Exploring the Anthropocene:

Mapping land-system change until 2100 under the Shared Socio-economic Pathways

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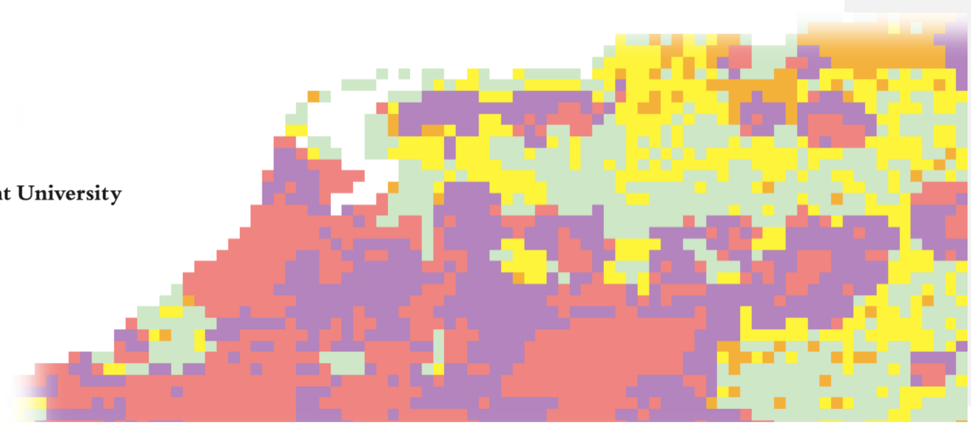

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(Cover image: Subset of future Anthromes (classified land-systems) under SSP3 in 2100 for my home-country The Netherlands)

Abstract

The effects of humans on the Earth are so profound, that it is argued that the Holocene has been substituted by the ‘Anthropocene’ era (Crutzen, 2002; Steffen & Mcneill, 2007; Zalasiewicz et al., 2011). Since it is likely that the global population, income, and food consumption will continue to increase, it is expected that the human-environmental interactions will do so too (Doelman et al., 2018). As human impacts on ecosystems become increasingly pronounced, nature-focused classification systems hinder our understanding and assessment of the broad-scale dynamics of planetary change (Ellis et al., 2010). To capture full global patterns of direct human interaction with ecosystems, an alternative quantification of the terrestrial biosphere in the Anthropocene has been introduced; ‘Anthropogenic biomes’ or ‘Anthromes’ (Ellis & Ramankutty, 2008). Anthromes provide a simple framework for assessing and mapping both past and future land-systems in the light of the extent, intensity and duration of their modification by humans (Ellis et al., 2010).

This research explores how global land-systems change under diverging human-land interactions up to 2100. This is done by mapping Anthromes under the full set of Shared Socio-economic Pathways (SSPs). It draws upon existing work on past Anthromes. To enable the exploration of future land-systems, the existing Anthrome framework is adapted, necessary input data on future human-land interactions is processed and subsequently future global and regional Anthromes are visualized.

Findings show that global composition of the Anthromes remains relatively stable for most scenarios. Regional differences in dynamics are sharper. Based on these results it can be concluded that influence of human impacts on the land-systems, and consequently Earth System, are increasing, especially in Africa. Though there are differences observed between the scenarios. At the very least, global human impact on the terrestrial Earth will not decrease until 2100 for all scenarios but SSP1-2.6. Therefore, this thesis emphasizes the importance of ‘sustainable development’ and contributes to the theory of the start of an Anthropocene era.

Keywords
Anthromes, Anthropocene, Earth System, Socio-economic Pathways, land-systems change

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1. Introduction

1.1 Earth system change

Humankind has arguably entered a new geological epoch (Crutzen, 2002; Steffen & Mcneill, 2007; Zalasiewicz et al., 2011). The effects of humans on the global environment are so profound, that the Holocene has been substituted by the ‘Anthropocene’ era.

Formally, the current Epoch has been the Holocene in the last 11.700 years. This epoch has created a stable condition for human survival (Barau & Ludin, 2012). It is the only state that certainly can support agriculture, settlements and cities, and complex human societies (Steffen, Richardson, & Rockström, 2020). Around 160.000 years ago, human impacts were relatively low due to their hunter-gatherer lifestyle. The functioning of the Earth Systems remained generally stable. About 10.000 years ago, agriculture was developed and villages, cities and complex civilizations were created spanning large regions (Steffen et al., 2011). These activities have had some effect on the Earth System due to CO_2 emissions, but stayed within its natural variability (Steffen et al., 2007).

Societal transformation over the last three centuries lies at the base of changes in the Earth System, consisting of land, climate, biodiversity, ocean acidity, atmospheric composition, soil and water quality and sediment flows (Crutzen, 2002; Steffen & Mcneill, 2007). Major social drivers of global change are ‘technology, resource consumption, population and settlement patterns, mobility, cultures and ideas, communication, trade and conflicts’ (Brondizio et al. 2016, p. 318). Both intentionally and unintentionally, humans have become Earth System engineers at the global level (Fuentes & Baynes-Rock, 2017). Human activity has become global and the dominant cause of most environmental change. Hence, human impacts will probably be observable in future geological stratigraphic records, just like meteor strikes and movement of continents (Lewis & Maslin, 2015).

Academic and popular usage of the ‘Anthropocene’ has rapidly escalated since the beginning of this century (Castree, 2021; Lewis & Maslin, 2015). The term provides a powerful framework for considering global change and how to manage it (Steffen et al., 2011). Semantically, the framework gathers many geoscientific ideas to understand ‘the age of humans’ (Castree, 2021). Climate change, biodiversity loss, pollution and other environmental issues as well as social issues such as high consumption, growing inequalities and urbanization are unified trough the Anthropocene framework (Steffen et al., 2020). In research terms, the framework contributes to the holistic development of sustainability science trough integration of natural sciences, social sciences and humanities (Steffen et al., 2020). It is even stated that the Anthropocene framework accommodates a paradigm shift; the dichotomy of humans versus nature arguably lost its significance. Humans should no longer be seen as a distinct unit surrounded by a non-human natural environment, but as integral part of complex socio-ecological systems at various scales, from local systems up to the Earth System (Biermann, 2020; Folke et al., 2021).

Current regulating policies on fertilizer use, agricultural intensification, and technological advancements are signs that humans are aware of the need to change their impacts on Earth. Nevertheless, greenhouse gases keep on increasing, tropical forest and woodland loss remains high and the pursuit of growth in the global economy continues (Steffen et al., 2015). Evidently, the Earth System will not go back to a pre-anthropogenic state for the foreseeable future (Ellis & Haff, 2009).

Planetary Boundaries Framework

The Planetary Boundaries (PB) framework has been used to set parameters around the impact of humans on the Earth System (Castree, 2021). The PB framework provides a natural-science-based observation that humans already rapidly altered the Earth System (Steffen et al., 2018). It was introduced by J. Rockström and colleagues in 2009, aiming to characterize the Holocene-like state of the Earth System and the global boundaries of the Holocene Earth System; a 'safe operating space' (Steffen, 2021). It links biophysical understanding of the Earth to the policy and governance communities at the global level. The framework is built around nine distinct processes which collectively describe the state of the Earth System (Steffen, Richardson, & Rockström, 2020). The nine processes are climate change, biogeochemical flows, land system change, freshwater use, aerosol loading, ozone depletion, ocean acidification, loss of biosphere integrity, and introduction of novel entities.

By pushing Earth's System out of the dynamics of the Holocene, humanity is at risk of moving our planet outside the safe operating space by altering important feedback loops, potentially producing abrupt and irreversible changes (Steffen et al., 2015). The PBs are tightly coupled so transgression of one boundary also creates serious risk for the others (Rockström et al., 2009; Steffen et al., 2015). Earth Systems often abruptly shift from the Holocene-state to another state, with undesirable or even disastrous consequences for humans, such as the loss of major ice sheets, accelerated sea-level rise and abrupt shifts in forest and agricultural systems (Rockström et al., 2009).

A distinction can be made between biophysically mediated and human mediated interactions between PBs (Lade et al., 2020). The former entail changes in a PB affecting another through biophysical mechanisms. For example, forest clearing (land-system change PB) affects the climate change planetary boundary, through released carbon. Human mediated interactions imply that a change in a PB leads to a change in human behavior, which affects another PB. Climate change leading to decreased agricultural productivity, could increase land clearing for agriculture, affecting the land-system change PB. Future human-mediated interactions are harder to anticipate due to their reactive nature. Some interactions may only occur after severe transgression of a PB (Lade et al., 2020).

1.2 Land-systems and land-system change

Land-system change has by far the most human-mediated interactions of all PBs (Lade et al., 2020; Rockström et al., 2009). Land systems are 'the terrestrial component of the Earth system that encompass all processes and activities related to the human use of land: Socioeconomic, technological and organizational investments and arrangements, benefits gained from land, as well as the unintended social and ecological outcomes of societal activities' (Verburg et al., 2013, p. 433). They are key in human development as they provide crucial products and ecosystem services (e.g. food and freshwater) (Foley et al., 2005). Moreover, Land systems play an important role in future global development and policy options for climate change, biodiversity, food security and sustainable development (Stehfest et al., 2019). Land system change is both a cause and consequence of global human-environment interactions (Verburg et al., 2015).

The amount of Earth's land surface estimated to be affected by humans varies within the Earth System science community. Contemporary assessments of the percentage of ice-free land affected by human action range from 20% to 100% (Hooke, Martín-Duque, & Pedraza, 2012). A recent study on the Human Footprint concluded that 58.4% of terrestrial Earth was under moderate or intense human pressure in 2013 (Williams et al., 2020). Jacobson et al. (2019) identified that 44% of land in landscapes currently has high human density and impacts, primarily managed for human use. Hooke et al. (2012) estimated that in 2007 between 48.4% - 58.6% of the land area was modified either directly by human earth moving or indirectly by actions causing changes in sediment fluxes (e.g. logging and reservoirs).

Although global-scale development is dependent on land-systems, actual land-system change occurs at a lower scale. In fact, Land-system change is one of five PBs that has strong regional operating scales (Steffen et al., 2015). Land system changes result from local land owners decisions to national scale land use planning and global trade agreements. The impacts of these changes play out at local to regional scales, affecting local livelihoods that depend on ecosystem services and biodiversity (Verburg et al., 2015). Local land system changes have consequences for the Earth System that feedback on ecosystem services, human well-being and decision making. For example, local land-system change has an effect on climate change and vice versa. Increased amounts of greenhouse gases are released due to deforestation or intensification of crop management with fertilizer and climate change (dis)favours growth of plants (Verburg et al., 2015). Therefore, land systems can also support climate change mitigation. Afforestation, reforestation and Biomass Energy with Carbon Capture and Storage (BECCS) are land-use change strategies to reduce CO_2 in the atmosphere (Harper et al., 2018). However, land-based climate mitigation might have consequences that are in conflict with the achievement of SDGs such as no poverty, zero hunger and life on land (Doelman et al., 2018).

Land-system change is a thus a key PB that affects other parts of the Earth System and must therefore be accurately quantified to understand the impacts of future changes (Steffen et al., 2018). Previous studies have analysed changes in the extent and composition of land systems through the classic biomes classification (Olson et al., 2001). In the PB framework, the amount of current global land-system change is quantified by the global area of particular biomes. Biomes are the most basic unit use to describe biophysical global patterns of land systems, based on general differences in vegetation type and regional climate. Tropical, temperate and boreal forests are the most important biomes regulating climate beyond local scale (Steffen et al., 2015). However, terrestrial ecosystems are no longer accurately depicted by the classic approach of mapping natural biomes (Ellis et al., 2010). As human impacts on ecosystems become increasingly pronounced, classification systems based on natural variation hinder our understanding and assessment of the broad-scale dynamics of planetary change (Alessa & Chapin, 2008).

1.3 Anthromes

To capture full global terrestrial patterns of direct human interaction with ecosystems, an alternative view of the terrestrial biosphere in the Anthropocene has been introduced; 'Anthropogenic biomes' or 'anthromes' (Ellis & Ramankutty, 2008). Anthromes provide a simple framework for assessing and mapping both past and future global biotic and ecological patterns in the light of the extent, intensity and duration of their modification by humans (Ellis et al., 2010). Population density, human land use and biophysical land cover are combined to classify types of human-land interactions from Wild to Seminatural to Used.

Past anthromes have been identified from 10,000 BCE to 2015 CE (Ellis et al., 2021; Ellis et al., 2020). Globally, land has been transformed considerably over the past 12,000 years due to changing use of land mainly due to human societies. The Anthromes differentiate between three major human intensity types. Wildlands, which are characterized by the complete absence of human populations and intensive land uses. Seminatural Anthromes, with less than 20% covered by intensive land uses, and Used anthromes are more than 20% covered by intensive land uses (Ellis et al., 2010). The majority of human transformation of terrestrial land did not result from recent conversions of uninhabited Wildlands to Used anthromes, but rather by processes of land use intensification of Seminatural land caused by population growth. Land-systems already inhabited and used got an increasingly intensive use globally (Ellis et al., 2020). Currently, over half of the terrestrial biosphere has already been transformed into Used Anthromes by human populations and their use of land (Ellis et al., 2020).

To date much of the research on the Anthropocene has focused on interpreting past and present changes, while saying little about the future. Moreover, research on the future has not been sufficiently connected to past changes (Bai et al., 2015). Using the Anthrome framework as a tool for looking at future land-systems gives the opportunity to compare them with past changes.

1.4 Scenario analysis

Future global land system patterns are uncertain due to the many driving forces modifying them (Ellis et al., 2010). Many key driving forces of the future land system are complex and uncertain, ranging from socio-economic variables such as population, economy, lifestyle, pollution and urbanization to biophysical parameters such as climate, yields, the carbon cycle and hydrological cycle at multiple scales. Since the global population, income, and food consumption have continued to increase over the past decades it is expected that the human impacts on the Earth System will do so too (Doelman et al., 2018). Their actual interactions will only reveal as the future unfolds (O'Neill et al., 2020).

Scientists use scenario approaches to deal with such uncertainty, and a range of futures have emerged with the design of the Shared Socio-economic Pathways (SSPs) that can be simulated with Integrated Assessment Models (IAMs). The SSP framework contains a wide range of futures by using five scenarios, outlining narratives and projections for the main socioeconomic drivers: population, education, urbanization and economic development. For example, SSP1 describes a gradual shift towards sustainable development, whereas SSP3 pushes the world to focus on national/regional issues (O'Neill et al., 2017). SSPs are widely adopted by many research communities (O'Neill et al., 2020). By also taking into account mitigation targets based on the Representative Concentration Pathways (RCPs) (Riahi et al., 2016), IAMs simulate the interactions between future human mitigation activities and the environment (Stehfest et al., 2014).

The future timing, extent and severity of land-system changes are unknown due to the uncertainty of socio-economic developments and their interactions with the environment. SSP-RCP scenarios can be used to quantify and compare the possible consequences of distinct socio-economic development patterns. This can help in anticipating if, when and where Earth Systems are likely to collapse. To date, the SSPs have been used to obtain future terrestrial scenarios of human land use (Chen et al., 2020), habitat ranges (Beyer & Manica, 2020), urban area (Gao & O'Neill, 2020), population (Jones & O'Neill, 2016) and agricultural land (Doelman et al., 2018; Popp et al., 2017). However, these studies tend not to delve deeper into the human-environment interactions.

1.5 Problem definition

Land systems steer and are steered by general, broad-scale economic, political, cultural, and environmental processes (Verburg et al., 2009). Without understanding the type, timing, magnitude and place of change in human-land interactions, adequate preparation and planning for transformation of human-environment systems is unachievable. Failing to do so could end up in collapses of land systems with global consequences for food, fuel, fibers and many other ecosystem services that support production functions, regulate risks of natural hazards, or provide cultural and spiritual services (Verburg et al., 2015). Understanding land-system change is essential to be able to design strategies to address sustainability challenges, such as climate change, food security, energy transition and biodiversity loss (Meyfroidt et al., 2019). Earth System transformations threaten to expose people, especially poor, vulnerable and marginalized communities, to unprecedented risk and harm. Climate change has been an example of global change with local impacts (Biermann, 2020). Building a better future requires the ability to anticipate how humans and the environment are linked across scales, and an understanding of how to shift these coupled systems to get towards a more desirable Earth System state (Bennett et al., 2016).

The biggest challenge in getting to such a position is to understand socio-economical pathways as the least predictable, but at present also the most influential component of our planet in the Anthropocene (Donges et al., 2017). The anthrome framework together with a scenario approach facilitates in exploring future human-environment interactions on global and regional level (Ellis et al., 2010). By combining Anthromes framework with a scenario framework, future Land system dynamics, where people and land are inherently connected, become clear, taking into account uncertainties.

1.6 Research objective

In this thesis, the change in human-environmental interactions will be investigated through Anthrome perspective over time and space with a global and regional scale. Hence, the Anthrome methodology created by Ellis et al. (2010, 2020) to analyze past land-system change is a basis for future land-system change analysis. The data used in this thesis will be based on SSP-RCP scenarios in order to explore a range of socio-economic futures.

The two objectives of this study are of methodological, descriptive and exploratory nature:

- Developing future Anthromes time-series for the full set of SSPs, drawing upon existing work on Anthromes (e.g. Ellis et al., 2020; Ellis et al., 2010).
- Exploring and describing land systems change, considering variation of SSP-RCP scenarios, to gain insight in land change through space and time, and defining future research directions.

The research is guided by the over-arching question: *'How do land-systems change under diverging human-land interactions up to 2100?'*

This will be answered through two sub-questions:

1. Globally, how will Anthromes change under different scenarios?
2. Regionally, where and when are those changes projected to happen under different scenarios?

1.7 Scientific relevance

The Earth System is influenced by humans in such a way that it has major implications for both Earth System science and societal decision making (Steffen et al., 2018). Even though it is widely accepted that humans are the dominant driver of Earth System change (Crutzen, 2002; Steffen et al., 2007), there is limited scientific understanding of coupled human and ecological systems (Ellis & Ramankutty, 2008). Anthromes provide a simple yet useful framework for assessing future modification of land by humans (Ellis et al., 2010).

By classifying and mapping future Anthromes, this research expands upon previous efforts in mapping historical and current global ecological patterns created by humans. Investigating future anthromes through a scenario perspective will add to the growing body of literature on socio-ecological systems and scenario analysis. By utilizing the highly-used SSP-RCP scenario framework for land-system change, this thesis adds to a larger body of scenario-based Earth System research of IAM modellers, climate modellers, and vulnerability, impact and adaptation researchers, since land-systems are a crucial interface between these fields (Doelman et al., 2017).

An exploration of the world's future anthromes would be a critical advance for efforts to understand and anticipate human–environment system response to forces of change (Ellis & Ramankutty, 2008). Even though the ability to observe global patterns of land cover through remote sensing have advanced, the causes of these patterns and their dynamics are not directly observable from above, or even from the ground (Ellis et al., 2010). To enhance understanding of the human-environmental systems, intensive local research is necessary, but that is costly and time-consuming. Therefore, global studies are required to allocate places for further local research effectively (Ellis et al., 2010). Exploring future change in Anthromes serves both as an aid in selecting local cases for observation and in gaining insight to general interactions between humans, land-systems and the Earth System as a whole. Ultimately, it contributes to a better understanding of the Anthropocene perspective.

1.8 Societal relevance

Exploring future Anthromes for five SSPs globally and regionally plays an important role in alerting not only scientists but also decision makers to potential future risks and opportunities of changing human-environment interactions at a global and regional level. In the Anthropocene, systems of people and nature are intertwined across temporal and spatial scales (Folke et al., 2021b). Although developing countries are experiencing most rapid land use change driven by population growth and the lifestyle changes that result from e.g. income growth (Hasan et al., 2020), land-system change is a global phenomenon.

The interdependencies and complex webs of interaction between social networks of humans and environment give rise to many impacts (Fuentes & Baynes-Rock, 2017), which reinforce one another (e.g. biodiversity loss, food insecurity, degradation of ecosystem services, and unsustainable development) (Stehfest et al., 2019). Anno 2021, an example of broad and current interest is that growing human-environmental interactions have increased disease transmission because of deforestation, forest/habitat fragmentation, agricultural development and irrigation, and urbanization (Gottdenker et al., 2014). Hence, it is argued that the increased interactions between humans, wildlife and domestic animals have also favored the all-disrupting insurgence of the COVID-19 pandemic (Rulli et al., 2020). The rapid spread of the corona-pandemic exposes the intertwined world of people and planet. Together their interactions shape the preconditions for civilizations (Folke et al., 2021b). Mapping when and where future interactions between humans and the environment will occur or intensify will help to understand, predict, prevent, and manage land use change-related issues like disease emergence (Gottdenker et al., 2014). Understanding of feedbacks between social and ecological systems is relevant to keep impacts of direct anthropogenic pressures on natural systems well within safe ecological limits (Mastrángelo et al., 2019).

Yet while the Anthropocene perspective reflects the type, scale and timing of human impacts on the Earth, its societal significance lies in how it can be used to explore and guide attitudes, choices, decisions and actions (Bai et al., 2015). Integrated action, such as the Sustainable Development Goals (SDGs), is required since many past protocols and agreements failed in reducing humanities global environmental influence (Castree, 2021). Also, understanding human-environment interactions and feedbacks are key knowledge gaps for achieving the SDGs (Mastrángelo et al., 2019), while staying within the PBs (Steffen et al., 2015). Identifying and recognizing the urgency and location of risk can support the development of proactive strategies to reduce impacts (Alessa & Chapin, 2008). Using a wide set of scenarios will explore how socio-economic effects can shape the land-system and what favorable socio-economic pathways can look like. By deploying decadal projections, this thesis will take into account both long term but also near-term temporal dynamics, useful for decision-makers who are concerned with managing more immediate risks (Trisos, Merow, & Pigot, 2020).

The thesis starts with a description of the research framework (2.1) followed by a description of the scenario approach (Section 2.2) Anthrome framework (Section 2.3) and subsequent data processing (2.4) and analysis (2.5) of the future Anthromes is explained. Next, results of land-system dynamics for the scenarios are presented on a global (Section 3.1) and regional scale (Section 3.2). Finally, conclusions, limitations and future research are discussed.

2. Research Method

2.1 Research framework

To answer the main research question, a scenario and Anthrome framework were combined (Fig. 1). Anthromes were mapped per scenario for each decade until 2100. Hence, the Anthromes classification algorithm (Ellis et al., 2020) will be utilized to create the six broad Anthrome classes and corresponding specific classes. Input to this algorithm originated from three models, which are all based on the same socio-economic scenarios:

1. Integrated Assessment Model (IAM): IMAGE 3.0 (van Vuuren et al., 2016)
2. Spatial model for urban area: Spatially-Explicit, Long-term, Empirical City development (SELECT) (Gao & O'Neill, 2020).
3. Parameterized gravity-based downscaling model for population density (Jones & O'Neill, 2016)

IMAGE 3.0 is an IAM that simulates the interactions between human activities and the environment (Stehfest et al., 2014), to explore long-term global environmental change and policy options in the areas of climate, land and sustainable development. The framework comprises a number of sub-models describing land use, agricultural economy, the energy system, natural vegetation, hydrology, and the climate system (Doelman et al., 2018). In the IMAGE model, interactions and feedbacks with the environment and humans generate many variables, including land use (e.g. urban, crops, pastures, irrigated and rice) (Stehfest et al., 2014).

For SELECT, decadal change in the fraction of urban land was estimated using temporally evolving spatial drivers from the SSP narratives (Gao & O'Neill, 2020). A unique part of the model was trained for each of the 375 sub-national regions using drivers and parameters most relevant for explaining the region's observed change in spatial urban land patterns and reflecting their respective past patterns.

Jones & O'Neill (2016) generated spatial population density change quantitatively consistent with national population and urbanization projections under the SSPs and qualitatively consistent with assumptions in the SSP narratives regarding spatial development patterns (Jones & O'Neill, 2016).

The Anthromes will be used as the basis for a spatiotemporal scenario analysis of land system change. Global Anthrome change (SQ1) will be elaborated by investigating which anthrome (sub)classes change as fractions of all terrestrial land per decade for each scenario. Regional Anthrome change (SQ2) will be examined by comparing the fractions of Anthrome (sub)classes for seven regions (North America plus Australia & New Zealand, Africa, Latin America & Carribean, Near East, Asia & Oceania, Europe, Eurasia).

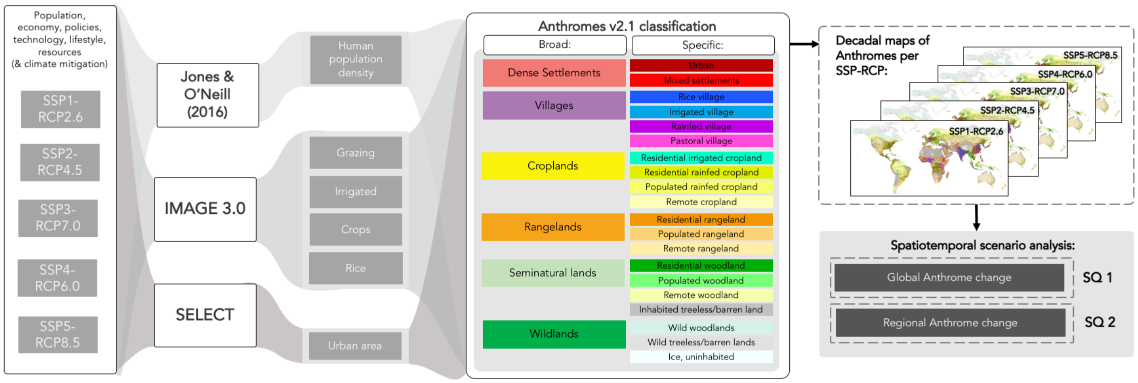

Figure 1. Research framework depicting the structure to be able to answer the research question (RQ) and sub questions (SQ). Starting left, there are five SSP-RCP combined scenarios that form the socio-economic basis for three individual models to create the input for the Anthromes v2.1 classification. For each scenario, spatiotemporal data aids in answering the sub questions (SQ) and research question (RQ).

2.2 Scenario approach

In this research, a scenario approach was adopted to account for the uncertainty of driving forces of global change, such as population and income development, technology development, lifestyle change and evolving production and consumption patterns (van Vuuren et al., 2016). Scenario analysis has been a key component of global change research for more than four decades to explore and characterize uncertainty in complex socio-ecological systems. Scenarios give the opportunity to explore how the future may evolve under a range of alternative conditions. A typical approach to model-based scenario analysis is to compare the results of two or more scenarios, to investigate the similarities and differences. These can emerge due to differing policies (mitigation or adaptation), alternative assumptions about a drivers (e.g. population growth) or climate change impacts (climate effects on crop yield) (O'Neill et al., 2020).

The Shared Socio-economic Pathways (SSPs) form a widely adopted global scenario framework with five scenarios that together describe a wide set of plausible trends in the evolution of humans and environment until 2100, in the absence of climate change or climate policies (O'neill et al., 2016; Riahi et al., 2016). They are aimed to reflect different socio-economic futures and the subsequent challenges to mitigation and adaptation. SSP1 describes a future pathway with low challenges for both adaptation and mitigation, whereas in SSP3 both are high. Next, two narratives are describing a future in with either high challenges to mitigation and low challenges to adaptation in SSP5, and the opposite in SSP4. The fifth narrative (SSP2) describes medium challenges of both to represent a future in which development trends are not extreme in the two dimensions, but rather follow 'middle-of-the-road' (Popp et al., 2017) (table 1).

Table 1. Scenario specific characteristics of drivers connected to land system change. Derived from (Doelman et al., 2018; Gao & O'Neill, 2020; Jones & O'Neill, 2016; Popp et al., 2017).

Type	*SSP1 – Sustainability*	*SSP2 – Middle of the road*	*SSP3 – Regional rivalry*	*SSP4 – Inequality*	*SSP5 – fossil-fueled development*
General: *(Popp et al., 2017)*					
Mitigation	Low	Medium	High	Low	High
Adaptation	Low	Medium	High	High	Low
Population (billion) (2050/2100)	8.5/7.0	9.2/9.1	10.0/12.8	9.2/9.5	8.6/7.4
GDP (thousand 2005 US$ per capita)	81	59	22	38	139
Population growth: *(Jones & O'Neill, 2016)*					
High fertility	Low	Medium	High	High	Low
Other low fertility	Low	Medium	High	Medium low	Low
Rich low fertility	Medium	Medium	Low	Medium low	High
Spatial pattern	Concentrated	Historical patterns	Mixed	Mixed	Sprawl
Urbanization level: *(Gao & O'Neill, 2020)*					
Urbanized	Low	Medium	Low	Medium	High
Steadily urbanizing	Low	Medium	Low	Medium	High
Rapidly urbanizing	medium	Medium	Low	Low	High
Land use: *(Popp et al., 2017)*					
Land use change regulation	High	Medium	Low	High (low for lower income)	Medium
Land productivity growth	High	Medium	Low	High (low for small-scale farming)	High
Environmental impact of food consumption	Low	Medium	High	Low (high for elite)	High
International trade	Medium	Medium	Low	Medium	High
Globalization	Medium	Medium	Low	Low (high for elite)	High
Land-based mitigation policies	High	Medium	Low	Medium	Low

The type and magnitude of the mitigation and adaptation challenges an SSP faces, is driven by more detailed narratives, of which the land system specific assumptions are summarized in Table 1 (e.g. population growth, urbanization level and land use). In short, SSP1 sees a gradual shift to more sustainable development, respecting environmental boundaries. Land-use is strongly regulated through global institutions. In SSP2, the world will keep on having historical patterns of social, economic and technological trends. Land use change is incompletely regulated. (e.g. tropical deforestation continues, though slowly declining over time). SSP3 describes a future where nationalism, competitiveness and conflicts cause a focus on domestic/regional issues. Weak global institutions imply hardly any land-use regulations. In SSP4 inequality between high and low income increases across and within countries (e.g. due to low investments in human capital). This also means land-use regulation is strong for high income countries, while low in low income countries. Lastly, SSP5 pushes the world towards more economic and social development, exploiting fossil fuel resources and creating energy intensive lifestyles around the world. Land use change is regulated incompletely (O'Neill et al., 2017; Popp et al., 2017).

The SSPs can be combined with different long-term mitigation targets based on the Representative Concentration Pathways (RCP) in IAMs like IMAGE. Together they produce a scenario matrix (Fig. 2) that allows assessment of different climate policy strategies (Riahi et al., 2017; van Vuuren et al., 2012). The RCP's correspond to radiative forcing levels; a measure of the effect of emissions and greenhouse gases on Earth's energy balance and global average temperature. They reflect the ability and efforts to mitigate climate change (e.g. a higher RCP indicates a higher probability of more global warming due to less mitigation policies) (van Vuuren et al., 2012).

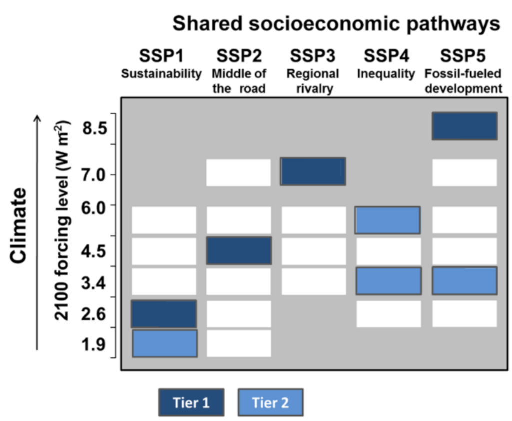

Figure 2. SSP-RCP scenario matrix illustrating IAM simulations. Each cell in the matrix indicates a combination of socio-economic development pathway (i.e., an SSP) and climate outcome based on a particular forcing pathway (RCP) that current IAM runs have shown to be feasible. Each upper block per scenario is the 'Baseline scenario' without any climate mitigation policies. Dark blue cells indicate scenarios that serve as the basis for climate model projections (Tier 1); light blue cells indicate extra scenarios (Tier 2). Matrix altered from O'Neill et al. (2016).

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Each SSP has a ‘baseline’ RCP outcome to describe the world without mitigation policies (the upper ‘block’ for each SSP in Fig. 2). The reduction of global warming (i.e. a lower RCP) can be achieved through a wide set of measures in the energy, industry and land-use sectors. Examples are the switch from fossil-fuels to cleaner alternatives, carbon capture and storage, measures reducing both agricultural fertilizer use and deforestation (Riahi et al., 2017).

Mitigation efforts required to achieve a specific RCP are path dependent. For every SSP, achieving lower forcing levels than the baseline imposes greater mitigation costs and thus challenge. Moreover, the size of the challenge also depends on the SSP being followed (Van Vuuren et al., 2013). Costs for mitigation towards RCP4.5 (e.g. global warming likely to be 1.1°C -2.6°C by the end of the 21st century (2081-2100) relative to 1986-2005) are found to be lower in SSP1 & SSP4 relative to SSP3 & SSP5 (Riahi et al., 2017). The lack of structural changes in the narrative of the latter two scenarios translate into the need for comparatively higher mitigation efforts to achieve a low RCP.

Scenario selection

For this research, five SSP-RCP combinations were selected based on three conditions. Firstly, not every SSP-RCP combination is capable of being attained (O’neill et al., 2016). Under the specific socioeconomic and policy assumptions of the specific SSP scenario, some mitigation targets cannot be achieved (e.g. SSP3-RCP2.6), due to the previously mentioned path-dependency (Riahi et al., 2016). Secondly, to capture a wide range of possible futures, not only all five SSPs were selected to analyze, but they were also combined with diverging RCPs. This created a range of possible futures that facilitate the representation of uncertainty of the development of driving forces and possible climate actions. Thirdly, the selected RCPs provide a link between the relatively new SSPs and the earlier developed RCPs developed in the initial phase of the community scenario process (Riahi et al., 2017). The final selection therefore is:

- SSP1 – RCP 2.6: this scenario represents the low end of the range of future forcing pathways in the IAM literature. It is anticipated that it will produce a less than 2°C warming by 2100 due to climate mitigation policies (O’neill et al., 2016).
- SSP2 – RCP 4.5: this scenario represents the medium part of the range of future forcing pathways and entails some mitigation policies to try to remain below 3°C warming by 2100 (O’neill et al., 2016).
- SSP3 – RCP 7.0: this baseline scenario represents the medium to high end of the range of future forcing pathways (O’neill et al., 2016).
- SSP4 – RCP 6.0: this baseline scenario fills in the range of medium forcing pathways (O’neill et al., 2016).
- SSP5 – RCP 8.5: this baseline scenario represents the high end of the range of future pathways in the IAM literature. It is the only SSP scenario with emissions high enough to produce a radiative forcing of $8.5Wm^2$ in 2100. (O’neill et al., 2016).

2.3 Anthromes method

To identify the most significant global patterns of human-land interactions, Ellis and Ramankutty (2008) applied a statistical cluster analysis to global data for human populations, land use and vegetation cover. It fitted Anthrome classes to patterns in the land system investigated. This created optimal but data- and time-specific classification thresholds, differing when time or data changes. To allow Anthromes to be classified over time, this approach was later updated using a rule-based methodology by Ellis et al. (2010) and slightly updated by Ellis et al. (2020) to Anthromes v2.1 (Fig. 3). Standardized land cover (urban, crops, grazing and pasture area) and population density thresholds were created. The dominant land cover threshold for urban, crops, grazing and pasture area was standardized at 20% (e.g. if >20% of the area is cropland, it is classified as that broad Anthrome). Together with standardized thresholds for population density, (urban, > 2500 persons/km^2; dense, > 100 persons/km^2; residential, 10–100 persons/km^2; populated, 1 -10 persons/km^2; remote; < 1 persons/km^2; wild, 0 persons/km^2), the specific Anthromes were classified using a Python3 script.

The future Anthromes dataset was computed for all 50 scenario-time points (5 SSP-RCPs x 10 decadal steps) by applying the Anthromes v2.1 classification to the input data using a custom Python3 script. The future-looking and scenario-based nature of this research required two major adjustments to the rule-based classification of Anthromes v2.1 by Ellis et al., (2020). Firstly, the IMAGE 3.0, SELECT and POPD datasets were utilized to substitute historical data. Also, fixed biome data was replaced by future, scenario-based biome data from IMAGE 3.0. These adjustments in input and subsequent necessary changes to the existing Python3 script lead to an updated classification algorithm. The custom Python3 script used in this thesis is provided in Annex 1.

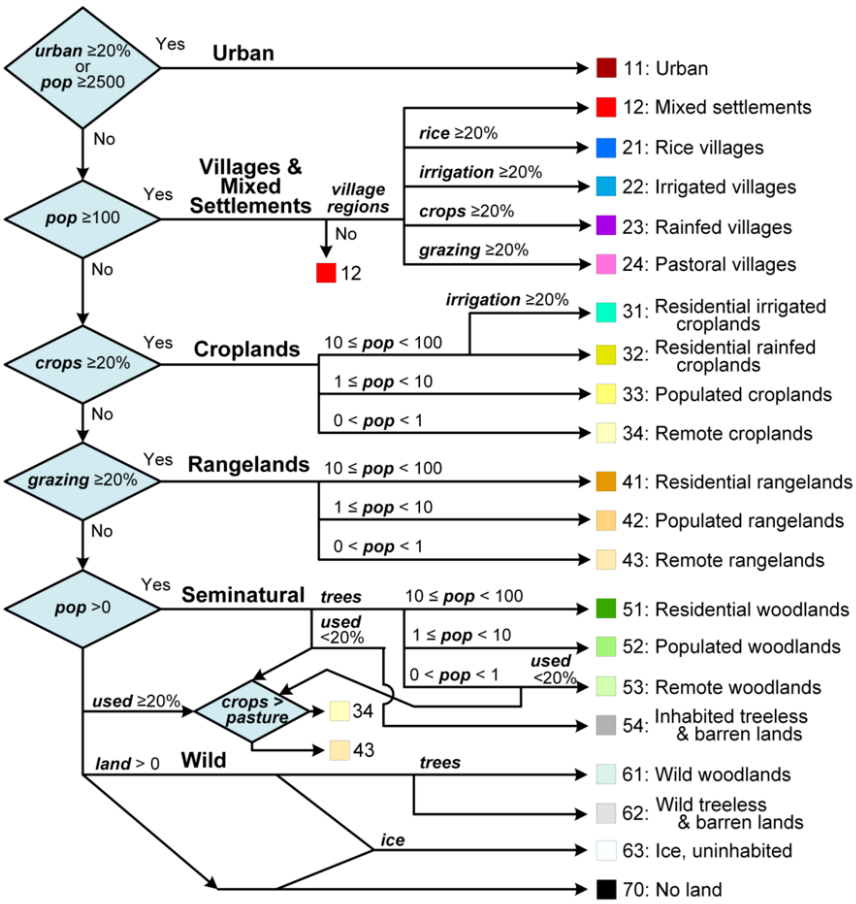

Figure 3. Anthromes v2.1 classification flowchart as created and used by Ellis et al (2020). Six broad Anthromes are labelled in large bold text (Dense settlements, Villages, Croplands, Rangelands, Seminatural lands and Wildlands), group 20 specific Anthrome classes (color coded boxes). Data inputs to the model are in italics: urban = % urban land cover, pop = population density (persons km2), rice = % cover by rice, irrigation = % land area irrigated, crops = % area covered by crops, grazing = % area covered by pastures and rangeland, used = urban + crops + grazing, trees = areas potentially covered by trees, is based on the 8 forest and woodland biomes in Prentice et al. (1992), village regions = regions with a history of agricultural village development (cells outside North America, Australia and New Zealand), land = cells with land area, ice = cells covered with permanent ice. Diagram copied from Ellis et al. (2010).

2.4 Data sources and processing

To be able to create future Anthromes until 2100 for each scenario, several global spatial datasets were used. All required datasets are summarized in Table 2. As a base, a global land map and region classification were sourced from previous work on Anthromes (Ellis et al., 2020, 2010). To classify the future Anthromes, four datasets were used. Both classic biomes (GNLCT) and land use data (GFRAC) were sourced from the IMAGE3.0 model (Doelman et al., 2018; van Vuuren et al., 2016). Population density (Jones & O'Neill, 2016) and percentage of Urban area (Gao & O'Neill, 2020) were used as well.

Every dataset required some processing before being functional in the Anthromes classification algorithm. 'GNLCT' from IMAGE 3.0 is necessary to define areas covered by trees and ice. It consists of 14 classes that were reclassified in RStudio to obtain 'trees' and 'ice' (Table 3). 'GFRAC' consists of 19 crop types (Table 4). For the Anthromes classification, 'crop', 'irrigated', 'grazing' and 'rice' area are required. RStudio was used to reclassify GFRAC into those four input datasets; 'grazing', 'irrigated', 'crops', and 'rice'.

Scenario-based spatial projections were produced for each of the five SSPs in 5 arc minutes resolution covering global land at 10-year intervals throughout the 21st century in WGS84 coordinate system. The choice of the resolution was made for consistency with earlier work (Ellis et al., 2020; Ellis et al., 2010). For the latter two datasets of Table 2, the resolution was changed. Two resampling operations had to be done to obtain homogenous resolution throughout the input datasets. Firstly, Population density (POPD) and Urban area (SELECT) have a 1/8th degree resolution and were therefore resampled using bilinear interpolation in RStudio. Bilinear interpolation resampling takes a weighted average of 4 pixels in the original image nearest to the new pixel location. It is suitable for continuous data like population density. The averaging process alters the original pixel values and creates entirely new digital values in the output image (Baboo & Devi, 2010). Secondly, GNLCT has a 30 arc minutes resolution and consists of 14 classes. To obtain 5 arc minute resolution, it was resampled using Nearest Neighbour method. It is the best resampling method for categorical data like land-use classification because it preserves the original values (Baboo & Devi, 2010). This resampling uses the exact value from the pixel in the original image, which is nearest to the new pixel location in the corrected image. Also, all datasets were converted into ASCII raster files, as this is the input file type that the Anthromes v2.1 algorithm requires. The final inputs to the Anthromes algorithm are depicted in Fig. 4.

Table 2. Global spatial data for research use

Type	*Datasets*	*Source*
Base data	Land area per 5 arc minute grid cell (ASCII)	(Ellis et al., 2020) *Anthromes v2.1*
Regions	Region classification	*(Ellis et al., 2010)*
Classic biome map	Global Natural Land Cover Type (GNLCT) (NetCDF4)	(van Vuuren et al., 2016) *IMAGE 3.0*
Land use	Global Fractions containing crop and pasture areas (GFRAC): (NetCDF4) % Crop area % Grazing area % Irrigated area % Rice area	(van Vuuren et al., 2016) *IMAGE 3.0*
Population	Population density (people per m^2) (ASCII)	*(Jones & O'Neill, 2016), POPD*
Urban Area	% Urban area (NetCDF4)	(*Gao & O'Neill, 2020), SELECT*

Table 3. Biome types from IMAGE 3.0 'GNLCT'. Green is grouped as 'trees' group and grey is grouped as 'ice' group. Other classes are not used.

	Biome type IMAGE		
1	Ice	8	Warm mixed forest
2	Tundra	9	Grassland/steppe
3	Wooded tundra	10	Hot desert
4	Boreal forest	11	Scrubland
5	Cool conifer forest	12	Savanna
6	Temp. mixed forest	13	Tropical woodland
7	Temp. deciduous forest	14	Tropical forest

Table 4. Crop types used and grouped from IMAGE 3.0 GFRAC.

Grazing	*Rice*	*Crops*	*Irrigated*
Grass	Rainfed rice	Temperate cereals	Irrigated temperate cereals
	Irrigated rice	Rainfed maize	Irrigated maize
		Rainfed tropical cereals	Irrigated tropical cereals
		Rainfed pulses	Irrigated pulses
		Rainfed roots and tubers	Irrigated roots and tubers
		Rainfed oil crops	Irrigated oil crops
		Sugar cane	Irrigated rice
		Woody biofuels	
		Non-woody biofuels	
		Rainfed rice	
		Irrigated rice	

a.
b.
c.
d.
e.
f.

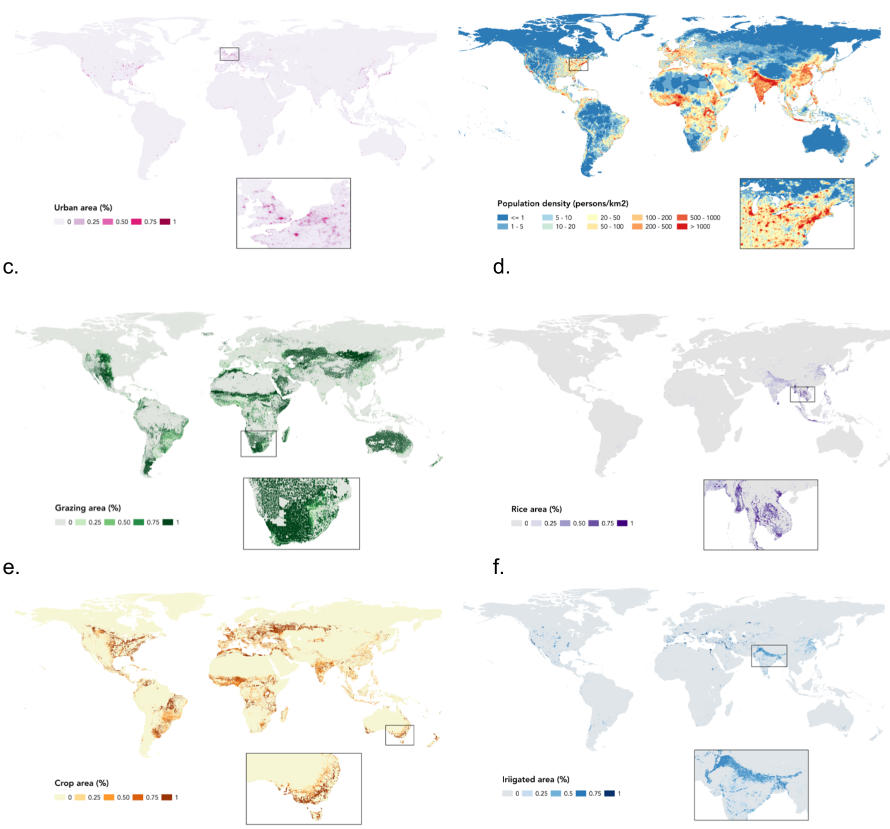

Figure 4. Example maps of final data sources for SSP1-RCPX in 2100. %Urban area (a), population density (b), %grazing (c), %rice (d), %crops (e) and %irrigated (f). Subset maps are included to show details.

2.4 Data analysis

After obtaining the Anthrome classifications as rasters for each SSP-RCP and decade, data analysis thereof was done. Spatial and temporal dynamics of Anthromes were assessed using RStudio, QGIS and Python at two scales; global and regional. Applied region boundaries are the same as Ellis at al. (2010): North America, Australia & New Zealand, Africa, Latin America & Caribbean, Near East, Asia and Oceania, Europe, and Eurasia (Fig. 5). Mind that Asia & Oceania does not contain Australia and New Zealand. The terrestrial land area that these regions cover varies from ~3.9 million km^2 (Europe), 11.0 million km^2 (Near East) to regions at least double this size and the largest being ~27.3 million km^2 (North America, Australia & New Zealand). Therefore, results of absolute area of the grouped Anthromes are accompanied by percentages relative to the relevant regions total terrestrial land area.

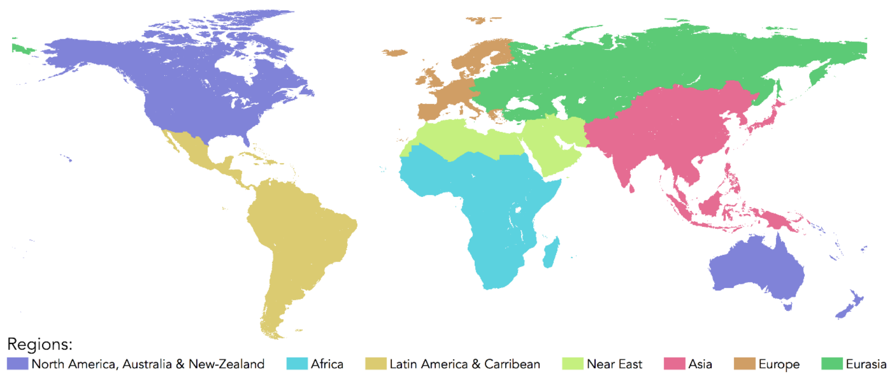

Figure 5. Region boundaries applied for analysis of regional Anthromes. Modified from Ellis et al. (2010).

To assess temporal and spatial dynamics, the global and regional raster files of Anthromes per scenario and decade were analyzed by creating maps and figures in QGIS and RStudio. For the maps, raster files were coloured according to their Anthrome class. For the figures, RStudio was used to translate the amount of cells per Anthrome into amount of area in km^2 using cell land area. Next, on global and regional level, the percentages of area (in km^2) per Anthrome class per decade were obtained by counting the amount of area per Anthrome class and dividing it over the total amount of land area.

To assess the type and timing of change, the Anthrome class for each cell was listed for decades 2010, 2050 and 2100 per SSP. A cell can either stay the same class or change to another class, creating a class type sequence for each cell (e.g. from wild in 2010, to seminatural in 2050 and staying seminatural in 2100). Next, all unique sequences were counted to create a list of the number of types of change with their subsequent area. This list was fed into a Python visualization script to create sankey diagrams, using the Plotly Python library.

To assess place of change, a separate map of each region was created. Next, regional summaries of the classified Anthromes were made using zonal statistics in QGIS. These statistics were combined into charts for all scenarios and selected time frames using Python.

To assess timing of change, the decade of first change in Anthrome class was determined by subtracting the class for a given decade by its value in the previous decade. Whenever the result was not zero, a change occurred in that cell during that decade and it was therefore assigned the value of that decade. Performing this calculation for each decade, produced a global raster with land cell values ranging from 2020 to 2100, or zero if there was no change in Anthrome class up until 2100. Maps were created from the raster files using QGIS. Next, the area in km^2 changing per decade was calculated per region to be able to analyze the regional differences in speed of Anthrome change.

3. Results

3.1 Future Anthromes

By the end of the century, the composition of global broad Anthromes changes relatively little compared to 2010 (Fig. 6a, Table 5(in bold)). The future division of Used versus Seminatural and Wild Anthromes on Earth's terrestrial lands does show some notable changes between the scenarios. The share of Used Anthromes (sum of Dense Settlements, Villages, Croplands and Rangelands) increases for all scenarios but SSP1-2.6. The share of Wildlands does not change

Comparing the composition of broad Anthromes between 2100 and 2010, shows that SSP3-7.0 has the most distinct composition, mainly due to the increase of Village area and decrease of Seminatural land (Fig. 6a). The former increases by just over 60% and the latter decreases by close to 19% (Table 5). Contrastingly, SSP5-8.5 has the most similar composition to 2010 Anthromes. Relative increase and decrease of broad Anthrome areas are small compared to the other scenarios (Table 5)

Looking at decadal changes throughout the 21st century, a trend of expansion followed by contraction is observed for Villages in all scenarios (except for SSP3-7.0). Moreover, that type of trend is also seen for Dense settlements in SSP1-2.6 throughout the 21st century. Within broad Anthrome levels, the specific Anthrome classes also show shifts (Fig. 6b, Table 5), such as the increase of Urban area and Pastoral Villages and decrease of Inhabited treeless & barren land for all scenarios (except SSP1-2.6) and most profoundly in SSP3-7.0. Relative increase of certain specific Anthromes compared to their area in 2010 is largest for SSP3-7.0, where the area of Remote Croplands and Pastoral Villages triples and Urban area more than doubles in 2100 (Table 5). Also, Remote cropland doubles in SSP4-6.0 and Residential Irrigated Cropland loses more than a quarter of area in SSP3-7.0 and SSP5-8.5.

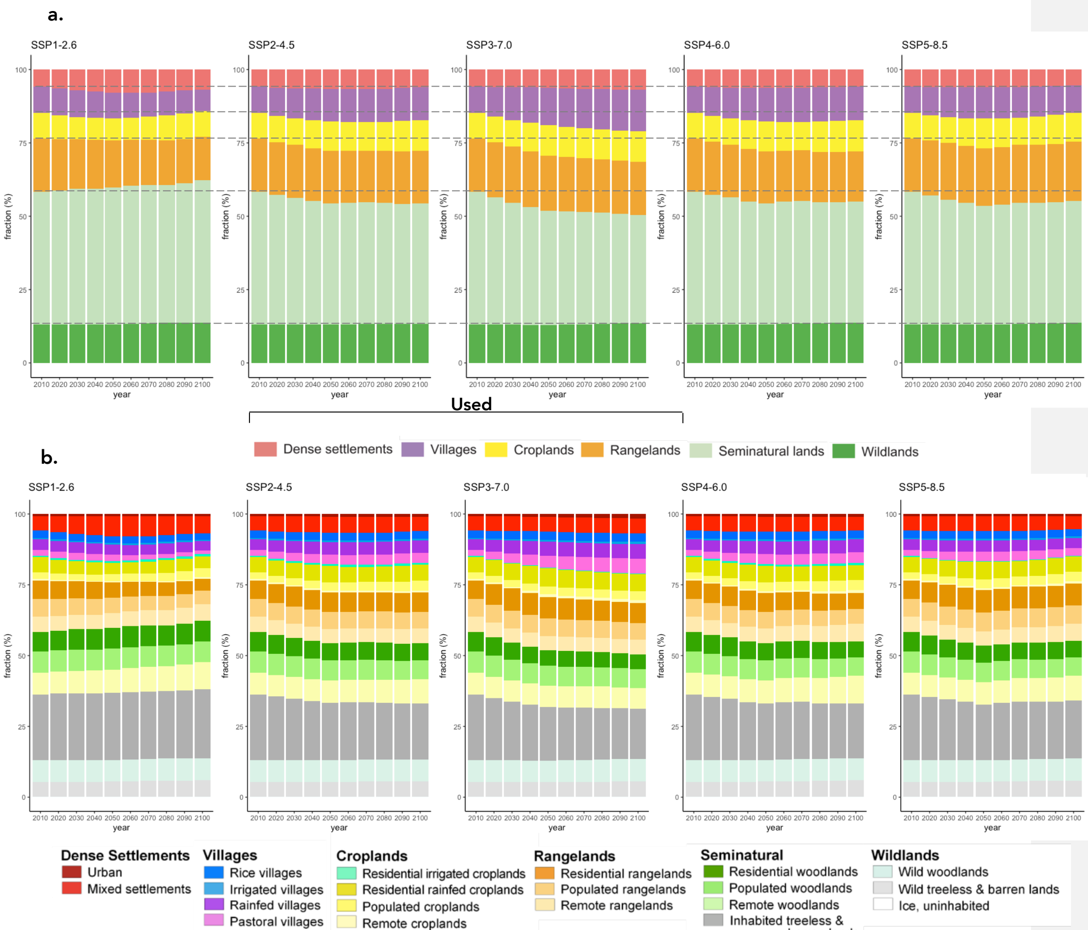

Figure 6. Change for all broad Anthromes (a) and specific Anthromes (b) per decade for each SSP-RCP combination.

Table 5. Area of broad Anthromes (in bold) and specific Anthromes in 2100 for each SSP-RCP combination, and the relative change in percentage compared to the area in 2010 (in italics).

	SSP1-2.6		SSP2-4.5		SSP3-7.0		SSP4-6.0		SSP5-8.5	
	km²	*%*	km²	*%*	km²	*%*	km²	*%*		*%*
Dense Settlements	**9,115,693**	***17.24***	**8,095,523**	***4.11***	**9,038,110**	***16.24***	**7,841,294**	***0.85***	**7,119,601**	***-8.44***
11: Urban	944,894	*2.11*	1,291,908	*39.61*	2,067,699	*123.45*	1,437,139	*55.31*	1,022,407	*10.49*
12: Mixed settlements	8,170,800	*19.28*	6,803,614	*-0.68*	6,970,411	*1.75*	6,404,155	*-6.51*	6,097,193	*-10.99*
Villages	**9,833,796**	***-16.44***	**14,769,133**	***25.49***	**18,905,028**	***60.63***	**15,088,347**	***28.20***	**12,459,543**	***5.87***
21: Rice villages	2,968,217	*-13.47*	3,608,439	*5.19*	4,053,499	*18.17*	3,414,999	*-0.45*	3,409,770	*-0.60*
22: Irrigated villages	651,375	*2.27*	823,268	*29.26*	1,081,604	*69.82*	748,310	*17.49*	717,613	*12.67*
23: Rainfed villages	4,494,939	*-8.30*	5,758,144	*17.47*	6,811,913	*38.97*	6,064,171	*23.71*	4,741,854	*-3.26*
24: Pastoral villages	1,719,265	*-38.60*	4,579,283	*63.53*	6,958,012	*148.48*	4,860,867	*73.59*	3,590,306	*28.22*
Croplands	**11,485,254**	***-1.48***	**14,113,623**	***28.18***	**14,033,393**	***20.38***	**14,154,560**	***21.42***	**13,060,737**	***12.03***
31: Residential irrigated croplands	960,196	*24.33*	989,888	*-28.81*	294,469	*-61.87*	1,042,274	*34.96*	319,238	*-58.66*
32: Residential rainfed croplands	5,688,193	*-20.54*	7,452,963	*4.11*	8,143,702	*13.76*	6,956,311	*-2.83*	7,238,836	*1.12*
33: Populated croplands	4,165,703	*34.16*	4,608,155	*48.41*	3,992,518	*28.59*	4,905,429	*57.99*	4,539,323	*46.20*
34: Remote croplands	671,163	*7.92*	1,062,617	*70.87*	1,602,705	*157.71*	1,250,546	*101.09*	963,340	*54.90*
Rangelands	**19,734,813**	***-18.63***	**23,832,255**	***-1.73***	**24,104,125**	***-0.61***	**22,780,801**	***-6.07***	**26,893,377**	***10.89***
41: Residential rangelands	5,724,461	*7.92*	8,989,907	*2.29*	9,365,751	*6.57*	7,696,121	*-12.43*	10,200,263	*16.06*
42: Populated rangelands	6,310,624	*-34.87*	7,790,766	*-5.85*	7,826,080	*-5.43*	6,766,669	*-18.23*	8,835,692	*6.77*
43: Remote rangelands	7,699,727	*-23.74*	7,051,581	*-1.90*	6,912,294	*-3.84*	8,318,010	*15.71*	7,857,422	*9.31*
Seminatural lands	**64,638,478**	***7.11***	**54,505,970**	***-9.68***	**48,992,789**	***-18.81***	**54,941,987**	***-8.96***	**55,488,018**	***-8.05***
51: Residential woodlands	9,877,046	*8.63*	7,876,018	*-13.38*	6,755,480	*-25.70*	7,613,605	*-16.27*	7,881,784	*-13.32*
52: Populated woodlands	9,573,958	*-5.79*	8,914,074	*-12.28*	9,104,326	*-10.41*	8,606,272	*-15.31*	8,473,874	*-16.61*
53: Remote woodlands	12,688,999	*25.79*	11,353,146	*12.55*	9,587,356	*-4.96*	12,847,221	*27.36*	11,760,766	*16.59*
54: Inhabited treeless & barren lands	32,498,476	*4.82*	26,362,732	*-14.97*	23,545,627	*-24.06*	25,874,889	*-16.54*	27,371,593	*-11.72*
Wildlands	**18,323,661**	***5.73***	**17,815,191**	***2.80***	**18,058,250**	***4.20***	**18,324,707**	***5.74***	**18,110,419**	***4.50***
61: Wild woodlands	10,434,805	*2.98*	10,350,436	*2.15*	10,749,960	*6.09*	10,470,133	*3.33*	10,385,365	*2.50*
62: Wild treeless and barren lands	7,772,808	*9.70*	7,352,303	*3.76*	7,196,252	*1.56*	7,738,319	*9.21*	7,609,006	*7.39*
63: Ice, uninhabited	116,048	*3.58*	112,452	*0.37*	112,039	*0.00*	116,255	*3.76*	116,048	*3.58*

3.2 Global patterns: type and timing of conversion

Although the global composition of the broad and specific Anthromes changes relatively little, change in spatial arrangement does occur (e.g. from 2010 to 2050, Cropland is converted into other broad Anthromes, but also gained from others) (Fig. 7). No broad Anthrome has a single conversion destination or origin. Principally, all broad Anthromes convert to all other in at least some part of the world, except Wildlands. The amount of area converting does differ per Anthrome, scenario and timing.

For every scenario it applies that more change is projected to occur before 2050 rather than after (Fig. 7). Zooming in to the amount of change until mid-century for each scenario shows most change happens in SSP3-7.0 until 2050 (6.30%). In the second half of the century, SSP4-RCP6.0 sees most change, although it is still smaller than the amount that most scenarios see in the first half of the century. SSP1-2.6 and SSP2-4.5 have the least amount of conversion between both 2010-2050 and 2050-2100.

Until 2050, the most changing Anthrome type is Seminatural land, converting to Rangelands, Croplands, Villages or Dense settlements for all scenarios but SSP1-2.6, which sees most change in Rangelands and Croplands converting to Seminatural lands. Also, about three times as much Village area becomes Dense settlement area in SSP1-2.6 compared to the other scenarios. Villages gain area originating from Dense Settlements, Croplands, Rangelands and Seminatural lands in a similar magnitude (except SSP1-2.6).

From 2050 to 2100, the type of conversion has a different pattern than it has in the former half of the century. Only in SSP3-7.0 and SSP4-6.0 the most converted broad Anthrome is still Seminatural land, which converts here into cropland and Dense settlements. Moreover, in this time-period Seminatural land also converts into Wildlands for SSP1-2.6, SSP3-7.0 and SSP4-6.0. Just as in the previous 50 years, for SSP1-2.6 Rangelands will convert to either Seminatural lands or Croplands more than in other scenarios. SSP1-2.6, SSP2-4.5, SSP4-6.0 and SSP5-8.5 all are projected to show a conversion of most Dense settlements towards Seminatural lands. For SSP3-7.0, most of Dense settlements conversion occurs towards Villages.

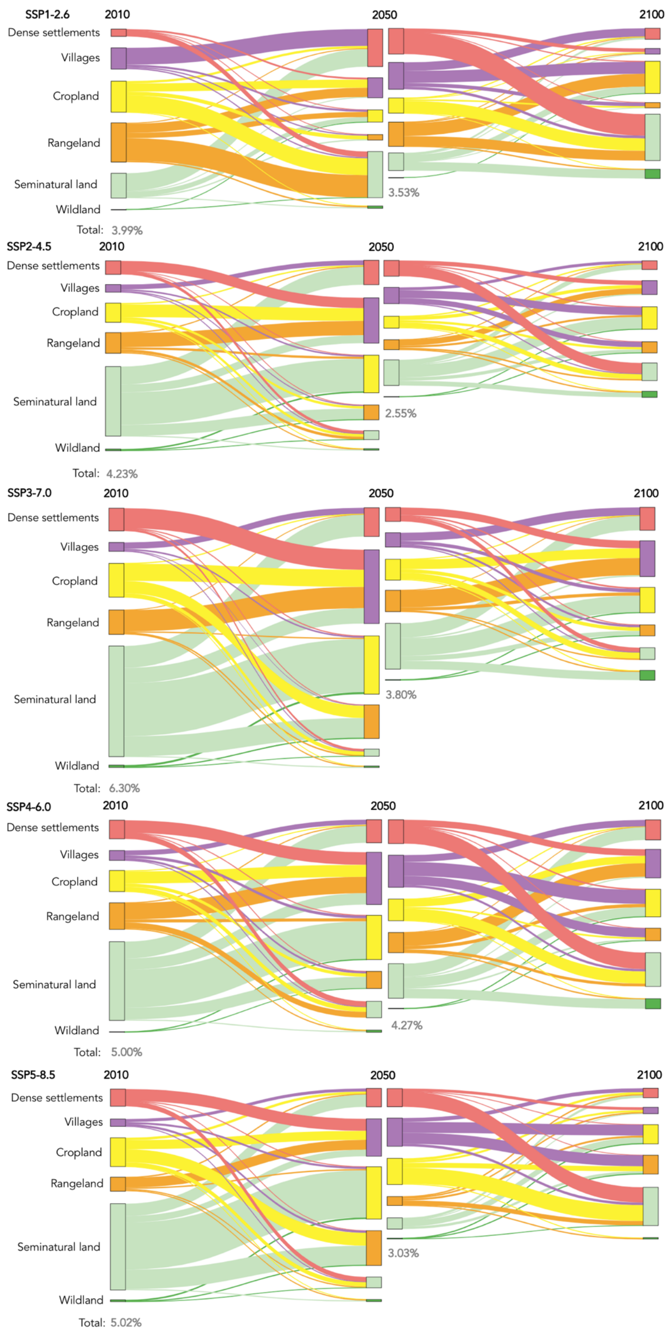

Figure 7. Sankey diagrams with the size depicting the percentage of area per Anthrome group that changes into another class globally. Change to another class is depicted in the form of colored lines towards other classes (e.g. from 2010 to 2050, many seminatural land converts into cropland in SSP3-7.0. From 2050 to 2100 even more seminatural land coverts into cropland). Area changing in 2010-2050 is not necessarily the same as area changing 2050-2100, but it may be.

3.3 Regional patterns

Current Anthromes

In 2010, broad Anthromes already differ largely per region not only in area size but also in composition (Fig. 8, Fig. 9 (left bar for each region) & Fig. 10 (2010 map)). In 2010, Earth's share of Wildlands appears predominantly in North America, Australia & New Zealand and in Eurasia. Seminatural lands are the dominant Anthrome in all regions except North America, Australia & New Zealand (Fig. 9, left bar of each region). Used Anthromes already are a large share of the total amount of land in Asia & Oceania and Europe to a lesser extent. Eurasia and Near East have are relatively small share of Used Anthromes.

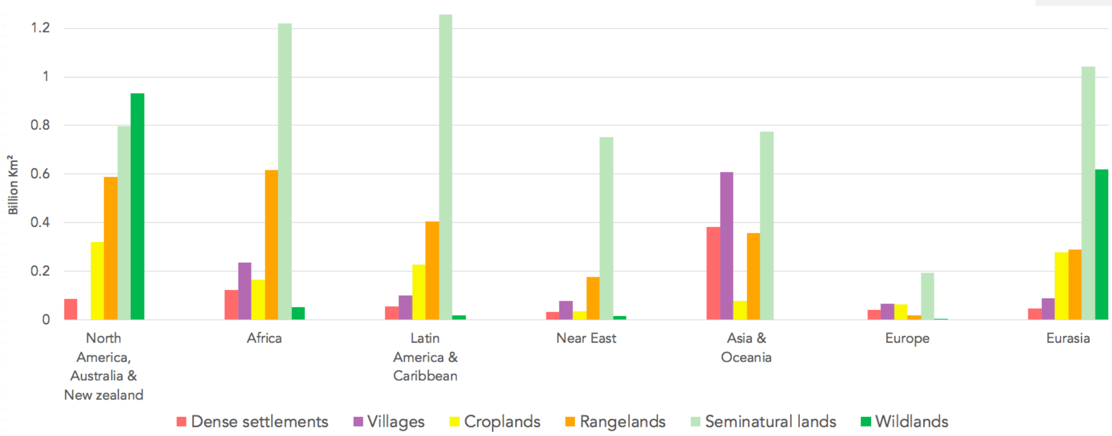

Figure 8. Absolute area per broad Anthrome in billions of km^2 for 2010. Major differences can be observed between the regions total area and Anthromes composition.

Figure 9. Change in percentage of broad Anthrome area per scenario for 2050 and 2100 compared to 2010 for North America, Australia & New Zealand, Africa, Latin America & Caribbean, Near East, Asia and Oceania, Europe, and Eurasia.

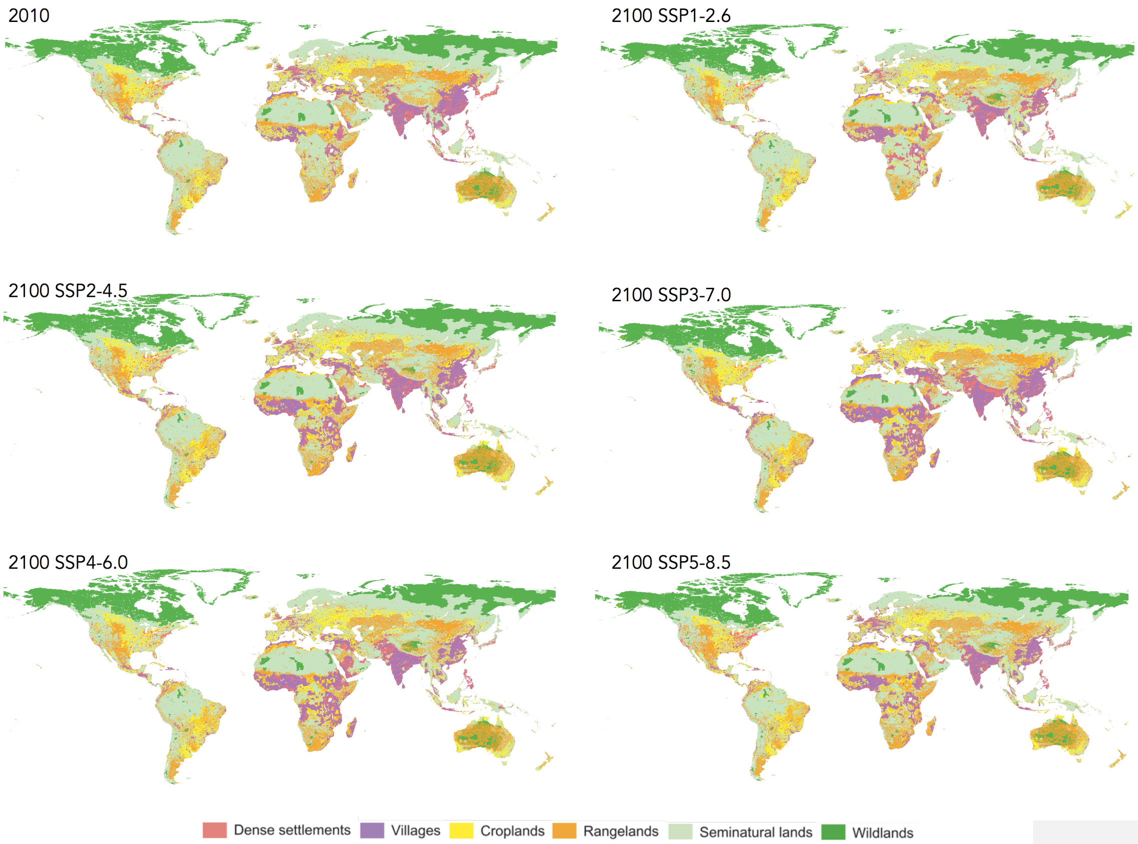

Figure 10. Mapped broad Anthrome classes of 2010 and for all scenarios in 2100 for comparison. Projection: EPSG 4326 – WGS84. Mapped specific Anthromes can be found in Appendix Figure 1.

Type of change

Assessing the future development of the share of Used Anthromes shows regional and scenario-dependent differences (Fig. 9). The spread between the scenarios is large for Africa, Latin America & Caribbean and Asia & Oceania, while smaller for the other regions (Appendix Fig. 2). For every region SSP1-2.6 sees the least amount of Used land in 2100. Relative to Used land in 2010, a decrease is observed in this scenario, except for Africa and Near East. SSP3-7.0 gives the most increase in Used lands for most regions, except for Near East and Europe.

Up until 2100, there are large regional differences in where and how much change occurs per broad Anthrome, combined with the effects of the driving scenario. Global change is concentrated in certain regions (Fig. 10, Fig. 11 & Appendix Table 1). Most absolute change as a percentage of all Earth's terrestrial land area occurs in Africa with an increase of 3.84% in km^2 of Village area and a decrease of 3.76% of Seminatural land occurring from 2010 to 2100 in SSP3-7.0. The runner-up region with most change is Asia & Oceania with a decrease of 1.37% in Village area and an increase of 1.57% in Seminatural lands for SSP1-2.6. Least amount of Earth's change occurs in Europe, due to the small size of the region compared to the other regions.

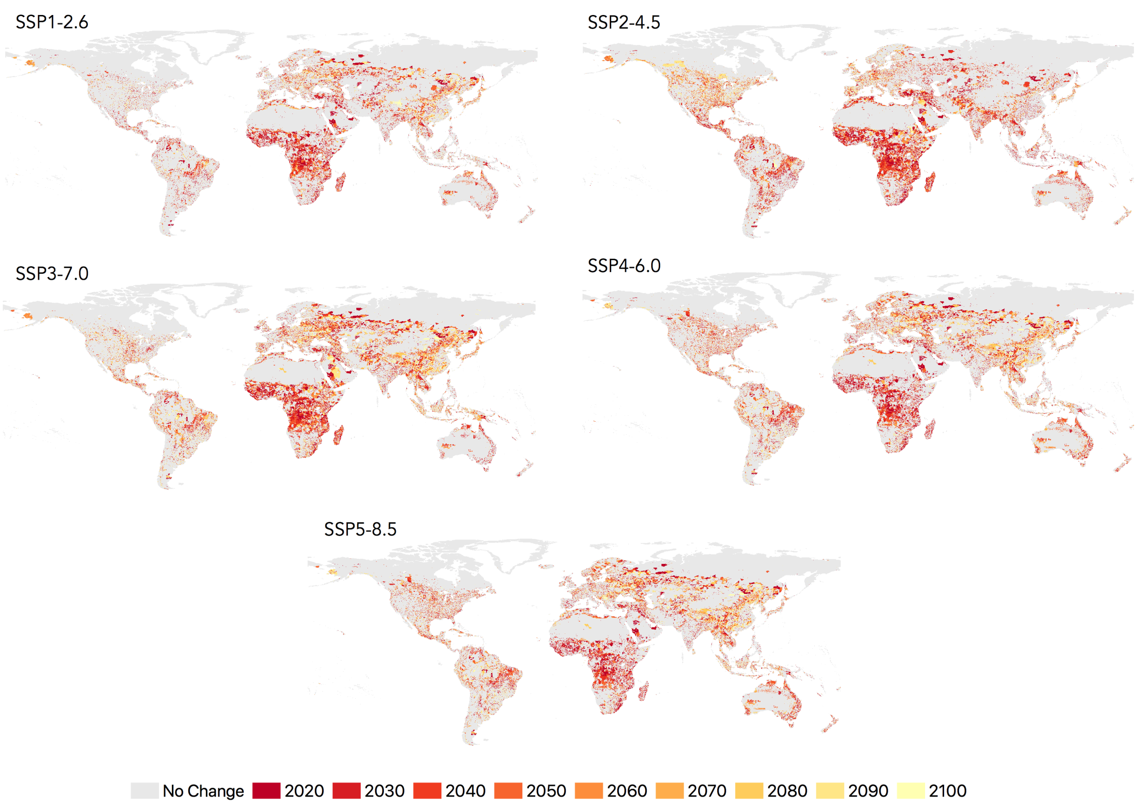

Figure 11. Place and timing of first change of specific Anthrome classes per scenario. More change can happen in that area throughout the 21st century, but first change occurs by the depicted decade. Projection: EPSG 4326 – WGS84.

Comparing relative changes as a percentage of a region's terrestrial land (Fig. 9 & Appendix Table 2) shows that Africa, Latin America, Asia & Oceania and Europe have more dynamics in broad Anthromes, while in North America Australia & New Zealand, Near East and Eurasia the Anthromes remain relatively stable. Also, the regions with more dynamics see more variation between the scenarios. Especially SSP1-2.6 and SSP3-7.0 vary largely, mainly in the amount of Village and Seminatural Anthromes. Striking is that for Africa even the scenario with least change (SSP1-2.6) still brings about more change in area than many other regions change at most.

Timing and place of change

The timing of the described dynamics varies per region and scenario. Africa already sees major changes in Anthromes in 2050 compared to 2010, and Latin America & Caribbean to a lesser extent as well (Fig. 9 & Fig. 11). In contrast, Asia & Oceania see most change occurring in the second half of the century.

Variation is not only observed between scenarios and regions, but also within regions. Observed regional change is concentrated in certain places, whereas other places do not change much compared in 2100 to 2010 (Fig. 10 & Fig. 11). Examples of places that change are West, Central and East Africa, Central America, the Arabian Peninsula, Eastern Europe, central China, Central Asia and Coastal Australia.

4. Discussion

4.1 Global human impact

Globally, land-systems have changed over the past 12,000 years, mainly due to human societies. The share of Used Anthromes has increased up until now (Ellis et al., 2020). The results from this research suggest that the future global change in the share of Used Anthromes will differ depending on the scenario driving the land system change, although this global change is of a relatively little extent. SSP narratives together with the RCP forcing's do show diverging change the type and intensity of human-land interactions. Only SSP1-2.6 sees a decrease in the share of Used Anthromes globally in 2100 (37.7% compared to 41.7% in 2010). The gradual and global expansion of forests and other natural area is fostered by the baseline SSP1 assumptions (e.g. focus on sustainable development, respecting environmental boundaries and strongly regulated land-use (O'Neill et al., 2017; Popp et al., 2017)), and amplified by high mitigation efforts to get towards RCP2.6 in 2100 (e.g. forest expansion of over 250 million ha, while about 100 million ha in SSP1 baseline) (Riahi et al., 2017). A combination of the SSP1 narrative and climate mitigation to reach RCP2.6 lead to an increase in Seminatural and Wildland, therefore contributing to staying within the Planetary Boundaries, keeping the Earth System in its current state.

Contrastingly, SSP3-7.0 sees most increase in Used Anthromes. These observations are caused by high population growth in SSP3, combined with nationalism, competitiveness and conflicts causing a focus on domestic/regional issues (e.g. weak global institutions imply hardly any land-use regulations) (O'Neill et al., 2017; Popp et al., 2017). The other scenarios do not show substantially distinct dynamics on a global level. Additionally, in all scenarios most of the observed change occurs in the first half of the 21st century, with little distinction in timing between the scenarios.

4.2 Regional human impact

Although the global composition of the Anthromes remains relatively stable for most scenarios, regional differences in dynamics of the share of Used Anthromes are sharper. Most land intensification occurs in Africa and Latin America & Caribbean, although the magnitude is depending on the driving scenario. That is, the spread of the estimated change in Used lands between the scenarios is large for these regions, thereby decreasing the certainty of future composition of land-systems.

Africa and to a lesser extent Latin America, Asia & Oceania and Europe have more dynamics in broad Anthromes, while in North America Australia & New Zealand, Near East and Eurasia the Anthromes remain relatively stable. Also, the regions with more dynamics see more variation among the scenarios than is seen with a global perspective. Especially SSP1-2.6 and SSP3-7.0 vary largely.

Lastly, there are differences in timing of Anthrome change on regional level. Africa sees a lot of change in the first half of the century. This early change, together with the magnitude and uncertainty of the change, raises difficulties in preparedness to land-system change. The other regions change more gradually over the century.

4.3 Past and future Anthrome dynamics

The main findings of this research are in agreement with previous Anthrome research of Ellis et al. (2020). The majority of past human transformation of terrestrial land did not result from conversions of Wildlands into Used Anthromes, but rather by processes of land use intensification in landscapes already inhabited and used (Ellis et al., 2020). This trend is also observed for future Anthromes, where Wildlands change only slightly, regardless of the scenario.

The results in this research show a smaller amount of Wildland area than found by Ellis et al. (2020), although methodological similarities are substantial. Ellis et al. (2020) defined that over half (50.0%) of the terrestrial biosphere has already been transformed into Used Anthromes by human populations and their use of land, and 25.8% Wildland in 2010. This research estimates 41.7% and 13% respectively. Compared to Ellis et al. (2020) both dense settlements and Village areas are more abundant while Croplands and Rangelands are sparser in this research (Appendix Table 3). Most of the variation is caused by the difference in input data between Anthromes v2.1 and this research, combined with effects due the methodology using classification boundaries; Instead of using past-oriented HYDE 3.2 data as Ellis et al. (2020) did, this research employed SSP-RCP based data. Additionally, the use of the standardization to a single 'dominant' land-cover threshold of 20% forces lands into different categories, even if they may differ only slightly. Therefore, the distinction between Wildlands versus Remote Woodlands, Rangelands and Croplands Anthromes differ only because of very small differences in population density and land use (Ellis et al., 2010).

Regionally, historical composition and timing of Anthrome change varied among regions due to their different environmental and especially human impacts over time (Ellis et al., 2021). The observed past trends relate well to the future dynamics according to this research. This indicates that the methods and results of this research connect to previous scientific efforts.

4.4 Comparing future developments

Looking at future land-system patterns under SSPs in other studies shows similar trends as this research. Popp et al. (2017) see that the SSP1 has the most positive effects for sustainable development, due to sustainable food consumption (i.e. low food waste, diets with low shares of animal products), rapid growth in agricultural productivity and globalized trade. Such activities could provide a bridge towards a sustainable future (van Vuuren et al., 2016). Doelman et al. (2018) observed the largest distinction between SSP1 and SSP3, looking at land-use change under the baseline SSP scenarios. Similar to this research, Sub-Saharan Africa experiences the most extreme land use change of all regions in the various scenarios. A key driver is reported to be high population growth. Moreover, according to Steffen et al. (2015), the future trajectory of the Anthropocene may well be determined by what development pathways will look like particularly in Asia and Africa (Steffen et al., 2015). Changes at a regional level can influence functioning at the global level. Thus, avoiding the transgression of regional PBs would contribute to a planetary-level safe operating space (Steffen et al., 2015).

4.5 Limitations and future research

Reliability of this thesis is high due to the application of ready-to-use and well-established data and methods. Solely existing data was put into the latest version of the Anthrome classification algorithm. The land system futures under the SSP-RCP scenarios, combined with the Anthrome framework presented in this study serve multiple purposes. They can be used by a broad range of different communities to investigate global consequences of changes in the global reshaping of terrestrial land by humans (e.g. biodiversity, primary productivity, fire, nature conservation, disease etc.). The selected SSP-RCP combinations link very well with previous research on future Earth System scenarios. Nevertheless, a finer spatial resolution is needed, especially for climate model projections, impacts, vulnerability and adaption assessments (Popp et al., 2017).

Due to limitations of classification frameworks and IAMs, the validity of this research needs careful clarification. Anthromes are built on subjective trade-offs between detail and simplicity and contain a variety of practical compromises to make their mapping and comparison possible over time and space. An example is the use of the a priori classification thresholds, which force the division of lands into different categories at a given value of a variable, even when they may differ only slightly. Ellis et al. (2010) discussed that some Anthromes are categorized by just small differences in population density and land use. It is therefore necessary to acknowledge the classifications are arbitrary. Different classification systems might be appropriate and will probably yield different results, depending on both the classification model itself and on the input data used. Hence, this method remains not more than one of many possible ways to look at future land-systems. Furthermore, a cluster analysis could be done to identify an optimal number of distinct natural groupings (clusters) within this dataset (Ellis & Ramankutty, 2008), and may even find novel Anthromes.

There are major uncertainties in our understanding of and ability of modelling current and future global patterns of human-environment interactions (Ellis et al., 2010). Global land-use change models in IAMs such as IMAGE 3.0 are rarely validated, because adequate data for evaluation is not available (Stehfest et al., 2014). Using a range of different scenarios is a good approach to account for these uncertainties. By using a single starting point of Anthrome composition in 2010, from which the scenarios started to diverge thereafter, comparison between the implemented scenarios and their effect on future land systems is feasible. A wide variety of SSP-RCP scenarios was selected to cover a range of possible futures that facilitate the representation of uncertainty of the development of driving forces and possible climate actions.

The input data of this research did not account for the potential impacts of climate change, which may lead to alternative, unanticipated population, urbanization and land-system outcomes. Examples are the movement of people away from coastal urban areas facing sea-level rise or the potential effects of global warming on crop yields (Gao & O'Neill 2020; Doelman et al., 2018).

Top-down global scenarios such as the SSPs are useful because of their coherency across disciplines. Also, they help in investigating contrast between socio-economic assumptions and their effect on Earth through space and time. Therefore, after years of research on the dynamics of the Earth System and the effect of humans, Steffen (2021) recently called for a focus on solutions rather than 'yet another diagnosis of the problem'. The future-focused and scenario-based nature of this thesis and the data set created offers a first step in this direction. However, the SSPs are just a limited number of possible futures that are hard to downscale to local realities (Bennett et al., 2016). Extrapolating unwanted developments into an unknown future run the risk of becoming self-fulfilling. Focusing on local initiatives for a ‘good Anthropocene’ offers a way forward because it can help sustain and amplify existing efforts (Bennett et al., 2016). Yet, there is more than one way to create a ‘good’ Anthropocene, not just because several practical options are available but also because many judgements exist about what counts as ‘good’ (Dalby, 2015).

5. Conclusions

This research has developed future Anthromes time-series for the full set of SSPs, drawing upon existing work on Anthromes (e.g. Ellis et al., 2020; Ellis et al., 2010). To enable the exploration of future Anthromes, substantial efforts were put into adapting the existing Anthrome framework, processing the necessary input data on future human-land interactions and visualization thereof.

The results from this research suggest that the future global change in the share of Used Anthromes will differ depending on the scenario driving the land system change, although this global change is relatively small. SSP narratives together with the RCP forcing's do show diverging change the type and intensity of human-land interactions. Only SSP1-2.6 contributes to staying within the Planetary Boundaries, keeping the Earth System in its current state. Contrastingly, SSP3-7.0 sees most increase in Used Anthromes.

Although the global composition of the Anthromes remains relatively stable for most scenarios, regional differences in dynamics of the share of Used Anthromes are sharper. Most land intensification occurs in Africa and Latin America & Caribbean, although the magnitude is depending on the driving scenario. Early change, together with the magnitude and uncertainty of the change in especially Africa, raises difficulties in preparedness to land-system change. The other regions change more gradually over the 21st century.

Based on these results it can be concluded that influence of human impact on the land-systems, and consequently Earth System, is increasing and therefore it contributes to the theory of the start of an Anthropocene era. At the very least, human impact will not decrease until 2100 for all scenarios but SSP1. Yet, this statement needs to be nuanced for some scenarios and regions. Even though this research does not determine the value of change, it is probable that scenario SSP1-2.6, entitled 'sustainability', will have most positive influence on Earth System as it forces least of Earth's terrestrial land to intensive use by humans.

Therefore, using future-oriented research on global, regional and local level combined with policy efforts provides a prospect for 'sustainable development' of the Earth. As Steffen et al. put it: "We are the first generation with the knowledge of how our activities influence the Earth System, and thus the first generation with the power and the responsibility to change our relationship with the planet." (Steffen et al., 2011, p. 749).

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Appendix

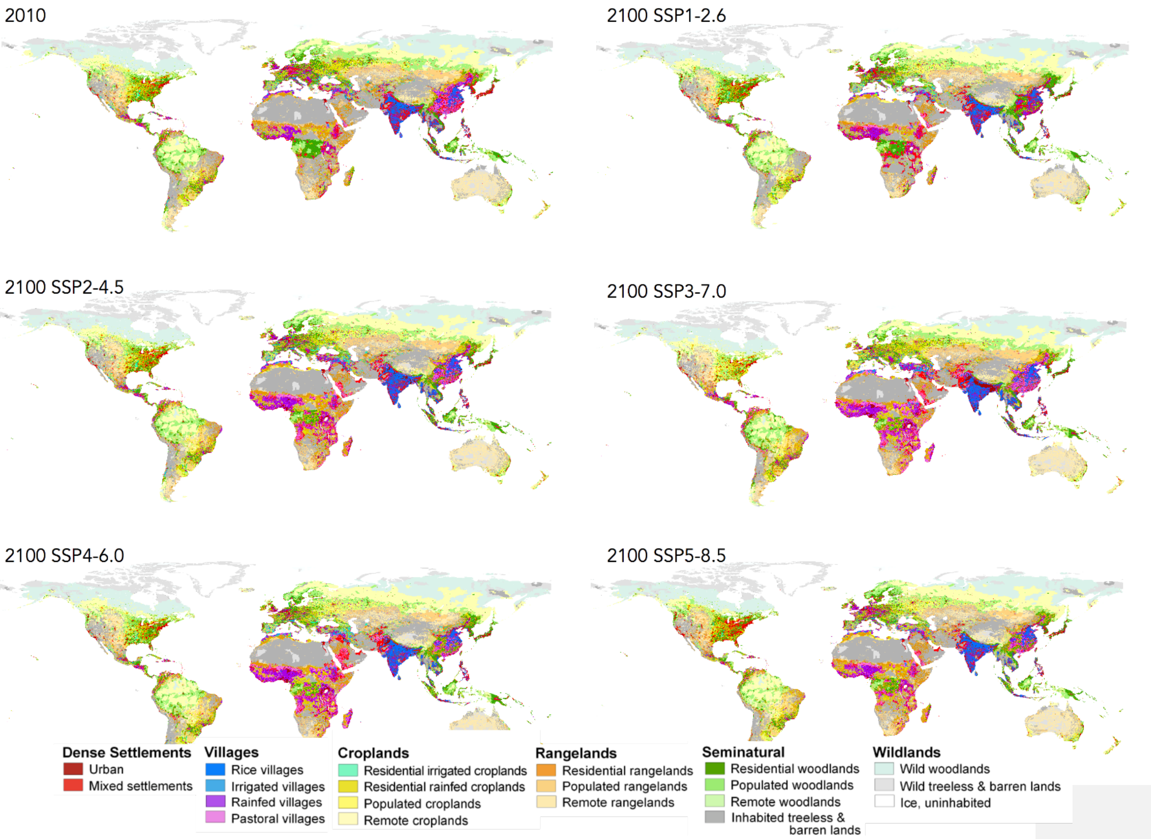

Figure 1. Mapped specific Anthrome classes of 2010 and for all scenarios in 2100 for comparison. Projection: EPSG 4326 - WGS84.

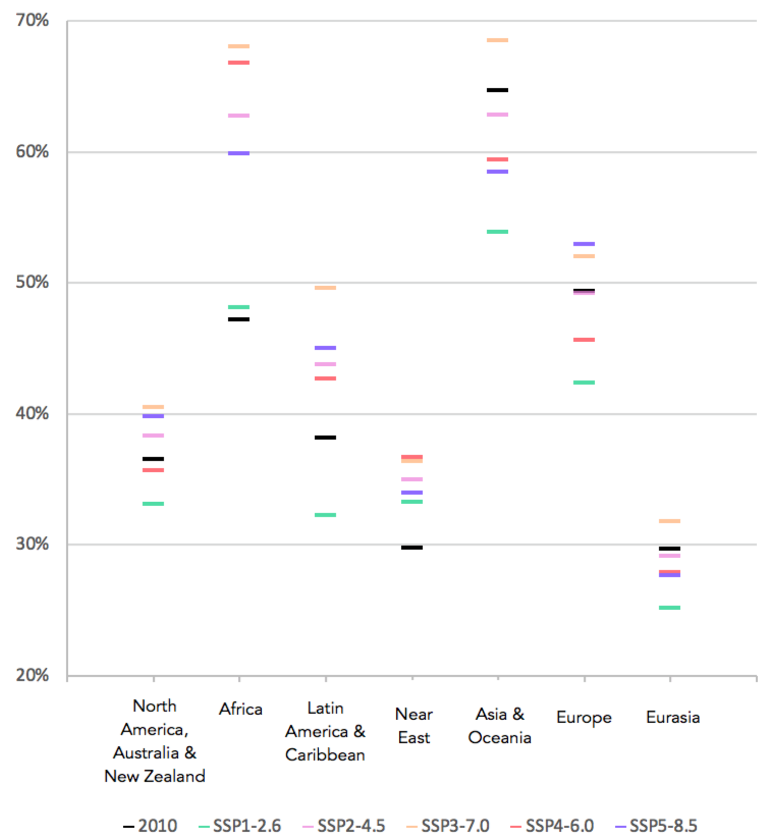

Figure 2. Comparison of future Used Anthromes (sum of Dense Settlements, Villages, Cropland and Rangeland) in 2100 scenarios and 2010. Depicted as percentage of Used Anthromes area per region relative to the total amount of land in the region.

Table 1. Change in percentage of total global terrestrial land area per broad Anthrome for 2100 relative to 2010. For each broad Anthrome (columns) values of all regions and scenarios are colored from highest increase in green to lowest decrease in red.

SSP1-2.6	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	0.19	0.00	-0.43	-0.46	0.48	0.22
Africa	1.07	0.65	-0.25	-1.30	-0.20	0.03
Latin America & Caribbean	-0.02	-0.28	0.33	-0.94	0.80	0.12
Near East	0.11	0.03	0.22	-0.08	-0.34	0.05
Asia & Oceania	-0.31	-1.37	0.13	-0.25	1.52	0.29
Europe	0.04	-0.16	-0.02	-0.06	0.20	0.00
Eurasia	-0.04	-0.34	-0.09	-0.32	0.78	0.02

SSP2-4.5	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	0.18	0.00	0.30	-0.11	-0.51	0.14
Africa	0.56	2.38	0.16	-0.30	-2.82	0.01
Latin America & Caribbean	-0.01	0.06	0.56	0.26	-0.94	0.07
Near East	0.19	0.21	0.18	-0.15	-0.43	0.00
Asia & Oceania	-0.60	-0.26	0.36	0.17	0.22	0.12
Europe	-0.06	-0.05	0.10	0.00	0.00	0.00
Eurasia	-0.03	-0.08	0.20	-0.20	0.10	0.01

SSP3-7.0	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	-0.09	0.00	0.91	0.06	-1.36	0.48
Africa	0.73	3.84	0.13	-0.94	-3.76	0.00
Latin America & Caribbean	0.19	0.56	0.56	0.48	-1.83	0.04
Near East	0.44	0.50	-0.03	-0.35	-0.56	0.00
Asia & Oceania	-0.08	0.38	0.25	0.10	-0.65	0.00
Europe	-0.17	-0.17	0.35	0.08	-0.10	0.01
Eurasia	-0.04	0.20	0.27	-0.02	-0.42	0.00

SSP4-6.0	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	0.05	0.00	0.11	-0.34	-0.02	0.20
Africa	0.68	3.44	0.31	-0.90	-3.57	0.05
Latin America & Caribbean	-0.07	-0.12	0.57	0.31	-0.79	0.10
Near East	0.47	0.26	0.09	-0.25	-0.62	0.05
Asia & Oceania	-0.88	-0.69	0.37	0.30	0.59	0.30
Europe	-0.08	-0.16	0.13	-0.01	0.11	0.00
Eurasia	-0.10	-0.27	0.26	-0.23	0.30	0.03

SSP5-8.5	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	0.54	0.00	0.11	0.09	-0.82	0.08
Africa	0.13	1.50	0.28	0.38	-2.33	0.03
Latin America & Caribbean	-0.16	-0.21	0.82	0.64	-1.20	0.11
Near East	0.10	0.02	0.24	0.01	-0.42	0.05
Asia & Oceania	-1.01	-0.68	0.24	0.41	0.75	0.29
Europe	0.01	0.14	-0.05	0.02	-0.12	0.00
Eurasia	-0.12	-0.23	0.09	-0.07	0.30	0.02

Table 2. Change in percentage of total regional terrestrial land area per broad Anthrome for 2100 relative to 2010. For each Anthrome (columns) values of all regions and scenarios are colored from highest increase in green to lowest decrease in red.

SSP1-2.6	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	0.91	0.00	-2.11	-2.21	2.34	1.07
Africa	5.86	3.56	-1.38	-7.12	-1.10	0.18
Latin America & Caribbean	-0.16	-1.83	2.13	-6.06	5.15	0.76
Near East	1.31	0.42	2.69	-0.97	-4.09	0.64
Asia & Oceania	-1.87	-8.26	0.79	-1.51	9.12	1.74
Europe	1.29	-5.54	-0.78	-1.92	6.83	0.12
Eurasia	-0.24	-1.89	-0.53	-1.82	4.35	0.13

SSP2-4.5	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	0.88	0.00	1.45	-0.53	-2.49	0.69
Africa	3.09	13.10	0.88	-1.62	-15.51	0.06
Latin America & Caribbean	-0.08	0.36	3.61	1.67	-6.02	0.46
Near East	2.34	2.49	2.14	-1.79	-5.18	0.01
Asia & Oceania	-3.64	-1.58	2.17	1.05	1.29	0.70
Europe	-1.95	-1.61	3.49	-0.10	0.09	0.08
Eurasia	-0.16	-0.44	1.12	-1.14	0.56	0.06

SSP3-7.0	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	-0.46	0.02	4.40	0.29	-6.61	2.36
Africa	4.02	21.11	0.69	-5.18	-20.66	0.02
Latin America & Caribbean	1.23	3.59	3.61	3.08	-11.74	0.23
Near East	5.35	6.07	-0.34	-4.27	-6.81	-0.01
Asia & Oceania	-0.50	2.31	1.50	0.61	-3.92	0.00
Europe	-5.67	-5.74	12.00	2.57	-3.47	0.31
Eurasia	-0.20	1.14	1.52	-0.13	-2.33	0.00

SSP4-6.0	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	0.25	0.00	0.56	-1.64	-0.12	0.95
Africa	3.71	18.91	1.68	-4.93	-19.63	0.25
Latin America & Caribbean	-0.47	-0.80	3.67	2.01	-5.10	0.67
Near East	5.64	3.18	1.06	-2.97	-7.54	0.63
Asia & Oceania	-5.29	-4.13	2.20	1.82	3.56	1.83
Europe	-2.72	-5.30	4.58	-0.25	3.57	0.11
Eurasia	-0.54	-1.50	1.46	-1.30	1.70	0.18

SSP5-8.5	Dense Settlements	Villages	Cropland	Rangeland	Seminatural lands	Wildlands
North America, Australia & New Zealand	2.62	-0.01	0.55	0.45	-4.00	0.39
Africa	0.70	8.25	1.55	2.11	-12.79	0.17
Latin America & Caribbean	-1.05	-1.35	5.26	4.11	-7.69	0.72
Near East	1.20	0.27	2.91	0.06	-5.08	0.64
Asia & Oceania	-6.08	-4.08	1.44	2.48	4.51	1.72
Europe	0.25	4.81	-1.62	0.68	-4.20	0.07
Eurasia	-0.66	-1.27	0.53	-0.38	1.69	0.09

Table 3. Comparison of broad Anthrome (bold text) and specific classes in this research and Anthromes v2.1 (Ellis et al., 2020). Both global land areas in km^2 and percent global land area are presented. Difference in percentage computed by subtracting this research Anthromes percentages from Anthromes 12K percentages.

	This research (2010)	%	Anthromes v2.1 (2000)	%	Difference (%)
Dense Settlements	7,775,565	5.84	2,144,994	1.63	4.21
11: Urban	925,345	*0.70*	670,252	0.51	0.19
12: Mixed settlements	6,850,221	*5.15*	1,474,742	1.12	4.03
Villages	11,769,205	8.84	9,079,915	6.89	1.95
21: Rice villages	3,430,303	*2.58*	1,062,914	0.81	1.77
22: Irrigated villages	636,912	*0.48*	1,864,946	1.41	-0.94
23: Rainfed villages	4,901,794	*3.68*	5,305,955	4.03	-0.34
24: Pastoral villages	2,800,195	*2.10*	846,100	0.64	1.46
Croplands	11,657,753	8.76	19,140,513	14.52	-5.77
31: Residential irrigated croplands	772,278	*0.58*	1,016,380	0.77	-0.19
32: Residential rainfed croplands	7,158,645	*5.38*	9,992,113	7.58	-2.20
33: Populated croplands	3,104,936	*2.33*	5,406,669	4.10	-1.77
34: Remote croplands	621,894	*0.47*	2,725,352	2.07	-1.60
Rangelands	24,252,338	18.22	35,468,580	26.91	-8.69
41: Residential rangelands	8,788,707	*6.60*	6,859,690	5.20	1.40
42: Populated rangelands	8,275,215	*6.22*	11,068,664	8.40	-2.18
43: Remote rangelands Seminatural	7,188,415	*5.40*	17,540,226	13.31	-7.91
Seminatural lands	60,346,731	45.33	31,924,003	24.22	21.11
51: Residential woodlands	9,092,600	*6.83*	4,255,601	3.23	3.60
52: Populated woodlands	10,162,160	*7.63*	7,414,058	5.63	2.01
53: Remote woodlands	10,087,498	*7.58*	8,754,954	6.64	0.93
54: Inhabited treeless & barren lands	31,004,473	*23.29*	11,499,391	8.72	14.56
Wildlands	17,330,104	13.02	34,046,033	25.83	-12.81
61: Wild woodlands	10,132,416	*7.61*	15,463,177	11.73	-4.12
62: Wild treeless and barren lands	7,085,649	*5.32*	16,023,665	12.16	-6.83
63: Ice, uninhabited	112,039	*0.08*	2,559,191	1.94	-1.86