.se/en/catalogue/study/SND0910). Based on tax records, historical maps, land survey records and inventories of farmers, Palm et al. (2014) developed agricultural statistics (The database Sweden 1570-1810: population, agriculture, land ownership) covering all parishes within Sweden's contemporary boundaries and the periods between 1570 and 1810. In the database, cropland was called "åker" in Swedish, which was also used in the data sources from 1875 to 1999 in Sweden. However, the "total åker" in the dataset recorded the volume of seed used in each parish (*socken*) but not the cropland area. The administrative division map of 1750 was used as the base map for cropland data before 1875.

For Norway, cropland data in 1665 and 1723 was from *Statistiske studier over folkemængde og jordbrug i Norges landdistrikter i det syttende og attende aarhundrede* (Statistical studies on population and agriculture: in the rural areas of Norway in the seventeenth and eighteenth centuries, Aschehoug, 1890). Cropland data in 1809 was from the study of Hovland (Hovland, 1978). In the above two sources, the volumes of different types of seeds, such as wheat, rye, barley, oat, peas and potatoes were recorded but not the cropland area. The cropland data of 17 counties (*amts*) were presented. The administrative map of 1875 which was from Norwegian Centre for Research Data (termed NSD, https://nsd.no/nsd/english/) was used for cropland data before 1875.

For Denmark, data of cropland were from multiple sources. Data in 1688 was based on *Atlas over Denmark: Historisk-Geografisk Atlas* (Atlas over Denmark: Historical-Geographic Atlas,

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Dam and Jakobsen, 2008). Dam and Jakobsen's map showed cropland land fraction of each "ejerlav" (area under a village, a manor or a group of single farms) in Denmark. The cropland was called "Ager" in Denmark and it meant the total area under crop rotation, including the cultivated land and the fallowing cropland. The cropland data in 1800, 1881 and 1998 was provided by Pia Frederiksen from Aarhus University, based on data developed by Jørgen Rydén Rømer, Aalborg, Bernd Münier and Morten Stenak, Roskilde (Odgaard and Rømer, 2009). In detail, data in 1800 was from the map Videnskabernes selskabs kort (VSK) in 1762-1806 and further developed from agricultural statistics. Data in 1881 was generated from the national statistics. The data in 1998 was merged from maps and statistics. The data in 1800, 1881 and 1998 had a smallest spatial unit of "sogn" (parish). The cropland was called "Agerjord" and it can be divided into two subgroups, namely "Besået areal" (the areas annually sown with various one-year or two-year crops) and "Græs i omdrift" (the areas for shorter or longer time usually from 1 to 4-6 years which is for grazing or in various types of fallow before land again plowed up for sowing). "Besået areal" and "Græs i omdrift" corresponds to the cultivated land and the fallowed cropland in 1688, respectively. The cropland area data in 1907 was from *Statistisk Aarbog 1912* (Statistical Yearbook 1912, Danmarks Statistik, 1912) and the spatial resolution is "*amt*" (County). The cropland area data in 1936, 1950 and 1980 were from agricultural statistics of Statistiske Meddelelser (Danmarks Statistik, 1936, 1950 and 1980). The spatial resolution of cropland data in 1936, 1950 and 1980 was "*amt*" (County), "*amtsrådskreds*" (County council) and "*kommuner*" (Municipality), respectively. The base maps were downloaded from the HisKIS network (http://hiskis2.dk/?page_id=110) and the web of Danish Geodata Agency (http://download.kortforsyningen.dk/).

After 1999, cropland area data were downloaded from websites of the Bureau of Statistics. The Swedish cropland area data in 2015 was from Statistics Sweden (termed SCB, https://www.scb.se/en/) and the spatial resolution was *län* (County). The Norwegian cropland area of each county (*Fylke*) in 2015 were from Norwegian Centre for Research Data (termed NSD, https://nsd.no/nsd/english/index.html). The Danish cropland data in 2016 was from

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Statistics Denmark (https://www.dst.dk/) and the cropland area of each province (*Landsdele*) was recorded. Base maps were extracted from the GADM database (www.gadm.org)

Table 1 Description of data sources used in this study

Data source	Spatial coverage	Years	Spatial Resolution	Reference
Sockenvis jordbruksstatistik	Sweden	1690,1750,1810	Parish	SND
Statistiske studier over folkemængde og jordbrug i Norges	Norway	1665,1723	County	Aschehoug, 1890
Historisk Tidsskrift	Norway	1809	County	Hovland, 1978
Atlas over Denmark: Historisk-Geografisk Atlas	Denmark	1688	*Ejerlav*	Dam and Jakobsen, 2008
Danske landbrugs-landskaber gennem 2000 år	Denmark	1800, 1881, 1998	Parish	Odgaard and Rømer, 2009
Statistisk Aarbog 1912	Denmark	1907	County	Danmarks Statistik, 1912
Statistiske Meddelelser 1936, 1950 and 1980	Denmark	1936, 1950, 1980	County; County council; Municipality	Danmarks Statistik, 1936, 1950 and 1980
Cropland in Scandinavian Peninsula	Sweden, Norway	1875, 1910, 1930, 1950, 1980, 1999	County/0.5-degree	Li et al., 2013
Agricultural statistics 2015	Sweden	2015	County	SCB, https://webbutiken.jordbruksverket.se/sv/artiklar/jo1

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				1501.html
Agriculture and the environment 2016	Norway	2015	County	SSB, https://ssb.brage.unit.no/ssb-xmlui/handle/11250/2443276
Land by Land Cover 2016	Denmark	2016	Province	Statistics Denmark, https://www.statbank.dk/statbank5a/default.asp?w=1280

3 Methods

3.1 Data preprocessing

The main goal of the data preprocessing is to map the cropland area change at the parish/county level from 1690 to 2015 in Scandinavia based on the collected data sources and base maps.

According to the years when cropland area data are available in Sweden, Norway and Denmark, we chose 10 points of time that could present the trend of cropland change from 1690 to 2015. Compared to the data sources in Norway and Denmark, the numbers of cropland data from the data sources of Sweden were the most abundant and complete, so we selected 10 points of time based on the data sources in Sweden, which were 1690, 1750, 1810, 1875, 1910, 1930, 1950, 1980, 1999 and 2015. 1690, 1750 and 1810 corresponds to 1665, 1723 and 1809 from the data sources in Norway. 1690, 1810, 1910, 1930, 1950, 1980, 1999 and 2015 corresponds to 1688, 1800, 1881, 1912, 1936, 1950, 1998 and 2016 from the data sources in Denmark.

Because the Swedish data in 1690, 1750 and 1810 from SND only provided the amount of seeds sowed into the land, we used the formula of 1 barrel of seed = 4936m^2 of cropland = 0.4936 ha of cropland (Cardarelli, 2003) to obtain the cropland area of each parish. The Norwegian data in 1665, 1723 and 1809 also showed the volume of seed but not the cropland area. We collected the relationships between the volume of seed and the cropland area from four sources (see Table 2). The values of liter per *maal* (1 *maal*=10 hectare) regarding seven

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types of seeds were close to each other, except for the value based on the statistics from NSD. We chose the values of liter per *maal* in 1835 from *Statistiske Oversigter 1914* (Aschehoug, 1914) because 1835 was the closest year to the 3 points of time, 1665, 1723 and 1809. For the data in 1875, we used the values of liter per *maal* in 1865 to convert the volume of seed to cropland area. For data sources in the remaining years and in Denmark, cropland areas were recorded and we unified the units to million hectare (million ha). There was no record for cropland area of Denmark in 1750, we therefore assumed that the cropland area change rate from 1690 to 1810 was constant and computed the cropland area in 1750.

Table2 The relation of *maal* to liter from different sources in Norway

Sources	*Oversigt over det norske landbruks utvikling siden 1750* (Klokk, 1920)			*Norges Landbrug i Dette Aarhundrede* (Smitt, 1888)	*Statistiske oversigter 1914* (Aschehoug, 1914)		NSD
Liter per maal\Year	1896-1900	1901-1905	1907	1866-1875	1835	1865	1907
Hvete (wheat)	29.0	27.8	28.2	26.4	25.0	25.2	39.2
Rug (rye)	20.4	20.8	22.5	19.5	19.5	19.3	31.2
Byg (barley)	32.8	31.9	32.2	33.4	34.8	34.7	44.8
Havre (oats)	46.9	45.5	45.2	51.4	52.8	53.2	62.9
Blandkorn (mix)	42.6	40.5	40.2	47.3	47.3	47.0	55.9
Erter (peas)	30.4	26.8	30.9	29.2	30.6	30.9	42.9
Poteter (potato)	302.2	306.8	302.7	290.5	290.5	290.3	420.7

To map the spatial patterns of cropland distribution in Sweden, administrative map at the parish level in 1750 was used. The digital version of the administrative divisions of Sweden in 1750 was initially developed at the National Archives of Sweden (Riksarkivet). It was later revised at the Department of Human Geography, Stockholm University. The version used here was kindly provided by Ulf Jansson. We linked the datasets in 1690-1810 to the base map in 1750 based on the code of parish. Four cities (*stad*) in the datasets failed to be connected with the corresponding areas on the base map and 14 parishes in the base map were also without cropland data. After checking their administrative codes, a relationship between the four cities (*stad*) and 14 parishes was found. 6 parishes out of 14, namely Stockholms

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Domkyrko, Adolf Fredrik, Hedvig Eleonora, Maria Magdalena, Katarina and Kungsholm Eller Ulrika Eleonora composed Stockholms stad; 2 parishes namely Norrköpings Sankt Olai and Norrköpings Hedvig composed Norrköpings stad, Jönköpings stad consisted of Jönköpings Sofia, Jönköpings Kristina and Ljungarum, and Göteborgs stad consisted of Domkyrko í Göteborg, Nylöse and Göteborgs Karl Johan. After that, all the 2390 parishes found their corresponding cropland area data.

Because the cropland data before 1875 was at the county (*amt*) level and the administrative division didn't change dramatically from 1690 to 1875 in Norway, administrative map in 1875 from NSD's kommunedatabase was used for data in 1690-1810 as the base map.

For Denmark, cropland area data in 184 "*ejerlavs*" was missing in 1688. The missing data were interpolated based on the cropland fractions of their neighboring "*ejerlavs*" in 1688 and the cropland changes from 1688 to 1800. Using the same method, 56 missing data in 1800 and two missing data in 1881 were also interpolated. We selected administrative map in 1688 from the HisKIS network as the base map for cropland data that year. Cropland area data in 1800, 1881 and 1999 had their corresponding base maps (Odgaard and Rømer, 2009). The base maps for data in 1936, 1950 and 1980 were from the web of *Danish Geodata Agency* (https://eng.gst.dk/).

3.2 Cropland area allocation

As the cropland area data of each administrative unit cannot be used as input for the climate and environment simulations directly, we allocated the cropland area into 30 arc-second (~1km) grid cells based on the cropland area allocation model built by Li et al. (2015).

In the allocation of cropland, we have allocated all historical cropland within the maximum extent of cropland in modern times. This is a source of error since at the maximum extent of cropland in historical times more marginal lands may have been cultivated (see more under Discussion). However, at the scale in which we present the data the error is probably negligible. The 300m CCI-LC maps (http://maps.elie.ucl.ac.be/CCI/viewer/index.php)

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developed by European Space Agency (ESA) provide 22 land cover classes. They were used to determine the maximum extent of cropland cover. The 300m resolution CCI-LC maps in 2000 and 2015 were resampled to 30 arc-second maps. For our cropland area data in 1999 and 2015, 4 classes (10 Cropland, rainfed, 20 Cropland, irrigated or post-flooding, 30 Mosaic cropland and 40 Mosaic natural vegetation) were combined as the Boolean maximum cropland cover extent map $MC_{1999}(i)$ and $MC_{2015}(i)$, based on the CCI-LC maps in 2000 and 2015, respectively. For the reconstructed cropland area before 1999, beside the above 4 classes of the CCI-LC map in 2000, Urban areas were also used to generate the Boolean maximum cropland cover extent map $MC_{bf1999}(i)$, since urban land is usually built on rural and cultivated land. $MC_{bf1999}(i)$, $MC_{1999}(i)$ and $MC_{2015}(i)$ shows whether there was cropland (value 1) in each 30-arc second grid or not (value 0) before 1999, in 1999 and in 2015, respectively and they were used as a baseline map to allocate the cropland area of each administrative units.

We analyzed the factors affecting the distribution of cropland. In previous studies, elevation, slope, climate, soil, water and population was used as causes that relate to the change of the spatial distribution of cropland (Klein Goldewijk et al., 2011; Li et al., 2015; Paudel et al., 2017). Agricultural land is usually constrained by both elevation and slope. People tend to be more inclined to start from areas with lower elevations and gentler slopes when cultivating land. Land with high elevations and slopes has negative characteristics that constrain cropland cultivation, which will only be used after low-elevation and gentle-slope land has been cultivated. Elevation and slope also effects climates and water availability. Climate can be used as one of the secondary characteristics of elevation and slope that affect cropland distribution and it accounts for more of the regional differences in the types of crops grown. Moreover, in Scandinavia, there is little climate difference in each administrative unit and we assumed the impact of climate for cropland distribution had been included in the effects of elevation and slope in each administrative unit. Soil provide the physical base and nutrients for crops. Soil properties such as texture, fertility and organic-matter content impact suitability for growing crops, but it is not a limitation for land cultivation in most areas. With the development of agricultural technology, agriculture modification can make soils more

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favorable for growing crops. In addition, the soil in the cultivated area has been generally ripened. Thus, modern soil datasets are unsuitable to be used for cropland area allocation. According to statistics, population in Scandinavia increased constantly from 17th century to present (SCB, SSB and Statistics Denmark), while the cropland area decreased from 1950. The continuous increase in population has inevitably led to the increase in urban land and the reduction in cropland. Population growth was not the most important reason for cropland area increase after 1950, especially in Sweden and Denmark. However, the spatial distribution of population data before 1950 at a high spatial resolution is rather hard to obtain. Therefore, elevation, slope and water were selected as the factors in the cropland area allocation model (Li et al., 2015). Used the NASA Shuttle Radar Topographic Mission (SRTM) 90m digital elevation data (DEMs), we resampled the DEMs in Scandinavia to 30 arc-second resolution and normalized the value of elevation and slope using the following formulas:

$$E'(i)=\frac{E_{\max}-E(i)}{E_{\max}-E_{\min}} \quad (1)$$

$$S'(i)=\frac{S_{\max}-S(i)}{S_{\max}-S_{\min}} \quad (2)$$

where $E'(i)$ and $S'(i)$ are the normalized elevation and slope value of grid i; $E(i)$ and $S(i)$ are original elevation and slope value of grid i; $E_{\max}$ and $S_{\min}$ are the maximum elevation and slope value of grid i in Scandinavia; $E_{\min}$ and $S_{\min}$ are the minimum elevation and slope value of grid i in Scandinavia.

$W(i)$ was defined as the water area in grid i, the value 0 indicates grid i is occupied by water, the value 1 indicates grid i is occupied by land.

The value of land cultivation suitability $Suit_{bf1999}(i)$, $Suit_{1999}(i)$ and $Suit_{2015}(i)$ of grid i before 1999, in 1999 and in 2015 were calculated using the following formulas, respectively:

$$Suit_{bf1999}(i)=MC_{bf1999}(i)\times E'(i)\times S'(i)\times W(i) \quad (3)$$

$$Suit_{1999}(i)=MC_{1999}(i)\times E'(i)\times S'(i)\times W(i) \quad (4)$$

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$$Suit_{2015}(i)=MC_{2015}(i)\times E'(i)\times S'(i)\times W(i) \quad (5)$$

For convenience, $Suit_{bf1999}(i)$, $Suit_{1999}(i)$ and $Suit_{2015}(i)$ were denoted by $St(i)$ in the following formulas.

The total weight of each administrative unit for cropland area allocation was defined as 1, then the weight of grid i for cropland area allocation (w_{crop}(i)) and the cropland area of grid i (Cr (i)) became:

$$w_{crop}(i)=\frac{St(i)}{\sum_{i=1}^{n} St(i)} \quad (6)$$

$$Cr(i)=w(i)\times T(p_n) \quad (7)$$

$T(p_n)$ is the total cropland area of administrative unit p_n.

The cropland area of each administrative unit was allocated in 30 arc-second grids followed by the above formulas. However, in a few grids, the allocated cropland area was larger than the total area of grid *i*. Formulas of (3), (4), (5), (6), and (7) were used to allocate the over-allocated cropland area to the grids where the allocated cropland area was smaller than the grids area. This step was repeated until the cropland area of each grid was smaller than the grid area. The cropland area allocation process was used for the 10 selected points of time and we created a cropland area dataset at 30 arc-resolution from 1690 to 2015 in Scandinavia.

4 Results

4.1 Changes of cropland area

4.1.1 Changes of the total cropland area in Scandinavia

The total cropland area change in Scandinavia during the period 1690 to 2015 is shown in Figure1. As an overall trend, cropland area developed slowly before 1810, and kept rapidly even increase until the beginning of the 20th century, then remained stable for around 40 years before dropping in 2015. The process of cropland area change can be divided into the following four stages: (1) slight increase in 1690-1810, with an annual growth rate of 0.37%

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on average. In 1690, the cropland area stood at 1.81 million ha, accounting for 2.06% of the land area. The cropland area rose steadily to 2.82 million ha in 1810. (2) rapid increase in 1810-1910, with growth rate of 0.89% on average annually. After 1810, the cropland area rose dramatically over the next century, reaching 6.80 million ha in 1910. 3) steady rise in 1910-1950, with 0.11% average annual growth rate. The period between 1910 and 1950 experienced a slight rise in the cropland area, and the area reached 7.10 million ha. (4) gradual decrease in 1950-2015, with -0.25% average annual growth rate. After 1950, the cropland area declined and dropped to 6.02 million ha in 2015, constituting 6.86% of the land area.

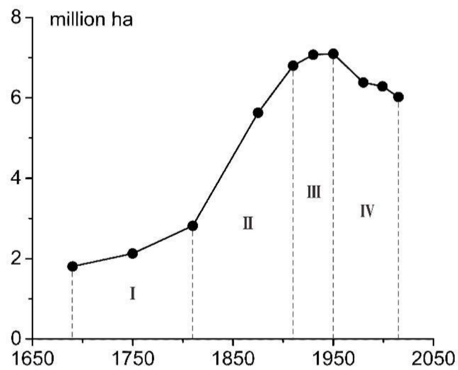

Figure1 Changes of the total cropland area in Scandinavia 1690-2015

4.1.2 Changes at the country level

Figure2 shows cropland area changes in Sweden, Norway and Denmark between 1690 and 2015. The trend of cropland area in Sweden was almost the same as the trend in Scandinavia as a whole. In 1690, the cropland area was just 0.68 million ha and rose slowly to 1.21 million ha in 1810. After 1810, Sweden had the largest cropland area in Scandinavia, rising from 2.89 million ha in 1875 to around 3.60 million ha in 1910. The next 40 years experienced a slight growth in cropland area, which reached a peak in 1950 with 3.66 million ha and represented 52.57% of the total cropland area in Sweden. Then the cropland area declined to 2.59 million ha in 2015. For the first three time points, the cropland area in Denmark grew gradually and accounted for 58.91%, 59.84% and 52.59% of the total cropland area in Denmark in 1690, 1750 and 1810, respectively. Then the cropland area continued to rise with an average annual growth rate of 0.36% until 1950 that reached its highest, 2.68 million ha. After that the figure slowly dropped by 2.45 million ha in 2015 and the average annual growth rate was -0.14%. The cropland area difference between Sweden and Denmark had been narrowed. Compared with Sweden and Denmark, Norway had the smallest cropland area, which made up only 3.63% of the total cropland area. After a slow increase from 1690 to 1810, there was also a noticeable growth between 1810 and 1910, during which time the cropland area increased by six times. After that, despite of some slight fluctuations, the cropland area rose from 0.72 million ha in 1910 to 1.04 million ha in 1999, with an average annual growth rate of 0.41%. Then the figure began to decline between 1999 and 2015.

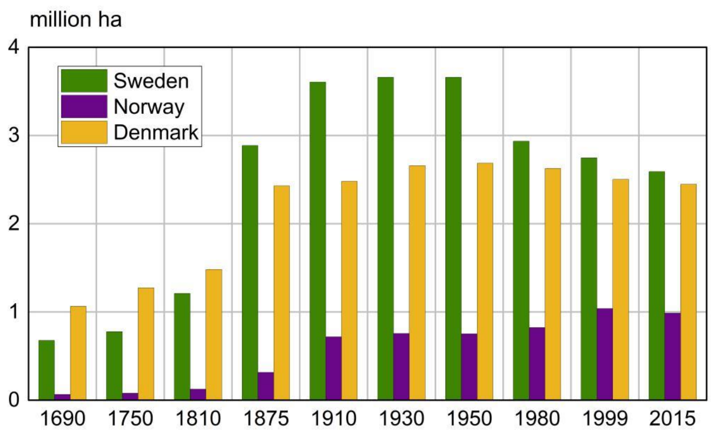

Figure2 Cropland area changes during 1690-2015 in Sweden, Norway and Denmark

4.2 Spatial patterns of cropland distribution

Figure3 shows the spatial patterns of cropland distribution from 1690 to 2015 in Scandinavia. Denmark and south Sweden already had extensive cropland cover in 1690, which reflected they have had a long history of agricultural practice. Before 1810, cropland cover expanded in southern Scandinavia and remained stable in north. Grid cells with more than 5% cropland account for 7.51% and 9.05% of the total number of grids cells between 1690 and 1810, while

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grid cells with more than 60% cropland increased 241.84%. After 1810, northern Scandinavia experienced slight expansion and the cropland fractions increased rapidly based on the spatial patterns of cropland in 1810 in southern Scandinavia. From 1810 to 1910, grid cells with more than 5% cropland represented proportion around 9%, while percentage of grid cells with more than 60% cropland grew from 1.27% to 7.97%. During 1910-1950, cropland area changed gently, cropland fraction changes in most grid cells were between -20%~20% (see Figure4). After 1950, cropland area began to decrease in most regions, especially in the eastern part of Scandinavia. In western Scandinavia, cropland area increased gradually and expanded to the north. Grids cells with more than 60% cropland account for 7.59% of the total number of grid cells in 1999 and 7.38% in 2015. We analyzed in detail the spatial patterns of cropland change in Sweden, Norway and Denmark from 1690 to 2015 in the following sections.

4.2.1 Sweden

In Sweden, about half of the area is covered by forest. Mountains, marshes and lakes together cover approximately one third. The cropland area accounted for 1.50%~8.13% of Sweden's total land area over the past 300 years. In 1690 croplands were especially dense in south Sweden, especially around the lakes Vänern, Vättern, Mälaren and Hjälmaren and in Skåne, reflective of the long history of cultivation. After that, the spatial patterns of cropland became more intensive in the southern Sweden and began to spread to the north. In 1750, we see the appearance of cropland in several grid cells of county of Västerbotten and Norrbotten and the cropland fractions in these grid cells were above 10% since 1875. A large number of grid cells with more than 80% cropland were seen and increased in 1910, account for 55.65% of the total grid cells with cropland in Sweden. During 1910-1950, spatial patterns of cropland distribution remained stable, except for slight increase in Västerbotten and Norrbotten counties in the north and gentle change in Skåne (Malmöhus and Kristianstad counties) and Gotland. In the following years, the cropland area declined in most regions and the percentage of grids cells with more than 80% cropland dropped to 20.17% in 1980 and 17.18% in 2015 of all grid cells with cropland. However, the coastal areas of Halland and Skåne still maintained high cropland fraction.

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4.2.2 Norway

Mountains, forests, open heathlands and grasslands dominate the landscapes of Norway and only about 3% of the land surface is suited for cultivation or arable farming (FAO, http://www.fao.org/family-farming/detail/en/c/358178/). In 1690, there was a small amount of cropland in Norway, which was distributed around the two agricultural centers, Olsofjorden and Trondheimsfjorden. During 1750 to 1810, the spatial patterns of cropland around the two fjords expanded and cropland appeared in the northern county of Norway, Nordland. Then, the cropland fraction increased in the two agricultural centers over the period 1810-1910 and by 1910 the croplands began to appear in the northernmost county, Finnmark. Cropland fractions of all the grid cells were below 20% in 1690, while the grid cells with more than 60% and more than 80% cropland accounted for 35.67% and 14.70% of the total grid cells with cropland, respectively. The total cropland area grew slightly from 1910 to 1950, but cropland changed differently in different regions. Cropland in the two agricultural centers stabilized and even decreased, and increased in other regions. After 1950, cropland around Olsofjorden and Trondheimsfjorden started growing again and the dramatic growth was in the southwestern of Rogaland. We also see the increased cropland in the coastal area with low elevation. The grid cells with more than 80% cropland accounted for 32.53% of the total grid cells with cropland in 2015.

4.2.3 Denmark

Denmark is among the most intensively cultivated countries in Europe. Long history of land cultivation brought widespread cropland cover since 1690 in Denmark. Grid cells with more than 20% cropland accounted for 60.11% of the total number of grid cells and most high-fraction grid cells were distributed in eastern Denmark, since soil conditions were more suitable for crop planting than the west part of the country. The period between 1690 and 1810 experienced a gradual growth and the most rapid cropland increase occurred in eastern Denmark. During 1810 and 1910, we saw a sharp increase in cropland area, in both eastern and western of Denmark. Grid cells with more than 20% and 60% cropland accounted for 83.42% and 71.24% of the total number of grid cells in 1910. Since 1910, we saw negative

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rates of change of cropland areas in northern and eastern Denmark, but positive rates in western part, including Ribe, Ringkjøbing and Viborg Counties. But the changes of cropland areas of most grid cells were less than 20%. After that, increased afforestation and the need for areas for urban expansion and infrastructure had gradually reduced the agricultural area (Pedersen and Møllenberg, 2017). Although cropland areas in South Jutland, Ribe, Ringkjøbing, Viborg, and South Jutland Counties increased moderately, those in other counties of Denmark declined from 1950 to 2015. We also saw the areas with more cropland had been changed from the eastern area with soil conditions suitable for cultivation to the western area dominated by sand.

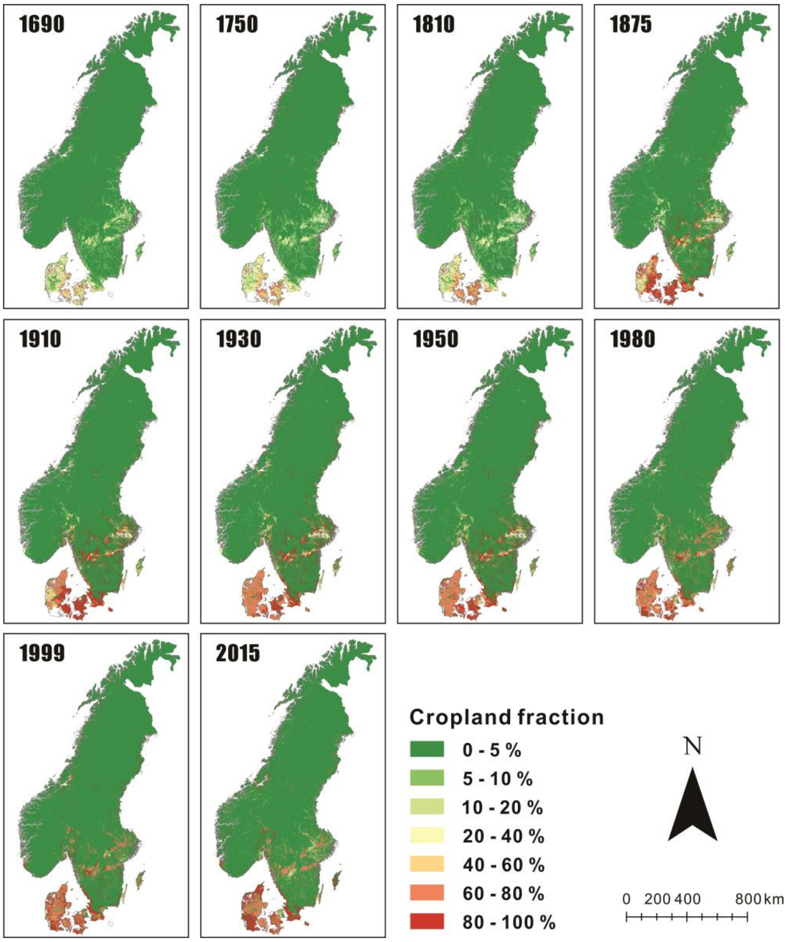

Figure3 The spatial distribution of cropland area from 1690 to 2015 in Scandinavia

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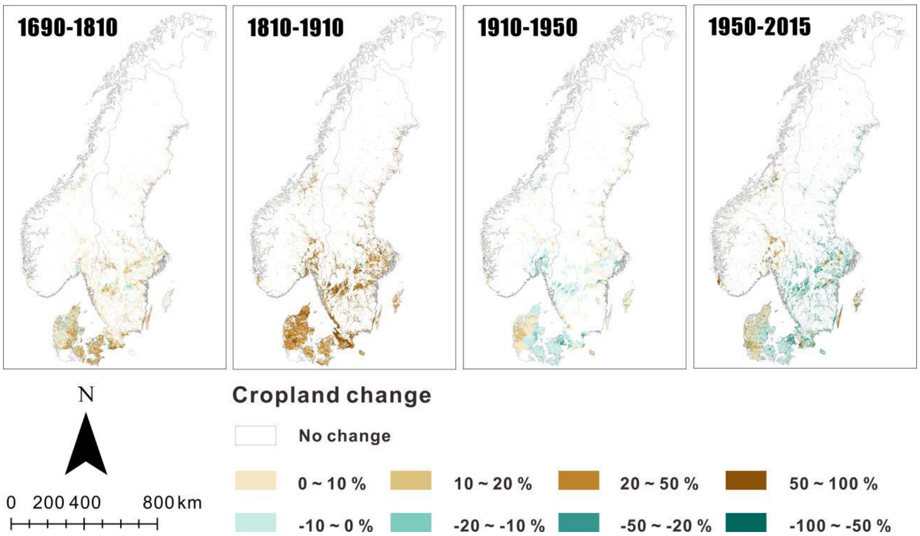

Figure4 Cropland change in Scandinavia during 1690-1810, 1810-1910, 1910-1950 and 1950-2015

5 Discussion

5.1 Comparison of cropland change with HYDE3.2

As one of the most widely used datasets for global historical land use, HYDE has relatively high temporal and spatial resolution. Moreover, it keeps providing new versions with improved quality. The latest version is HYDE3.2, which covers the period from 10000BC to 2015AD and has the spatial resolution of 5’×5’ (Klein Goldewijk et al., 2017). Thus, we compared our historical record-based reconstructed results with HYDE3.2 to further analyze the accuracy of HYDE3.2. We selected 1700, 1750, 1800, 1880, 1910, 1930, 1950, 1980, 2000, and 2015 from the HYDE3.2 dataset in correspondence to the 10 points of time of our dataset and transformed the spatial resolution of our dataset to the same as HYDE3.2. Both the total cropland area and spatial patterns of cropland distribution in each point of time were compared (See Figure5 and Figure6).

For Scandinavia, the total cropland areas of HYDE3.2 were close to those of this study from 1700 to 2015. Four stages were also identified in HYDE3.2: slight increase in 1690-1810, with the average annual growth rate of 0.31%; rapid increase in 1810-1910, with the average

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annual growth rate of 1.00%; steady rise in 1910-1950, with the average annual growth rate of 0.29% and gradual decrease in 1950-2015, with the average annual growth rate of -0.46%. We found little difference after 1910 and the maximum absolute difference of the total cropland area was 0.45 million ha in 1950. For Sweden, HYDE3.2 and this study showed the similar trend in cropland area change over the past 300 years, except the period 1910-1950. The total cropland data in HYDE3.2 were higher than those in this study before 1910 and the cropland area in HYDE3.2 was decreased but slightly increased in this study. The maximum absolute difference of the total cropland area was 0.91 million ha in 1880. However, we saw larger differences for Norway and Denmark between HYDE3.2 and this study. In Norway, the total cropland areas in HYDE3.2 were consistently higher than those in this study from 1700 to 1950. Especially in 1880, the total cropland area of HYDE3.2 stood at 0.77 million ha whilst the cropland area of this study was only 0.32 million ha. By contrast, the total cropland areas in Norway from HYDE3.2 were lower than those from this study. In Denmark, three stages were identified in HYDE3.2: rapid growth from 1700 to 1950, sharp decrease from 1950 to 1999 and gentle increase from 1999 to 2015. While only two stages were identified in this study: steady increase from 1700 to 1950 and slight decrease from 1950 to 2015. The largest difference was found before 1910.

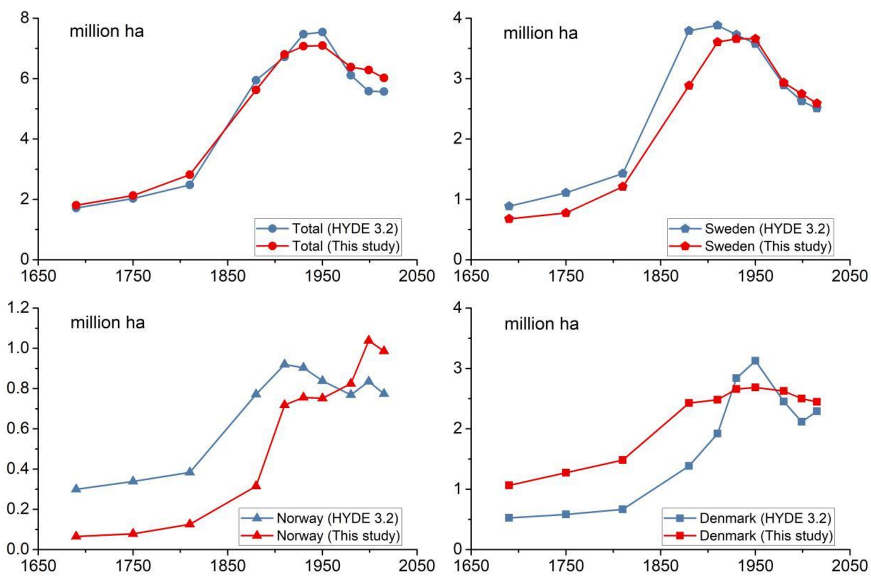

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Figure5 Comparison of the total cropland area between HYDE3.2 and this study

The spatial patterns of cropland distribution in Scandinavia over the past 300 years from HYDE3.2 and this study were quite similar (See Figure6). Both HYDE3.2 and this study showed that croplands were mainly distributed in southern Sweden, around Olsofjorden and Trondheimsfjorden in Norway and in Denmark. However, there were still differences between the two datasets, especially for the spatial patterns of cropland before 1950. After 1950, the differences of spatial patterns of cropland between two datasets were much smaller than before. For Sweden, HYDE3.2 had more cropland area around lakes Vänern, Vättern, Hjälmaren and Mälaren in the ten time points. For Norway, from 1700 to 1810, HYDE3.2 showed that cropland fractions around Olsofjorden in Norway were more than 20%, but this study showed there was few grid cells with cropland fraction more than 20% in Norway. After 1880, cropland areas in the counties of Sogn & Fjordane, Hordaland and Rogaland in Southwestern Norway from HYDE3.2 were greater than those from this study. For Denmark, the negative differences in eastern Denmark between HYDE3.2 and this study indicated that HYDE3.2 underestimated the cropland area for the period 1700~1880. From 1910 to 1950, HYDE3.2 revealed that the cropland area increased significantly in the whole Denmark and decreased gradually after 1950, which was contradictory to the spatial patterns of cropland distribution in this study. This study suggested that the area with high cropland fraction began to change from east to west in 1875 and remained stable from 1930 to 1980, then the cropland area decreased gently after 1980. The extensive positive differences in Denmark from 1930 to 2015 indicated the overestimation in HYDE3.2. For all of the three countries, more differences in spatial patterns of cropland distribution between HYDE3.2 and this study were observed in regions which were highly cultivated (which have grid cells with high cropland fraction).

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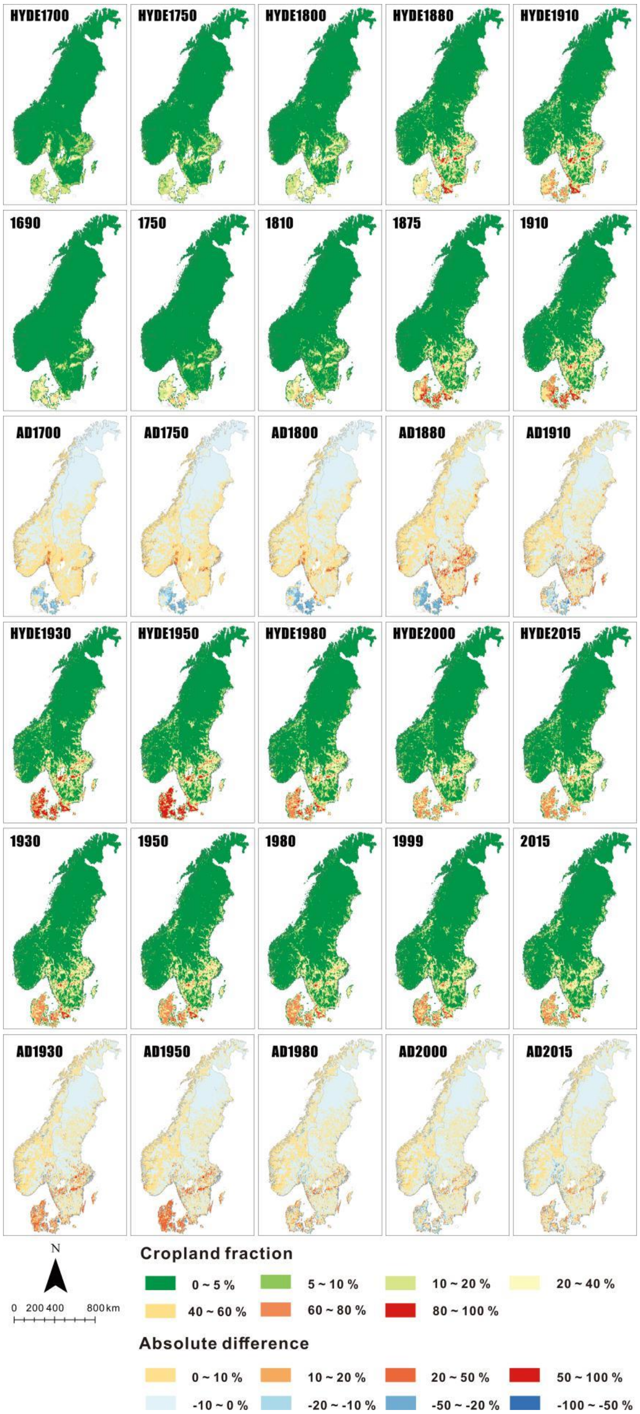

Figure6 Comparison of spatial distribution of cropland area between HYDE3.2 and this study

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5.2 Uncertainties

5.2.1 Definition of cropland

Due to the large number of data sources, inconsistent definitions of cropland of different sources may cause uncertainties of the cropland dataset derived by this study. The Food and Agriculture Organization (FAO) defines cropland as the total of areas under "Arable land" and "Permanent crops". "Arable land" represents the total of areas under temporary crops, temporary meadows and pastures, and land with temporary fallow. "Permanent crops" represents land cultivated with long-term crops. In this study, based on the data sources, the definition of cropland is slightly different in different countries at different time periods. Thus, we tried to unify the definition of cropland in Scandinavia. In Sweden, in the periods of 1690-1810 and 1930-1950, 1875-1910, and 1980-2015, though "*Åker*", "*Åker och annan odlad jord*" and "*Åkermark*" were used to record cropland, respectively, their meanings were similar to the cropland defined by FAO. In Denmark, the cropland was called "*Ager*" in 1690 and "*Agerjord*" in 1800, 1881 and 1998. Both "*Ager*" and "*Agerjord*" represent the total of areas which are annually sown with various crops and the resting land, and have the same meaning as cropland defined by FAO. In the rest points of time, various types of agricultural land areas were recorded and we used the types which were included in cropland. In Norway, from 1690 to 1875, only volumes of seeds regarding different crops were recorded, which represented the land area for cultivation in the corresponding years. From 1910 to 1980, NSD classified the agricultural land according to the purpose of land use and recorded the agricultural land area of each classification. After 1980, the data source only recorded the agricultural land area directly. As a result, in this study, cropland areas from 1690 to 1875 were lower and cropland areas after 1980 were higher than the real cropland areas in Norway.

5.2.2 Uncertainties in cropland area allocation

Uncertainties also exist in process of cropland area allocation. We used CCI-LC maps in 2000 and 2015 and combined 4 classes of rainfed cropland, irrigated or post-flooding cropland, mosaic cropland(>50%)/ natural vegetation (tree, shrub, herbaceous cover) (<50%) and mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%) to

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determine the maximum extent of cropland cover. However, since the maximum cropland cover extent map is Boolean, grid cells of mosaic cropland (>50%) and mosaic cropland (<50%) were considered as full of cropland area. More cropland area may be allocated in those grid cells. In Sweden and Denmark, the cropland area reached its maximum in 1950. The spatial distribution of cropland around 1950 may have been greater than the maximum cropland extent we selected, so that no cropland was allocated in the grids that should have had cropland. The difference between the total cropland area after cropland allocation and the total cropland area obtained from statistics is -7%~7% at the national scale, except for Norway in 1999. After allocation, the total cropland area of Norway in 1999 was even smaller than that in 2015, which shows the difference between remote sensing data and statistics. For example, statistics show that there were 314 ha cropland in Vegårshei in 1999, but the ESA CCI-LC map of 2000 shows that there was no cropland in this county. Figure 7 shows the difference between statistics in 1999 and the ESA CCI-LC2000 map. Moreover, the land area of different levels of administrative units varies greatly. Especially in Sweden, even for the same level of administrative units, the land areas are much different. For example, the land area of Jokkmokk Parish (*socken*) is almost 500 times larger than that of Brunnby Parish (*socken*). Using the same model to allocate cropland area of different levels of administrative units and administrative units with large difference of land areas to 30 arc-second grid cells may also increase the error of cropland area allocation. Therefore, in future studies, according to different levels or land areas of administrative units, different cropland area allocation models should be used to improve the accuracy of historical cropland cover datasets in Scandinavia.

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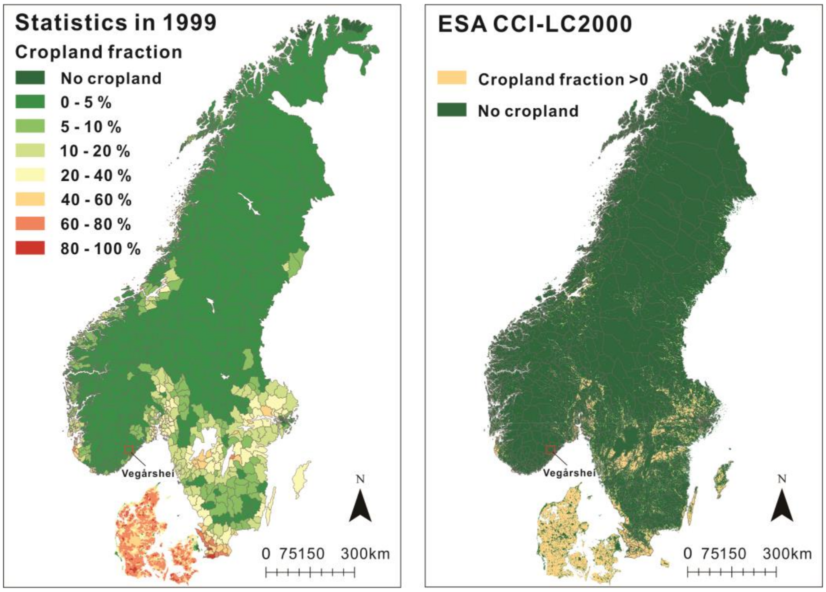

Figure7 The spatial distribution of cropland from statistics in 1999 and ESA CCI-LC map in 2000

6 Data availability

All cropland data cover 1690, 1750, 1810, 1875, 1910, 1930, 1950, 1980, 1999 and 2015 with spatial resolution of 30-arc second are available in https://doi.pangaea.de/10.1594/PANGAEA.919929 (Wei et al., 2020).

7 Conclusions

Based on the collected statistics of cropland area of each administrative unit, and using a range of methods for data preprocessing and cropland area allocation, we developed the dataset of cropland area at spatial resolution of 30 arc-second in Scandinavia from 1690 to 2015. Our reconstruction indicated that the cropland area developed slowly before 1810, then increased fairly rapidly until the beginning of the 20th century, remained stable for around 40 years before dropping in 2015. At the country level, the trends of cropland area change in Sweden and Denmark were almost the same as the trend in the whole of Scandinavia. The cropland areas of both Sweden and Denmark reached a peak in 1950. Norway had the least cropland area, which increased gradually from 1690 to 2015. The spatial patterns of cropland distribution showed that Denmark and south Sweden already had extensive cropland cover in 1690 and in the following 100 years, cropland expanded in southern Scandinavia and remained stable in the north. During 1910-1950, the cropland area changed gently and after 1950, cropland area began to decrease in most regions, especially in the east of Scandinavia.

The comparison of our dataset and HYDE3.2 shows that in the whole of Scandinavia and in Sweden, the total cropland areas of HYDE3.2 are close to those of this study from 1700 to 2015. However, large differences are found in Norway and Denmark, especially before 1950. The spatial patterns of cropland distribution in Scandinavia over the past 300 years from HYDE3.2 and this study are quite close and differences in cropland distribution over the past 300 years between HYDE3.2 and this study are mainly observed in regions which are highly cultivated.

Although the various definition of cropland in our data sources and errors in cropland area allocation brought uncertainties with our reconstruction, this study improves descriptions of historical cropland change in Scandinavia and the cropland dataset is an important reference for better understanding of the complex climate system.

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Author Contribution

WX, WM and LB designed the work. WX wrote the manuscript. FX, YY and CT provided suggestions on structure and methods. ZC provided some of the data for cropland allocation. All the authors contributed to the review of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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