Assessing the Validity of the Early Anthropocene Hypothesis Using the HYDE 3.2 Database

Bachelor Thesis Global Sustainability Science

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Abstract

Humans have always been interacting with their environment in the pursuit of food, fibre, and fuel. It is commonly accepted that anthropogenic impacts on the earth system during the since the Industrial Revolution during the 18th century and the Great Acceleration in the 1950s are significant enough to alter the earth's climatic conditions. The more controversial *early anthropogenic hypothesis* asserts that humanity has been altering the climate since the inception of agriculture around 8000 years ago. This study aims to determine the relationship between past anthropogenic land use change and climate change starting before the Industrial Revolution. To this end, statistical analysis to determine the correlation between land use numbers from the HYDE 3.2 database and temperature reconstructions based on dendroclimatological records is conducted. This analysis is conducted for Southern Europe, Western North America, and the Tibetan Plateau. For none of these regions statistically significant relations are found. This study highlights the need for improvements to the HYDE database with regards to temporal resolution and regional specificity of allocation algorithms, and thus contributes to advancements in the field of land use modelling.

Table of Contents

Introduction 4
Theory and concepts 5
  Anthropogenic land use and climate change 5
  The early anthropogenic hypothesis 6
Methods 7
  Type of data and sources 7
    Dendroclimatological data 8
    Land use data 9
  Research 9
Results 10
  Southern Europe 10
  Western North America 10
  Tibetan Plateau 11
Discussion 12
  Reliability of HYDE data 13
  Reliability of dendroclimatological data 14
  Limitations to the study design 15
  Recommendations 17
Conclusion 18
Acknowledgements 19
References 19
Appendices 22
  Appendix A: Countries and regions included in this study 22
  Appendix B: Data used for this analysis 23

Introduction

For as long as humans have been around, they have been interacting with their physical environment in pursuit of the acquisition of food, fibre, and fuel (Foley et al., 2005). The nature of these interactions has changed through time and with increasing technological capabilities, from foraging and hunting to exploitation of land for agriculture to even more impactful alterations during the industrial revolution and Great Acceleration (Stephens et al., 2019; Ellis, 2018). As part of the Earth's climate system, anthropogenic alterations to the biosphere resulting from land use changes have the potential to induce changes in climate. A plethora of modelling studies have demonstrated that anthropogenic land use and cover change (LUCC) affects climate, though there is no consensus in the literature on the scale at which this occurs. There is evidence for a global impact (Mahmood et al., 2014; Smith et al., 2016), though other studies only describe a local or regional influence (Findell et al., 2007; Bounoua et al., 2002).

These climatic influences range from increased greenhouse gas (GHG) emissions due to deforestation and direct emissions to changing the surface albedo. Though the climatic influence of anthropogenic LUCC has increased over time, the elements that are influenced have remained largely the same. There is ongoing scientific debate about when this human-induced LUCC started to have a noticeable effect on the climate system. Ruddiman (2003) proposes an *early anthropogenic hypothesis*, which asserts that "the Anthropocene actually began thousands of years ago as a result of the discovery of agriculture and subsequent technological innovations in the practice of farming". This hypothesis is based on the anomalous rise in CO_2 and CH_4 concentrations in the late Holocene that cannot be explained by natural factors. Decreases in summer insolation are expected to be accompanied by decreases in CO_2 and CH_4 concentrations as well, yet this is not what happened according to measurements from the Vostok ice core. By process of elimination, Ruddiman concludes that the only plausible explanation for the anomalous rise in CO_2 and CH_4 is anthropogenic emissions due to activities such as agriculture and deforestation for other purposes. This hypothesis is heavily debated, however, and there is ample archaeological and modelling evidence available both in favour and against Ruddiman's ideas. In the *Theories and Concepts Section*, this hypothesis will be further elaborated on.

The existing literature on the relation between LUCC and climate change mostly consists of modelling research, which tends to employ fictional scenarios to assess the nature and magnitude of the climate system's response to LUCC. What lacks is research that looks at actual changes in land use for the last thousands of years and studies the correlation between these changes and climate change over the same time period.

Inquiry into the interactions between past climate change and LUCC fits well within the contemporary context of sustainability, and contributes to achieving the UN's Sustainable Development Goals (SDGs). A better understanding of the dynamics that are at play between the climate system and the terrestrial ecosystem and human-impacted areas contributes to the knowledge on how to sustainably manage these areas, thus contributing to the implementation of sustainable practices in this regard (SDG 15.3). Additionally, knowledge on how the conversion of natural to anthropogenic land impacts climate change adds to the sense of urgency that is felt for the conservation of natural habitat, enhancing the protection of intact areas (SDG 15.5). Increased knowledge on the drivers behind climate change in the past contributes to the capacity and for climate action (SDG 13.1) (UN General Assembly, 2015)

Given this context, the primary aim of this study is to determine the relation between past anthropogenic LUCC and climate change during the Holocene, and to determine whether this is a statistically significant relation. To this end, this study will employ version 3.2 of the History Database of the Global Environment (HYDE) (Klein Goldewijk et al., 2017). In doing so, this study will also help to better understand the HYDE database and the anthropogenic footprint on the natural system that can be deducted from it the regional scale. To this end, the following research question and sub-questions have been formulated

- What is the relation between anthropogenic land use and cover change and climate change during the Holocene on the regional scale?
    - What is the relationship between regional anthropogenic LUCC and tree ring records from Southern Europe, the Tibetan Plateau, and Western North America?
    - Is relationships statistically significant at the 0.05 level?

Theory and concepts

Anthropogenic land use and climate change

This study implicitly relies on a certain understanding of what LUCC is and through which processes and mechanisms it interacts with the climate system. In this chapter, these processes and interactions will be further explained. Figure 1 provides a visual representation of this.

Through alteration of surface vegetation as a result of land use change, several earth system components and characteristics are altered as well, impacting the climate system. Distinct types of vegetation have different hydrological properties, which results in an alteration of the moisture cycle with altered land cover. Sen Roy (2010) found that with the shift of non-irrigated to irrigated crop types, sensible and latent heat fluxes (from evapotranspiration) could have increased by about 40 to 80 Wm^{-2}. Douglas et al. (2009) similarly found increases in vapour flux during both the dry and wet season. Changes in land cover influence surface albedo as well. Betts (2001) has estimated surface albedo to have decreased by $2Wm^{-2}$ compared to the natural situation. Different land surfaces have different albedos. Hence, the logical conclusion is that the transformation of land surface from one type of cover into another alters albedo as well to a certain extent. The albedo of cropland, for example, is lower than that of grassland, meaning that more incoming solar radiation is absorbed by the surface after conversion into cropland compared to the natural situation (Smithson et al., 2013). Deforestation associated with LUCC in many places in the world acts as a source of climate-altering carbon emissions into the atmosphere. Forests hold about 10% of terrestrial carbon, which are released with the removal of natural forest cover (Bonan, 2008). Additionally, anthropogenic land uses and activities on converted land contribute to greenhouse gas emissions as well (Smithson et al., 2013). Finally, surface roughness and convective fluxes are altered by LUCC as well, affecting atmospheric circulation and consequently weather patterns (Mahmood & Hubbard, 2003). If persistent, these changes in weather pattern could translate into altered climate conditions.

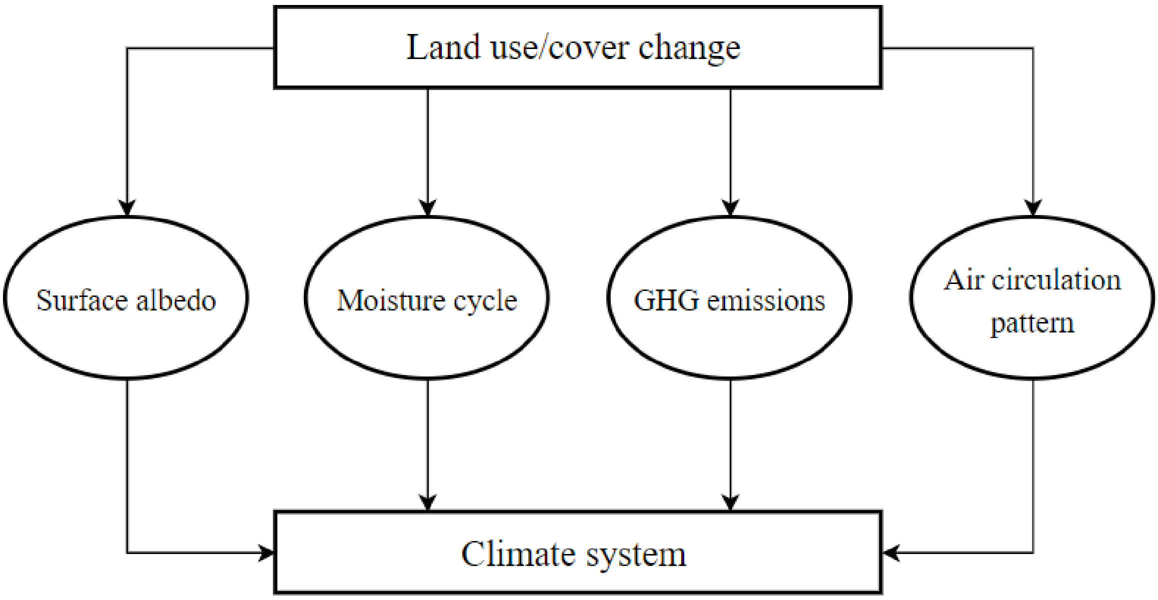

Figure 1 Framework illustrating through which processes and cycles LUCC influences the climate system

The early anthropogenic hypothesis

As mentioned in the *Introduction*, Ruddiman's early anthropogenic hypothesis asserts that humans have influenced the Earth's climate much longer than since the Industrial Revolution. The hypothesis is based on the CH_4 and CO_2 trends during this and previous interglaciations. For both these greenhouse gases, a decrease in atmospheric concentrations during the last 5,000 years would be expected, as this is the pattern that has repeated itself for the previous interglaciations. This is not what ice core records show, however. Different ice core records and measurements all show anomalous increases in CH_4 and CO_2 over the past about 5,000 years (Ruddiman, 2003; Ruddiman & Thomson, 2001; Ruddiman, Kutzbach & Vavrus, 2011).

Several natural causes could be responsible for this rise in CH_4 and CO_2. For the CH_4 trend, one of these includes release from wetlands, which is one of the main sources of natural methane. This hypothesis was discarded though, as of the three wetland regions that would be of sufficient size to lead to such increases in methane, two (Eurasia and North America) could be ruled out by palaeoclimatological evidence (Brook & Michel, 2007). This left only the wetlands of the Amazon Basin as a potential driver for the CH_4 increase of the current interglaciation. However, it is highly unlikely that this region is responsible for this anomalous trend, as for the preceding 400,000 years, methane concentrations had followed the trajectory of northern hemisphere monsoon trend, which is completely asynchronous to the southern hemisphere methane trajectory. Because of this, it would be at least improbable for the Amazon Basin wetlands to have taken control of the methane peaks during the last couple thousand years (Ruddiman, Kutzback & Varvus, 2011).

For CO_2 maxima, the possible natural causes include the *delayed ocean carbonate compensation* (Broecker et al., 1999). This hypothesis asserts that during times of growing forests in the northern hemisphere, taking up a lot of CO_2 from the oceans, and thus allowing for increased $CaCO_3$ deposition on the seafloor. With the stagnation of forest advancement about 7,000 years ago, this process reversed and emitted billions of tonnes of CO_2 back into the atmosphere. This theory remains a plausible explanation of the anomalous CO_2 rise.

An anthropogenic source of CH_4 and CO_2 that could lead to the anomalous trends in the climatic record would have to be disproportionate to population size, as the human population at this time was not big enough to be responsible for such changes (Ruddiman & Thomson, 2001). Because of this, emission sources such as livestock, human sewage, and anthropogenic biomass burning can be ruled out, as these are directly proportionate to population size. Ruddiman & Thomson (2001) propose ancient rice production to be such a disproportionate source of CH_4 emissions. Earlier cultivation practices required much larger area of land to be submerged than modern techniques, which lead to methane emissions much higher than what would be expected given the population size at the time. For the anomalous CO_2 trend, early land clearance could be a potential disproportionate source. Evidence suggests that land clearance in early history was much more extensive than it is today relative to population size (Kaplan, Krumhardt & Zimmermann, 2009). In other words, the per capita land use has decreased throughout the Holocene, and therefore emissions from land clearance thousands of years ago would have been much bigger than would be expected given the population size.

From the scientific findings and theories listed above, Ruddiman concluded that humans must have been responsible for the anomalous rise in CO_2 and CH_4 during the last couple thousands of years. This study will test this hypothesis by employing statistical analysis, and will simultaneously assess the capabilities of the HYDE 3.2 database to pick up on the anthropogenic influence on the earth's climate. The following section will elaborate on the methodology that was employed to this end.

Methods

Type of data and sources

For this study, two kinds of data were required: data and LUCC throughout the Holocene, and paleoclimate data for the same time period. For LUCC data, the HYDE 3.2 database was used. This database contains land use estimates for the past 12,000 years, and divides land use estimates into several categories. For this study, the relevant categories were combined, which resulted in one number for land that had shifted from natural to anthropogenic. Relevant categories were the ones that are associated with high deforestation, as this has the largest effect on climate through the emission of GHGs, changing surface albedo, and altering different biogeochemical cycles. These relevant categories include cropland, rice paddies, and pasture. It does not include rangeland, as this more extensive form of herding animals is associated with much less anthropogenic impact on the landscape. The analysis was conducted for three regions in the Northern Hemisphere:

- Tibetan Plateau (TIBP)
- Southern Europe (SEUR)
- Western North America (WNA)

Figure 2 gives an indication of the geographical extent of these regions, and how the tree ring chronologies are distributed within them. The regions were chosen because they give a reasonable geographical spread along the Northern Hemisphere, and because there is ample literature available on the development of climate and LUCC in these regions. Consecutive temperature data for these three regions starts reasonably early, albeit a lot more recent than CO2 and CH4 data. The earliest consecutive data available for TIBP, NEUR, and WNA are 1683, 1588, and 1443 respectively.

Dendroclimatological data

In this analysis, dendroclimatological data was used. The dataset by Briffa et al. (2001) contains April-September temperature reconstructions based on 387 tree ring chronologies. These temperatures are reported as anomalies from the 1961-1990 mean in degrees Celsius. Using dendroclimatological records gives an indication of the local climate, which can be correlated to land use trends. This gives an indication of the impact of land use change on climate on the regional level; a relation that is described in the literature.

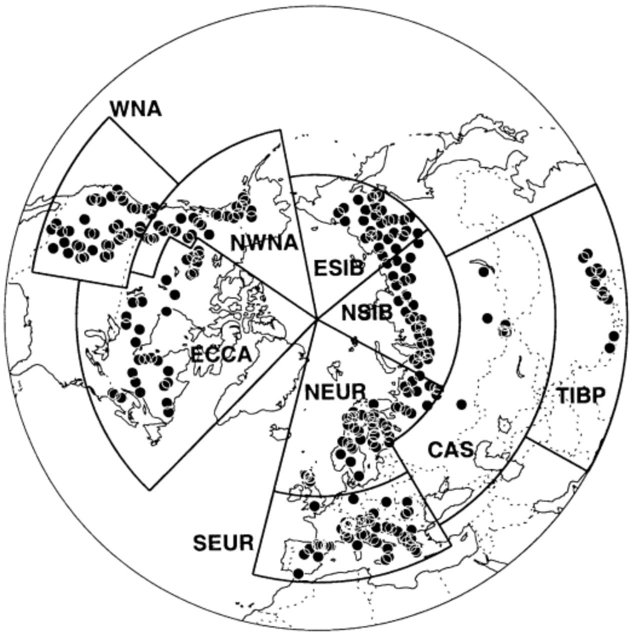

Figure 2 Distribution of tree ring chronologies and the boundaries of the regions studied by Briffa et al. (2001)

Land use data

To come to the land use numbers for the different regions, the combined total area of cropland and pasture from the HYDE 3.2 database was used as a proxy for land use change. The regions are composed of the countries within the regions as they are demarcated in Figure 2. For WNA and TIBP, land use numbers consist of a combination of the numbers for individual provinces/states. This was done because for these regions, only parts of countries are included. Including the whole country in the analysis would therefore yield unreliable results. Appendix A contains a list of all included countries and subnational entities.

Important to note is that data on the subnational level do not distinguish between rangeland and pasture, as this is not done by means of input data, but rather by means of calculation in a later stage. Therefore, the pasture data used for WNA and TIBP does include rangeland in the land use numbers, as otherwise pastureland would also have to be left out of the analysis, even though this is a very relevant source of anthropogenic influence on the climate.

Research

The aforementioned data were used for statistical analysis to determine whether there is a correlation between GHG concentrations and land use change. Since the relationship between these two variables is what is of interest, a two-tailed Pearson's r test was employed. To this end, SPSS was used, as well as excel for data clean-up. For all statistical tests, an alpha value of 0.05 was used, which means that the relation between the paleoclimate data and the LUCC data was deemed significant when the P-value ≥ 0.05, which means it could be concluded that current historical land use estimates were able to pick up the anthropogenic influence on the climate long before the industrial revolution. This would be in support of Ruddiman's early anthropogenic hypothesis.

Results

Southern Europe

Looking at the scatterplot for these two variables (Figure 3) gives a similar impression. From this, no real trend can be deducted.

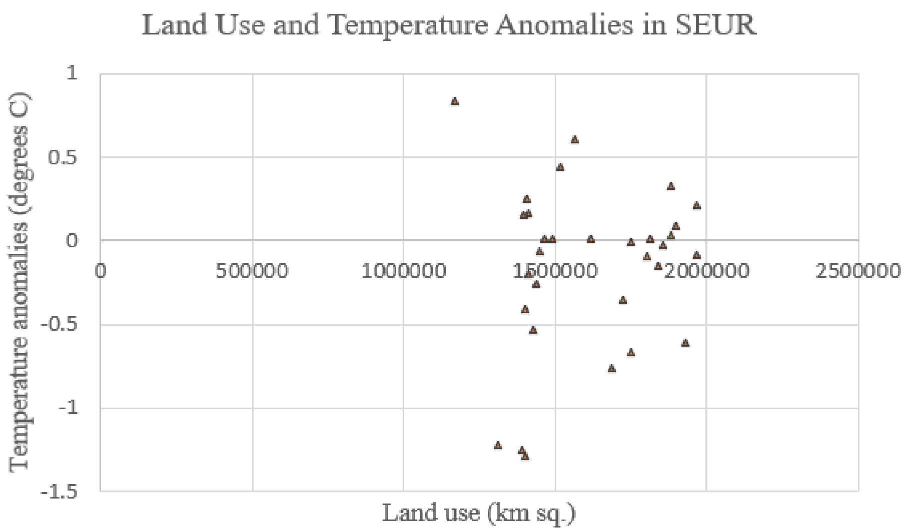

Figure 3 Scatterplot with land use and temperature anomalies for Southern Europe

Table 1 shows the outcome of A Pearson's r test on SEUR LUCC and SEUR temperature anomalies yielded a two-tailed P-value of 0.562, which far exceeds the 0.05 it would have to be for the correlation to be statistically significant. Therefore, the relation between land use change and climate change in Southern Europe cannot be deemed significant based on the data used in this study.

Correlations

		Land use in Southern Europe	Temperature anomalies in Southern Europe
Land use in Southern Europe	Pearson Correlation	1	.108
	Sig. (2-tailed)		.562
	N	75	31
Temperature anomalies in Southern Europe	Pearson Correlation	.108	1
	Sig. (2-tailed)	.562	
	N	31	31

Table 1 Outcome of the Pearson's r test for Southern Europe

Western North America

The scatterplot of the WNA variables (Figure 4) does show a slight positive trend. It seems as if with increasing land use, temperature anomalies increasingly tend to be positive. Further statistical tests will have to determine whether the apparent relationship is actually significant.

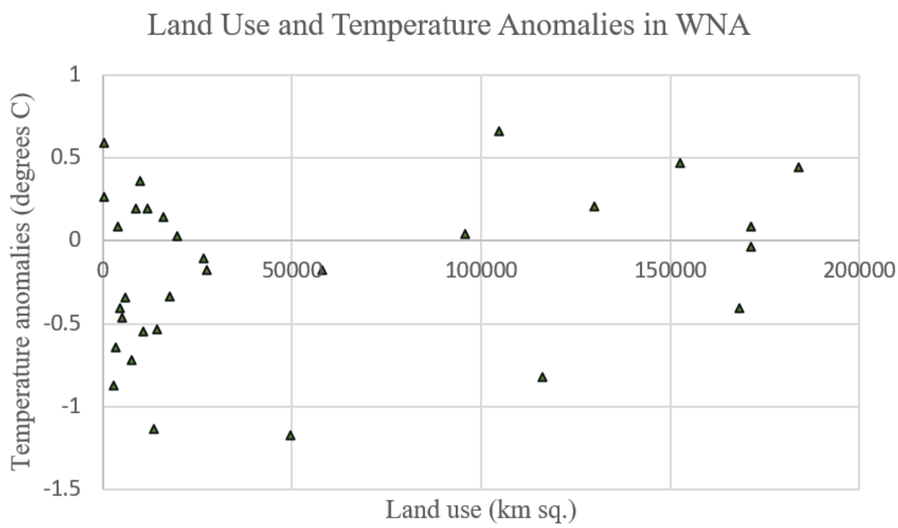

Figure 4 Scatterplot with land use and temperature anomalies for Western North America

Contrary to what seemed to be the case based on Figure 4, but similarly to the analysis for SEUR, the Pearson's r test for WNA yielded statistically insignificant results with a P-value of 0.143 (Table 2). Again, the relationship between Land use change and climate change in Western North America cannot be deemed statistically significant based on these data.

Correlations

		Land use in Western North America	Temperature Anomalies in Western North America
Land use in Western North America	Pearson Correlation	1	.270
	Sig. (2-tailed)		.143
	N	75	31
Temperature Anomalies in Western North America	Pearson Correlation	.270	1
	Sig. (2-tailed)	.143	
	N	31	31

Table 2 Outcome of the Pearson's r test for Western North America

Tibetan Plateau

Similarly to Figure 3, the relation between the TIBP variables appears to take on the shape of a cloud (Figure 5). No trend can be distinguished from this data.

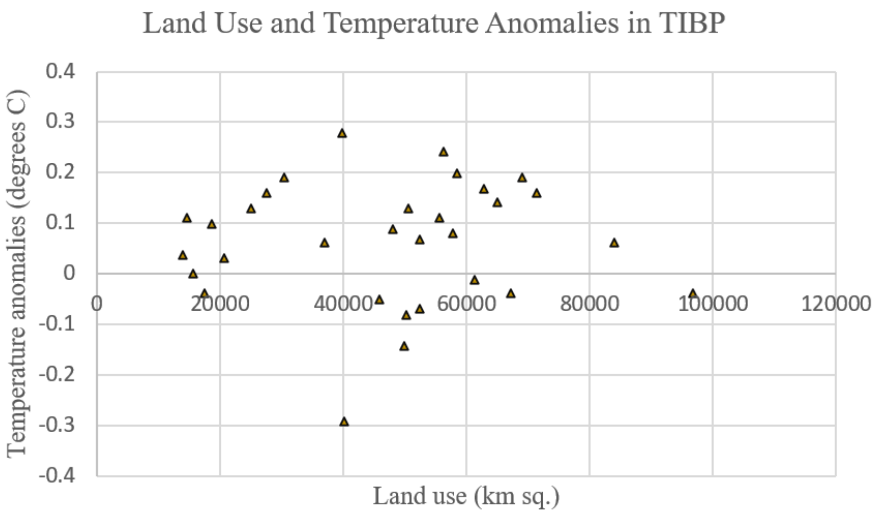

Figure 5 Scatterplot with land use and temperature anomalies for the Tibetan Plateau

This is confirmed by the Pearson's r test, which yields the highest P-value (Table 3). 0.9 far exceeds the 0.05 necessary for statistically significant results, and thus the relationship between land use and climate change on the TIBP cannot be deemed significant based on the data used in this analysis

Correlations

		Land Use on the Tibetan Plateau	Temperature Anomalies on the Tibetan Plateau
Land Use on the Tibetan Plateau	Pearson Correlation	1	.023
	Sig. (2-tailed)		.900
	N	75	31
Temperature Anomalies on the Tibetan Plateau	Pearson Correlation	.023	1
	Sig. (2-tailed)	.900	
	N	31	31

Table 3 Outcome of the Pearson's r test for the Tibetan Plateau

Discussion

The lack of statistically significant relations between regional LUCC and regional climate change is not in line with scientific literature, which did suggest correlations on the regional scale (Findell et al., 2007; Bounoua et al., 2002), and sometimes even on a global scale (Mahmood et al., 2014; Smith et al., 2016). Literature from the study regions gives a better idea of how the findings from this study do not fit well into the existing body of work. Bonan (1997) conducted modelling research into the relation between deforestation and climate change in the United States, and found a 1^{o}C spring warming effect over the Western United States. More recent work by Mahmood et al. (2004) shows that maximum and mean temperatures for specific agricultural sites in the midwestern United States have been steadily increasing as a result of agricultural practices. Modelling research on TIBP also indicates warmer and drier conditions under present circumstances compared to a non-anthropogenically-influenced situation

(Cui et al., 2006). Hence, given that other publications with different methodologies found an anthropogenic influence on the climate system, it would be reasonable to reflect on the methodology and data sources of this paper to see how future analysis using a similar methodology could be improved upon in the future.

Reliability of HYDE data

The HYDE 3.2 database makes use of different techniques to come to numbers for land use. For recent years, satellite data is used, whereas for 1960-2015, FAO data was used. Before 1960, Land use numbers were inferred from allocation formulae based on models predicting population numbers and land use demand (Goldewijk et al., 2017). Land use numbers further back in time are calibrated against archaeological and historical knowledge. A limitation that comes with this is the relative small number of sources available for calibration, and therefore the unreliability of the data.

Another challenge that comes with getting reliable data for a period without satellite imagery or reliable statistics is generalisation. HYDE 3.2 uses the same allocation algorithm for the entire globe, not accounting for regional nuances or cultural differences in how land is used. This is particularly true for the Americas, where knowledge on the land use practices of indigenous communities limits itself to a small amount of archaeological and palaeoecological evidence (Fulton & Yansa, 2019). This complicates the calibration of the land use data that come from the allocation algorithms. Studies have shown that native communities throughout history had distinct practices and preferences that have led to different patterns of land use, but also to different impacts on the natural environment. Thomas-Van Gundy, Nowacki & Cogbill (2015) showed that biomass burning practices around Iroquoian settlements along lakes in what is now upstate New York led to a distinct pattern of pyrophilic forests, and that Iroquoian agricultural villages tended to concentrate themselves in "fire-dependent, open-canopy savannah". Including such information in allocation algorithms would help improve the accuracy of these algorithms, and therefore the accuracy of any analysis conducted using the HYDE database.

Finally, a limitation to the usefulness of the HYDE database is the time interval between data entries. Especially for the years BCE. For this period, data entries exist at intervals of a 1000 years, which only gives a very sparse coverage of the trend of land use during this time. from 0 AD until 1700 AD, the interval is a 100 years, and then up until 2000 AD it is 10 years. After this, data entries come at an annual basis. Because of these intervals, the HYDE dataset only contains 10 datapoints before the year 0 AD, making reliable analysis of this time period with the HYDE dataset virtually impossible. The next smallest interval, 100 years, is still rather big to describe anthropogenic land use, as many socioeconomic processes that influence land use take place on much shorter timescales. With an interval of 100 years, the general trend can be picked up, but potentially significant alterations to land cover that occur and revert within these 100 years are missed, even though they could lead to climate responses. To illustrate, van Hoof et al. (2006) mention that for the direct effects of the Black Death to be detected in European pollen records, these records should be of a resolution of 10-20 years. They also mention that “it is essential to obtain information on the nature, timing and magnitude of land-cover changes triggered by massive depopulation events” when assessing whether forest regrowth during this time sequestered sufficient carbon to account for an atmospheric concentration decline. Given this information, it becomes apparent that a 100 year resolution is rather big the impact anthropogenic land use has on the climate.

Reliability of dendroclimatological data

The dendroclimatological data used in this study comes with their own potential sources of error, even though these mostly take on the form of standard errors that are commonplace in the statistical techniques employed when reconstructing temperature anomalies (Briffa et al, 2001). Figure 6 shows the standard errors around the temperature anomalies for all regions included in their analysis. for this study, only the graphs for SEUR, WNA, and TIBP are relevant. The figure shows that for TIBP and WNA, the margin of error was relatively small, whereas it was of more considerable size for SEUR. For all three regions, the reconstructions are considered to be reliable for most of the time for which they are described, though for SEUR and WNA there is a period of time for which they are considered less reliable. These facts have to be considered when interpreting the results of this study, and when drawing conclusions about the reliability of the findings of this study. Even though the dendroclimatological dataset does not go back in time as far as the HYDE database, it has annual data entries from the moment it starts, giving a much more detailed image of the trajectory of the climate than HYDE does of land use.

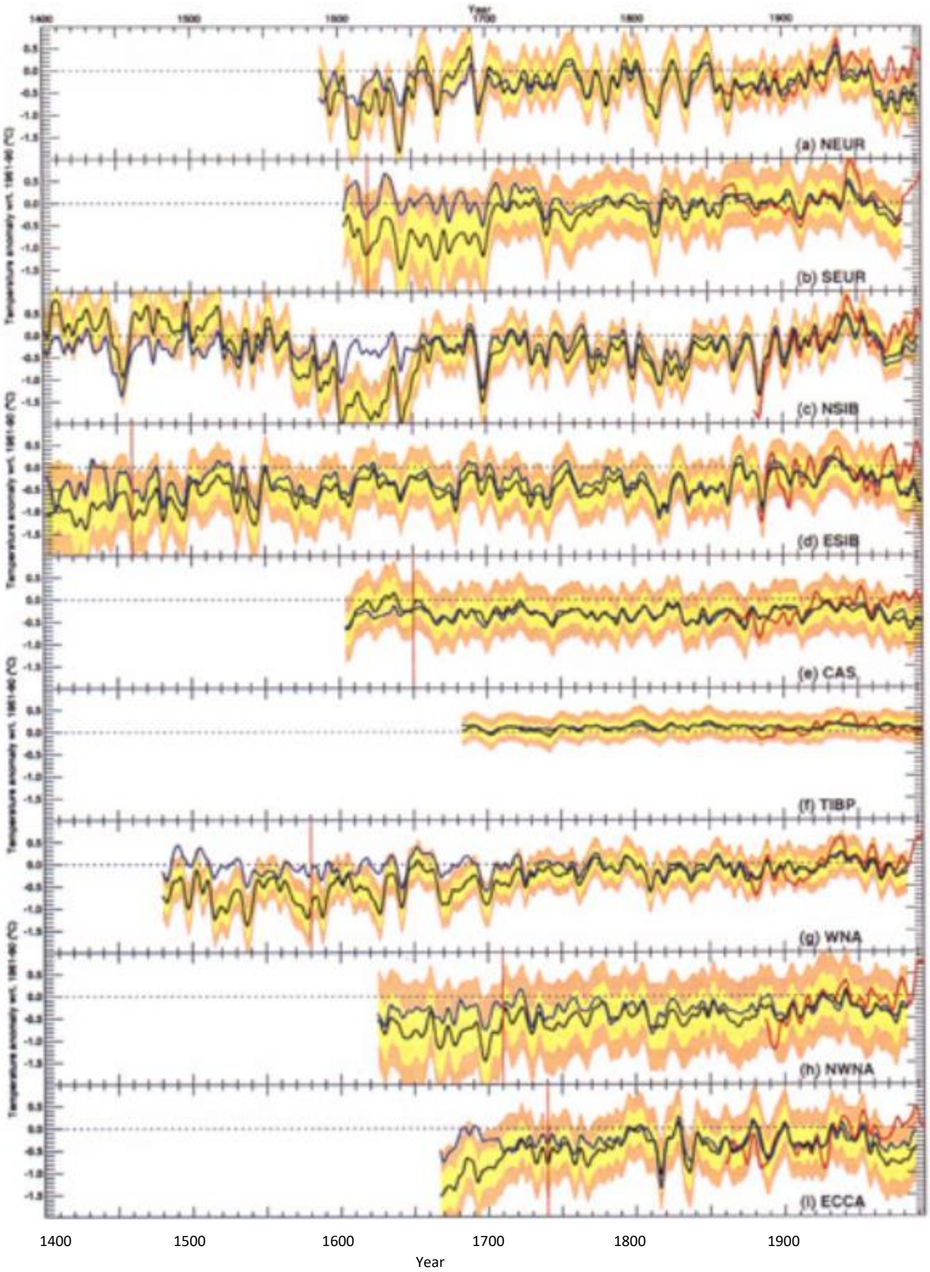

Figure 6 Reconstruction of April-September temperatures based on tree ring data. Observed temperatures are shown in red, reconstructed temperatures are shown in black. Standard errors are indicated by the orange and yellow around the lines. vertical red lines indicate up until where the authors deemed the reconstructions to be reliable (Briffa et al., 2001)

Limitations to the study design

The methodology of this paper also holds a couple potential sources of inaccuracy. Firstly, the coupling of land use data to palaeoclimatological data was done rather arbitrarily because of time constraints . For each year there was land use data, temperature reconstructions for the same year were picked. This while the modelling runs do not necessarily reflect the situation in that particular year, but rather represent the general trend of land use around that time. It would have been more accurate to use an average around the time in the HYDE database for the dendroclimatological data.

Furthermore, generalisations and assumptions were made before and during the analysis. Certain land use types that would have had an influence on the climate system were left out of the analysis because their impact was deemed too little to be included. These land use types include urban land and rangeland. The conversion of natural land to urban land is a significant alteration of the natural situation, so even though the extent of urban land is small compared to other land use types, it would have been more accurate to include it in the analysis. Rangeland as a land use type does not involve major conversions from natural to anthropogenic land. The inaccuracy lies in the fact that for the subnational land use numbers (i.e. for American states and Tibet), there is no division between pastureland and rangeland. Therefore, even though the exclusion of rangeland from the SEUR land use numbers makes for a more accurate analysis, it also means that there is a discrepancy between the data used in the SEUR and WNA/TIBP analyses. However, even though there is a discrepancy, the selection of data with respect to pasture-related land made for this study is the most accurate selection that was possible with the data available.

Finally, this study paints an oversimplified picture of the climate system and its interactions with the anthropogenic and natural system. There are many more factors that influence the climate than only anthropogenic, and humans have impacted the climate in many other ways than only through land use, especially in more modern times, where fossil fuel emissions have quickly overtaken land use as the most important factor in human emissions (Le Quéré et al., 2016). Figure 7 shows how land use emissions have remained about constant, but have been decreasing in relative importance because of the increase in fossil fuel emissions. Even though the early anthropogenic hypothesis asserts that the influence should have been significant well before the 1950s, and proving this hypothesis thus should not require accurate data after the Industrial Revolution, any analysis on the anthropogenic influence on climate change that fails to include human emissions from other sources paints a false (or oversimplified) picture of reality. Especially early on in human history, when anthropogenic impact on the climate system limited itself to small-scale interventions on the natural land cover, natural factors played a major role in the trajectory of greenhouse gas concentrations in the atmosphere. Volcanic eruptions, natural forest fires, and oscillations in the incoming solar radiation all profoundly impacted the earth's climate (Ruddiman, 2013). Therefore, taking the anthropogenic impact out of the context of the entire climate system and its interactions, and assessing if there is a statistically significant relationship between this single factor and climatic trends that were influenced by a wide array of factors has a rather slim chance of yielding significant results. It would thus be interesting to include more factors that influence the climate, as this would allow to determine the significance of anthropogenic LUCC relative to other factors such as direct emissions and whether give a more accurate view of whether LUCC has a significant impact at all.

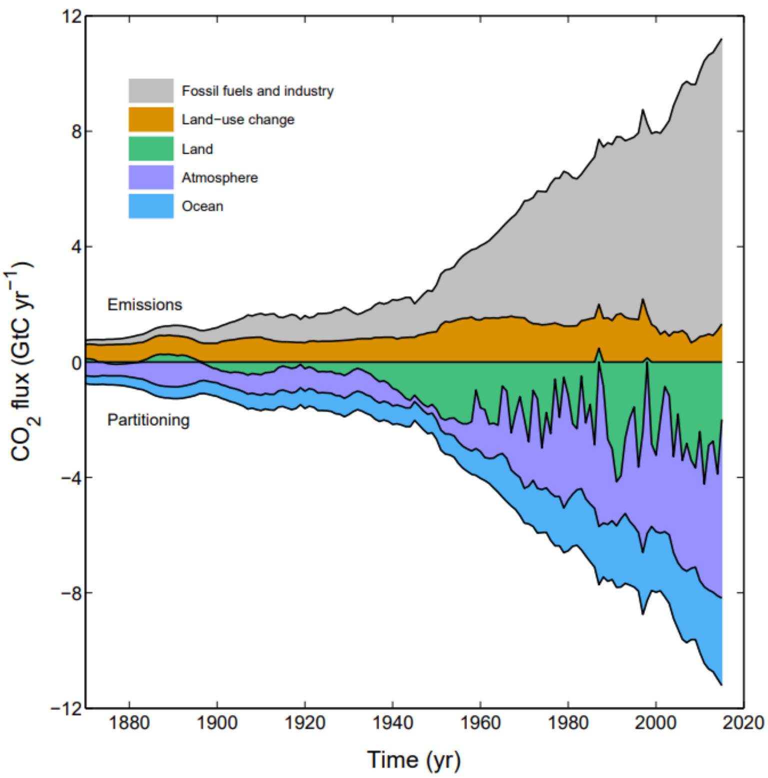

Figure 7 Emissions from anthropogenic land use have remained rather constant over the past century, whereas fossil fuel emissions have greatly increased since the 1950s. this decreases the relative importance of and use change emissions (Le Quéré et al., 2016)

Recommendations

Even though this study did not manage to confirm the statistically significant relationship between land use and climate change that is described in the literature, it still served an illustrative purpose, as it highlighted the challenged HYDE still faces when it comes to being used in research of this kind. And with the societal and scientific relevance of studies akin to this one being established in the introduction section, it is worthwhile to explore ways in which HYDE can be improved to facilitate similar research. Points of improvement that became apparent in this study include the improvement of allocation algorithms by differentiating between regions, creating room for regional differences and the influence of culture on land use practices. To this end, consultation with experts from disciplines such as history and archaeology would be worthwhile. Furthermore, improving these algorithms to the point where the temporal resolution of the HYDE database could be increased would allow for the HYDE database to be reliably used for research further back in time. Sadly, the technical details of how such an improvement could be achieved are beyond the scope of this study.

Of course, there is also the possibility that a statistically significant relation between anthropogenic land use change and past climate change does not exist. In that case, this study contributes to the body of work disproving the early anthropogenic hypothesis. However, given all the remarks on both the methodology of this study and of the data sources, combined with the fact that other studies did find a relationship on the regional scale, it seems highly unlikely that this is the case. Therefore, this study should not be interpreted as a rebuttal of the early anthropogenic hypothesis, but rather as a body of work exploring the feasibility of using databases such as HYDE and climatic records to assess the early anthropogenic impact on the climate system.

Conclusion

This study aimed to determine the relation between past anthropogenic LUCC and climate change during the Holocene, and to determine whether this is a statistically significant relation. To this end, statistical analysis was conducted using data from the HYDE 3.2 database running from 10.000 BCE to 2017 and a set of temperature reconstructions based on dendroclimatological data running from 1500 AD to 1990 AD. This analysis was conducted for three regions in the northern hemisphere; Southern Europe, Western North America, and the Tibetan Plateau. Based on the data, it could not be concluded that there is a statistically significant relationship between the two variables for any of the three regions. No relationship could be distinguished for SEUR and TIBP, and only a slight, albeit insignificant, positive relationship could be distinguished for WNA. Though there is a possibility the outcome of this study is correct and that there simply is no significant relationship between LUCC and climate change, it is more likely that the findings in this study are not representative of the nature and significance of the relationship, as there is broad support in the literature for a statistically significant relationship on the regional level. Therefore, several explanations for the lack of a significant outcome were presented. (1) The methodology for the acquisition of land use estimated in the HYDE database is not well-suited for this kind of study. The low temporal resolution leaves little data points and the use of a unified allocation algorithm leaves no room for regional nuance. (2) The statistical techniques used for the reconstruction of temperature anomalies from tree rings naturally come with a certain margin of error, and reconstructions were not deemed reliable all the way through by the original author. (3) The generalisations and simplifications made in this study paint an unrealistic image of the interactions between the climate system and the factors influencing it.

Regardless of these limitations, this study provides valuable insights into how databases such as HYDE could be improved upon to make them fit for analyses similar to the one conducted here. Important steps would be to increase HYDE’s temporal resolution, and improve its allocation algorithms to be specific to certain geographic regions. Once such improvements are made, this study should be repeated for a longer period of time, and potentially including more variables as to determine the significance of anthropogenic land use relative to other factors such as direct GHG emissions and natural factors. This is worthwhile, as inquiry into the relation between human land use and climate change contributes to the accomplishment of several Sustainable Development Goals.

Acknowledgements

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Appendices

Appendix A: Countries and regions included in this study

TIBP

- [Tibet]
- Nepal

SEUR

- Albania
- Austria
- Belgium
- Bosnia
- Bulgaria
- Croatia
- Czechia
- France
- Germany
- Greece
- Hungary
- Italy
- Liechtenstein
- Luxembourg
- Malta^
- Moldova
- Monaco*^
- Montenegro*^
- Netherlands
- North Macedonia
- Poland
- Portugal
- Romania
- San Marino*^
- Serbia*^
- Slovakia
- Slovenia
- Spain
- Switzerland
- Vatican city*^

* No cropland data available due to political reasons, or because of the small size of the country in question.
^No pasture data available due to political reasons, or because of the small size of the country in question.

WNA

- [Arizona]
- [California]
- [Colorado]
- [Idaho]
- [Montana]
- [Nevada]
- [New Mexico]
- [Oregon]
- [Utah]
- [Washington]
- [Wyoming]

Appendix B: Data used for this analysis

The table below contains data for the entire duration of the HYDE dataset. The green boxes are the data points that are actually used in this study

Year CE	SEUR LU	SEUR CLIM	WNA LU	WNA CLIM	TIBP LU	TIBP CLIM
-10000	0	-9999	0	-9999	0	-9999
-9000	0	-9999	0	-9999	0	-9999
-8000	0	-9999	0	-9999	0	-9999
-7000	94.10973	-9999	0	-9999	0	-9999
-6000	1922.391	-9999	0	-9999	184	-9999
-5000	3552.586	-9999	0	-9999	307	-9999
-4000	9334.028	-9999	0	-9999	678	-9999
-3000	30698.1	-9999	0	-9999	1476	-9999
-2000	69397.12	-9999	0	-9999	2200	-9999
-1000	146414.4	-9999	0	-9999	2395	-9999
0	410908.2	-9999	18	-9999	7586	-9999
100	431755.2	-9999	18	-9999	6915	-9999
200	438701.3	-9999	19	-9999	6062	-9999
300	398402.8	-9999	20	-9999	3783	-9999
400	356330.1	-9999	21	-9999	4732	-9999
500	292230.1	-9999	22	-9999	5589	-9999
600	237372.7	-9999	23	-9999	7075	-9999
700	302070.3	-9999	24	-9999	6204	-9999
800	399281	-9999	26	-9999	5292	-9999
900	537570.3	-9999	29	-9999	6110	-9999
1000	635363.9	-9999	32	-9999	5864	-9999
1100	895554	-9999	34	-9999	11883	-9999
1200	1104197	-9999	38	-9999	13427	-9999
1300	1360448	-9999	41	-9999	11016	-9999
1400	1022623	-9999	45	-9999	10187	-9999
1500	1170305	0.84	49	0.59	12520	-9999
1600	1312657	-1.22	20	0.26	13889	0.04
1700	1403312	-1.29	2942	-0.87	14665	0.11
1710	1413874	0.17	3420	-0.64	15459	0
1720	1409575	0.25	3946	0.08	17468	-0.04
1730	1401652	-0.41	4529	-0.41	18628	0.1
1740	1389316	-1.25	5181	-0.47	20732	0.03
1750	1395611	0.16	5935	-0.34	25001	0.13
1760	1411755	-0.2	7791	-0.72	27468	0.16
1770	1425846	-0.53	8707	0.19	30447	0.19
1780	1438955	-0.26	9701	0.36	37031	0.06
1790	1450035	-0.06	10778	-0.55	40076	-0.29
1800	1466618	0.01	11950	0.19	39886	0.28
1810	1491254	0.01	13227	-1.13	45968	-0.05
1820	1519992	0.44	14624	-0.54	47965	0.09
1830	1567912	0.61	16136	0.15	52383	-0.07

1840	1619248	0.01	17799	-0.33	56206	0.24
1850	1686098	-0.76	19442	0.02	58477	0.2
1860	1723135	-0.35	27539	-0.18	57707	0.08
1870	1750797	-0.01	26703	-0.11	49925	-0.14
1880	1802830	-0.09	49849	-1.17	50286	-0.08
1890	1841898	-0.15	58032	-0.18	50418	0.13
1900	1885112	0.03	95992	0.04	52277	0.07
1910	1933497	-0.61	104655	0.66	55616	0.11
1920	1885759	0.33	116341	-0.82	61122	-0.01
1930	1970228	0.21	130130	0.2	62680	0.17
1940	1966006	-0.08	152418	0.47	64898	0.14
1950	1898616	0.09	171525	-0.04	67296	-0.04
1960	1859347	-0.03	183823	0.45	68988	0.19
1970	1812865	0.01	171107	0.09	71197	0.16
1980	1749771	-0.67	168006	-0.4	83967	0.06
1990	1705951	-9999	172428	-9999	96792	-0.04
2000	1619848	-9999	168794	-9999	108244	-9999
2001	1604167	-9999	169101	-9999	107330	-9999
2002	1585904	-9999	168225	-9999	107088	-9999
2003	1568801	-9999	168096	-9999	106807	-9999
2004	1554892	-9999	165936	-9999	106653	-9999
2005	1543689	-9999	165429	-9999	106393	-9999
2006	1535352	-9999	163199	-9999	106178	-9999
2007	1520344	-9999	165213	-9999	105934	-9999
2008	1527557	-9999	165412	-9999	105749	-9999
2009	1519129	-9999	163121	-9999	105573	-9999
2010	1507388	-9999	161927	-9999	105391	-9999
2011	1499464	-9999	159268	-9999	105348	-9999
2012	1495773	-9999	162339	-9999	109497	-9999
2013	1489036	-9999	160632	-9999	109522	-9999
2014	1485541	-9999	162115	-9999	109625	-9999
2015	1478485	-9999	160926	-9999	109639	-9999
2016	1473612	-9999	161408	-9999	110134	-9999
2017	1467145	-9999	160468	-9999	110041	-9999