Analysis of the Amazonian tipping element in the 21^{st} century within the local safe operating space framework

A scientific article review

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Preface

This Bachelor's thesis is Sara Schützer's degree project in Physical Geography at the Department of Physical Geography, Stockholm University. The Bachelor's thesis comprises 15 credits (half a term of full-time studies).

Supervisor has been Fernando Jaramillo at the Department of Physical Geography, Stockholm University. Examiner has been Mattias Winterdahl at the Department of Physical Geography, Stockholm University.

The author is responsible for the contents of this thesis.

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Abstract

The Amazon River basin is a tipping element, a concept defined by Lenton (2013) as an Earth system component with a tipping point on at least sub-continental scale. Three possible stable states can cover the landscape: forest, savannah and a treeless state. The rainforest system in the Amazon river basin is exposed to a number of anthropogenic perturbations including deforestation, global warming and fire spread. The aim of this thesis is to analyse the potential future of the Amazonian tipping element during the 21st century. A literature review has been made to evaluate what controlling environmental conditions define the stable forest and savannah states, what kind of positive feedbacks these anthropogenic perturbations provoke and what consequences they are predicted to have on the Amazonian tipping element. The results are fitted into a local safe operating space framework to evaluate if current research can be used to set potential boundaries within which humanity is expected to be able to operate safely without risking a tipping of the forest system.

The results indicate that precipitation in the form of both mean annual precipitation, MAP for short, as well as seasonality is the main controlling variable for biosphere integrity. Fire also has an impact on what type of biome can grow but under intermediate rainfall only. Deforestation involves a biogeophysical feedback, which impact the climate system. Further deforestation is expected to result in a decrease in MAP during the 21st century. Global warming involves both biogeophysical feedbacks as well as carbon feedbacks. Seasonality is expected to increase in response to global warming, making the eastern parts of the basin suffer from more intense drought with higher frequency and amplitude. Increased deforestation and carbon emissions are expected to lead to an increase in the fire regime with increasing areas affected by fire. The result suggests a boundary for a land cover change to be set at 30% for the local safe operating space. Crossing such a threshold of land cover change could have great impact on the stability for land-atmosphere coupling, which could lead to state transitions in the Amazon River basin. Further research is needed to determine the impact on the climate system across the Amazon in response to global warming.

Keywords

Amazon, Tipping, Planetary boundaries, Water resilience

Contents

1. Introduction

Our environment was formerly assumed to be infinitely resistant and had the capacity to repair itself from all stress applied by humans (Folke, 2006). However, scientists have realized that this is not true; humanity is a major force of global change shaping ecosystem dynamics (Folke, 2006, Rockström et al., 2009). Human activities can cause different segments of the Earth system to cross thresholds and change into new ways to operate, which in turn affect both human life and ecological systems (Lenton et al., 2008). Moreover, crossing one boundary in one critical system on local or global scale could shift another system (Rockström et al., 2009). Amazonia is a tipping element, a concept defined by Lenton (2013) as an Earth system component with a tipping point on at least sub-continental scale. The Amazonian tipping element has been identified as potentially being able to affect the entire Earth System (Lenton et al., 2008; Rockström et al., 2009). Could major parts of or the entire rainforest in the Amazon River basin disappear because of its tipping nature? What would the consequenses be?

The ecological and ecosystem resilience concept characterizes resilience as how resistant a system is to disturbances while still maintaining its functions (Folke, 2006). This is one of several different resilience concepts that has evolved and is used to describe landscape stability where multiple stable equilibria are possible (Folke, 2006). The Amazon has three possible stable states that can cover the landscape: forest, savannah and a treeless state (Hirota et al., 2011, Staal et al., 2016, Staver et al., 2011). When a certain threshold is reached, the system transitions in a linear or non-linear way into a new state, establishing a new socio-ecological equilibrium (Falkenmark et al., 2019). Evidence shows that the transition between rainforest and savannah is non-linear (Boers et al., 2017, Staal et al., 2016). Falkenmark et al. (2019) explain that a non-linear collapse implicates a system characterized by negative feedbacks retaining the system in a semi-equilibrium state. A forest state is promoted by self-amplifying moisture feedbacks where recycling of evaporation regulates the water cycle and provides additional precipitation (Falkenmark et al., 2019, Boers et al., 2007) making forest development possible (Hirota et al., 2011; Staver et al., 2011). It is estimated that 25-50% of the total rainfall over the Amazon River basin is composed of atmospheric moisture recycling provided by the forest land cover (Zemp et al., 2017; Malhi et al., 2009). Falkenmark et al. (2019) explain that when a certain threshold is crossed due to disturbances, the forest system shifts into the new equilibrium state. In this case a savannah or treeless state. The new state is promoted by positive feedbacks, making it more difficult to transition back to the previous state creating a hysteresis effect. Fire dynamics also resemble a positive feedback promoting the savannah state by obstructing the growth of forest by burning plants down (Falkenmark et al., 2019). Strong positive feedback loops could magnify perturbation effects so that a collapse happen as a bifurcation, meaning that even a small change can create a sudden qualitative and topological change and state shift (Lenton, 2013). Moreover, periods of gradual change interact with periods of sudden change, leading to uncertainty and surprise in some tipping elements (Folke, 2006).

Human production, consumption and wellbeing involve both economic, social as well as ecological aspects, where society and global economy are dependent on ecosystem services and support (Folke, 2006). Brazil, the country with the largest extent of Amazon forests, is facing many social challenges such as reducing poverty, meeting both local and global markets for food production as well as improving nutrition, health and quality of life (Jonas et al., 2014). Deforestation and disturbance have mainly taken place in southern and eastern parts of the Amazon River basin, in the so-called ”arc of deforestation” (Bullock et al., 2020), making room for cattle and soy plantation (Malhi et al., 2008) as well as infrastructure such as roads (Nobre & Borma, 2009). The Amazonian rainforest system is exposed to a number of anthropogenic perturbations including deforestation, forest degradation and fragmentation, fires, emissions and climate change effects such as global warming and intensified and more frequent droughts and flooding extreme events (Nobre & Borma, 2009). Sudden full-scale dieback of the Amazon rainforest, where the whole rainforest in the Amazon River basin transitions into a savannah or a treeless desert state, could have major consequences due to the many important functions that the Amazon rainforest has on both regional and global scale. For instance, the Amazon contributes to the biogeochemical flows and biodiversity in the Earth system, hosting 25% of the terrestrial species in the world (Malhi et al., 2009). A state shift could lead to habitat loss and forest fragmentation leading to species extinction and biodiversity loss (Gleeson et al., 2020A). Moreover, 15% of global terrestrial photosynthesis takes place in the Amazon (Malhi et al., 2009), which means forest loss in the Amazon affects its role as a carbon sink (Gleeson et al., 2020A). Dieback of the forest would mean going from a carbon pool to a carbon source, contributing to global warming (Nobre & Borma, 2009). Furthermore, Amazonian rainforest has an important function in the global climate system through hydrological feedbacks (Rockström et al., 2009), where evaporation and condensation over the Amazon River basin feed atmospheric circulation in South America and the northern hemisphere (Malhi et al., 2009). Deforestation in the Amazon could cause changes in the global climate system by influencing convection and surface energy balance where a state shift could change temperatures and precipitation in Asia (Rockström et al., 2009). Moreover, strong interactions connect local, regional and global systems, suggesting that land cover changes at the local scale in the Amazon River basin may have an impact on a global scale (Jonas et al., 2014). Processes previously thought to act at the local scale can through dynamic and complex interactions have an impact on planetary resilience and disturbances from human activity that could destabilize the current state of our whole planet (Gleeson et al., 2020A). Avoiding such a state shift is thus necessary.

Rockström et al. (2009) have developed a framework for defining critical transitions and boundaries within which humans are expected to operate safely without risking a tipping of the Earth System. The framework is a function of the system's control and response variables, which are based on research of the Earth's capacity to sustain human activity, understanding of Earth System processes as well as a framework resilience. Resilience of processes and different components acting in the Earth System must be analysed in order to prevent driving the planet out of its current stable state (Rockström et al., 2009). Dearing et al. (2014) proposed that the framework also should be used at regional scales since sustainability also must be treated at this regional scale. The framework could be used to increase the impact of policy to contribute to the understanding of governance and policy-making and to be used as a communication tool (Dearing et al., 2014).

2. Purpose and limitations

2.1 Purpose

The aim of this thesis is to analyse the potential future of the Amazonian tipping element during the 21st century. In order to do this, it will focus on answering the following questions:

1. What controlling environmental conditions define the forest and savannah stable states?

2. What kind of feedbacks do anthropogenic perturbations in the form of deforestation, global warming as well as fire spread provoke, and what consequences do they have on the tipping element?

3. What impact do current scientific studies project that anthropogenic perturbation will have on the Amazon tipping element during 21st century?

4. Could current research focusing on the Amazonian tipping element be used to set boundaries for a local safe operating space framework?

2.2 Limitations

This thesis will only evaluate environmental aspects that relate to the water cycle, and as such, social, economic or political aspects are not considered into the analysis of the Amazonian tipping element. While many studies highlight the importance of integrating a social framework in sustainability frameworks (Dearing et al., 2014; Jonas et al., 2014; Gleeson et al 2020B; Zipper et al., 2020), evaluating the complex interactions of social, economical or political aspects of an Amazonian regime shift is then beyond the scope of this thesis.

3. Background

This section will provide a background to the Amazonian system tipping element. It will explain its major negative and positive feedbacks as well as the anthropogenic perturbations that cause changes to the system.

3.1 Study area

Nagy et al. (2016) shares that the Amazonia River basin covers an area of 6 million km^2, which is approximately 5% of the Earths terrestrial surface. Lowland rainforest covers about three quarters of the basin while seasonal forest, savannah, montane forest, alpine formations as well as grazed and cultivated areas compose the rest. Extensive climate change last occurred in the area after the Last Glacial Maximum, when the Earth climate gradually became warmer. During the last century, further warming has taken place due to human activities (Nagy et al., 2016).

Lowland forest in the Amazon River basin has an average yearly temperature of 26°C and a mean annual precipitation, MAP for short, varying between over 3000 mm/year in north-western parts of the basin to less than 1500 mm/year in the transition zones (Malhi et al., 2009). Evaporation and condensation from the Amazon River basin are a driving variable in global atmosphere circulation, affecting precipitation across South America as well as the northern hemisphere (Malhi et al., 2008).

3.2 Climate-vegetation interactions

Falkenmark et al. (2019) define water resilience as the role of water to sustain a certain state such as an ecosystem, biome, regional climate or water supply. Possible stable states in the Amazon River basin are forest, savannah and bare land (i.e. treeless) (Hirota et al., 2011; Staver et al., 2011; Staal et al., 2016). Brovkin et al. (1998) emphasize that vegetation-precipitation interactions enable the stability of these multiple states. The moist entropy gradient between the land area and the ocean is a main factor in precipitation dynamics. Climate and precipitation influence the type of biome and vegetation that is able to thrive. Vegetation is linearly dependent on precipitation and to a lesser degree temperature. Precipitation is in turn non-linearly dependent on vegetation as well as external parameters such as insolation and atmospheric carbon concentrations. Where the two relationships coincide are potential equilibria for the system. Enhanced carbon concentrations in the atmosphere will shift the relationship so that given vegetation cover results in higher MAP than previously. Vegetation impacts the climate and precipitation through surface albedo as well as surface roughness and has low albedo while bare ground has high albedo. A land cover change comes along with a change in albedo, possibly leading to a state shift of the system. Precipitation is sensitive to external climatic conditions as well as local factors (Brovkin et al., 1998).

Atmospheric water drives precipitation and is restocked by evapotranspiration from land areas and evaporation from the ocean (Gleeson et al, 2020A). Somewhere between 25-50% of total precipitation across the Amazon originates from atmospheric moisture recycling (Zemp et al., 2017; Malhi et al., 2008). This cycle of positive feedback in the Amazon ecosystem is self-amplifying and promotes the forest state (Falkenmark et al., 2019).

Alfieri et al. (2008) notes that soil moisture could have an impact on succeeding rainfall; however, this impact alone does not affect the probability of succeeding rainfall. They explain that high soil moisture results in a decrease in albedo, which leads to an energy flow away from the land surface as well as a convective instability and thereby convective rain. However, high soil moisture also means cooling of the land surface, which stabilize and prevent the albedo effect on energy flow. Only when one of these feedbacks is stronger than the other, the dominating feedback could have an impacting role. Soil moisture-precipitation feedbacks could be better explained combined with other variables of energy fluxes such as radiation and temperature (Alfieri et al., 2008).

3.3 Anthropogenic perturbations

Falkenmark et al. (2019) explain that deforestation and climate change are the main factors behind state transitions from forest to savannah. If deforestation and climate change cause precipitation reductions to reach below a certain threshold, moisture feedback dynamics are reduced. This has a great impact on forest resilience (Falkenmark et al., 2019). An earlier literature review over the Amazonian tipping element from Nobre and Borma (2009) identified tipping points at above 40% of current levels of deforestation and above 3-4°C increase in global warming.

3.3.1 Climate change and seasonality

In IPCC's AR5 Synthesis report, Pachauri et al. (2014) explain that there is clear evidence of a global warming trend on Earth. The atmosphere and ocean has warmed, the global total amount of snow and ice have been reduced and the global sea level has risen. Data shows that the global average of combined land and ocean surface temperatures has a linearly increase of 0.85°C during the period of 1880-2012. The cause for this warming is identified as anthropogenic greenhouse gas emissions as well as other anthropogenic drivers (Pachauri et al., 2014).

The carbon cycle is a negative feedback in the Amazonian system (Falkenmark et al., 2019). Elevated levels of carbon in the atmosphere due to anthropogenic emissions could in theory have a positive effect on biomass productivity because vegetation responds to high levels of carbon by increased rates of photosynthesis and development of leaf area, which in turn increases precipitation (Nobre & Borma, 2009; Malhi et al., 2008).

Rainfall in the Amazon is seasonal (Fang et al., 2017). The El Niño Southern Oscillation, ENSO for short, involves seasonal inter-annual variations of rainfall. Variations occur due to anomalies in the atmospheric circulation, warm water in the tropical North Atlantic and other climate modes of variability (Fang, 2017). The patterns of sea surface temperatures, SST for short, that provoke the variations, reoccur every four years (Latif & Keenlyside, 2009). The ocean circulation variability depends on average depth and sharpness of the thermocline as well as strength of the annual cycle (Lenton et al., 2008). Latif and Keenlyside (2009) share that a weak zonal SST gradient results in a warm El Niño phase. Meanwhile, a strong zonal SST gradient result in a cold La Niña phase. The gradient drives the atmospheric circulation in the Walker cell and provokes large-scale ocean-atmosphere interactions. The two different phase phenomenon, El Niño and La Niña, depend on the interactions between SST, Walker circulation and the thermocline depth (Latif & Keenlyside, 2009). Changes in heat absorption during a potential global warming of approximately a 3-6°C increase could according to Lenton et al. (2008) change thermocline depth, which could lead to changes in amplitude and frequencies of the ENSO. Such a future scenario could have an impact on a global scale. The temporal scale is estimated to approximately 100 years (Lenton et al., 2008).

Marengo et al. (2018) highlight that the flooding events of 2009, 2012 and 2014 as well as the drought events of 2005, 2010 and 2016 in the Amazon River basin were of such an amplitude that the probability of their occurrence normally are 1/100 years. Such evident increase in frequency of mega-events suggests that there has already been an increase in frequency and intensity of drought and flooding events. During droughts, trees avoid drying by absorbing deep soil moisture and uptake rainwater and dew from leaves (Marengo et al., 2018). Roots can extract soil water down to ten meters of depth for transpiration (Malhi et al., 2008). Nobre and Borma (2009) explain that while rainforest can be resilient to short periods of drought they are vulnerable to long periods of drought. The forest acts as a carbon sink during the first period of drought due to low soil moisture. In time, biomass starts decay and release carbon. During the drought of 2005, vegetation became greener in areas with precipitation over 1700 mm/year. Nobre and Borma (2009) suggest that this was due to increased radiation and evapotranspiration in response to the drought. After 2-3 years the same area became a carbon source (Nobre & Borma, 2009). Furthermore, Klausmeier (1999) agrees that vegetation can adapt to water shortage to streamline water availability through vegetation-water dynamics. Vegetation on gentle slopes, for example, has shown to grow in stripes at conditions of low rainfall in order to increase water infiltration. The vegetation creates soil differences between the stripes, which hinder the water from infiltrating between the stripes of vegetation. Instead, it runs down to the vegetation and provides extra soil moisture for the vegetation. On flat ground, on the other hand, vegetation can form mosaics. Klausmeier (1999) suggest that they are created by a slight topographic variation. This could lead to large variations of plant density when water flows from sparse ground at slightly higher elevation towards the more dense patches at slightly lower vegetation (Klausmeier, 1999).

Fang et al. (2017) also highlight the effect of topography on groundwater table and runoff. Available precipitation and soil moisture storage for transpiration depend on the ability of vegetation to maintain function during and after the dry season as well as during a potential future drying climate. Runoff, groundwater storage as well as interaction between surface water and groundwater depend on available soil moisture for evapotranspiration. In their simulations of surface water and groundwater interactions they showed that groundwater could suppress soil water stress. It is therefor important in the Amazonian water cycle. Topography affects groundwater table and runoff. Results showed elevated evapotranspiration during dry season and increased radiation (Fang et al., 2017).

3.3.2 Deforestation

Falkenmark et al (2019) explain that deforestation disturbs the water cycle. Deforestation involves a positive self-sustaining feedback loop promoting reductions in precipitation, biomass and evaporation. This in turn, increases the risk of drought and fire (Falkenmark et al., 2019).

Bullock et al. (2020) has mapped deforestation, degradation and natural disturbances in the Amazon River basin during 1995-2017. Their results show that degradation and natural disturbances has had approximately the same impact on the rainforest as deforestation during this interval. The largest impact took place during periods connected to the severe drought events of 1998, 2005, 2010 and 2015-2016. They concluded that 11% of the original forest area had been deforested and 17% had been disturbed up to 2017. During 1995-2017, 6,5% of the 1995 natural forest had been deforested and 6,3% had been lost due to degradation and natural disturbances (Bullock et al., 2020).

3.3.3 Fire

Falkenmark et al. (2019) explain that while high precipitation keeps vegetation wet and therefore decreases the risk of drought and fire, once a transition to a savannah state has occurred, other feedbacks promoting the savannah state can be maintained. Fire is such a positive feedback, inhibiting tree growth and therefore sustaining a savannah state. Meanwhile, the tree cover reduction during fire lead to a decrease in biomass, evapotranspiration and rainfall, all of which promote the forest state. A more open canopy instead increases evaporation, decreases moisture recycling and increases fire risk (Falkenmark et al., 2019). Open canopies allow for grass to grow, which can spread fire easily (Staver et al. 2011). These feedbacks help sustain the savannah state and make the threshold in precipitation to transition back to rainforest much higher than the transition to savannah state (Falkenmark et al., 2019).

Human activity such as logging and forest fragmentation open closed canopies and increases forest edges, which increases the risk of fire (Malhi et al., 2008). Fire used in agriculture can spread and become forest fires, increasing forest vulnerability (Nobre & Borma, 2009). A forest subjected to fire loses species, biomass and is more susceptible to further fire (Malhi et al., 2008). Marengo et al. (2018) underline that almost all fires in the Amazon are caused by human activity. Fires are more common in the same areas as deforestation. The arc of deforestation, which is subject to deforestation, water stress and elevated temperatures also have a higher probability of fire. During the drought of 2016 however, fire spread over a large area beyond the arc of deforestation. Fire reached into central parts of the Amazon River basin, which had previously barely been affected by fire. The total area burned during the drought of 2016 is estimated to 799 243 km^3 (Marengo et al., 2018).

4. Framework

This section will explain the theory behind the planetary boundary framework and its application at a local scale as well as from a hydrological perspective, according to Zipper et al. (2020). The planetary boundary framework was developed to define the critical transitions and boundaries in which humans are expected to operate safely without risking a tipping of the Earth System (Rockström et al., 2009). This section will also present the theory of hydrological sub-boundaries as well as a framework for temporal and spatial scales. The theory presented here will be used as our method for analysing potential boundaries for the Amazonian system in a local safe operating space framework.

4.1 Local safe operating space framework

The local safe operating space approach, described in Zipper et al. (2020), uses the same principle as the planetary boundaries framework in order to determine control and response variables as well as limits for local and stable states in water systems. The response variable is influenced by the control variable and describes the stable state for the local water system. For a given process, a quantifiable control variable may cause a response variable to destabilize. The response variable can be defined by local environmental thresholds and observed ranges during the Holocene. Both local and global boundaries are characterized by linear or non-linear relationships between control and response variables. These include tipping points with feedbacks and hysteresis effect. A transition into a new state could therefore require different control variable values for the local system than the shift back into an original state after a transition. Existing data of the relationship between control and response variables can be used to quantify control variables.

Determining local operating space involves three steps:

1. *Define meaningful control and response variables.* Like planetary boundaries, local control and response variables are based on biophysical and socio-economical premises within local water systems. A defined relationship between control and response variable is required to be able to set a local boundary.
2. *Determine limits* that define the local safe operating space using local limits for water system changes. An effective boundary includes a quantifiable control variable, under the influence of human actions.
3. *Quantify the current state of the control variables* (Zipper et al., 2020).

Gleeson et al., (2020B) add that each boundary has a defined interval of uncertainty. If the lower boundary of the interval is crossed, the system enters a danger zone. Crossing the higher boundary means entering a high-risk zone. The boundary is placed in the lower range of uncertainty as a precaution (Gleeson et al., 2020B). Since crossing a boundary could trigger rapid and non-linear environmental changes with catastrophic consequences, the control variable boundary must be placed from a safe distance from dangerous thresholds based on social and economic resilience (Rockström et al., 2009). It should be noted that due to interaction between systems in combination with lagging and hysteresis effect, relationships between control and response variables are dynamic (Zipper et al., 2020). Moreover, even though ecological boundaries are easier to set in retrospect than to predict, observations of early warning signals, model simulations and experts can be used (Dearing et al., 2014).

4.2 Hydrological framework

Gleeson et al. (2020A) highlight the crucial role of fresh water on Earth, one of the nine identified planetary boundaries in Rockström et al. (2009). Water exchange between atmosphere, land surface, soil, ice, snow and groundwater occur through hydro-climatic regulation. Fresh water storage integrates with the Earth system by controlling sea level and albedo. Fresh water transports, relocates and degrades elements such as nutrients and soil. Hydro-ecologic regulation creates and sustains water ecosystem (Gleeson et al., 2020A). Changes in the water cycle can thus disrupt processes that interact on different scales (Zipper et al., 2020).

The Amazonian tipping element has multiple stable systems primarily driven by precipitation, which make a state shift to a function of water (Gleeson et al, 2020A). The planetary boundary for fresh water had a preliminary boundary in Rockström et al. (2009) of 4000 km^3/year in runoff resources globally that could be removed and used while maintaining environmental flow requirements. Gleeson et al. (2020B) instead advocate a division of the freshwater boundary into six sub-boundaries, based on different forms of water in the Earth System: atmospheric water hydro-climate, atmospheric water hydro-ecology, soil moisture, surface water, groundwater and frozen water. Such a division is scientifically more substantial since it enables fresh water from different parts of the hydrological system to be taken into consideration and would be useful for decision-making. Interactions and feedbacks between sub-boundaries make them overlap (Gleeson et al., 2020B). The current comprehensions of key aspects from the six sub-boundaries from Gleeson et al. (2020A&B) are presented in Table 1.

Zipper et al., (2020) points out that these freshwater sub-boundaries illuminate important interactions between changes in the water cycle, climate change as well as land systems and can be used on local scale. This approach can be combined with a ”fair share” approach, which distributes the global boundary into local shares (Zipper et al., 2020, Dearing et al, 2014).

Table 1. Table below is taken from Gleeson et al. (2020A, Figure 2c & 2020B, Table 2) and illustrate the key aspects of their six water sub-boundaries.

Sub-boundary	Possible Control variable	Possible Response variable	Possible spatial scale
Atmospheric boundary (Hydroecology)	Land area (%) with precipitation change	Terrestrial biosphere integrity	Biomes or hydroclimatic regimes
Atmospheric boundary (Hydroclimate)	Land area (%) with evaporation change	Land-atmosphere coupling /Climate pattern stability	Distributed hydrological unit
Soil moisture (Hydroclimate)	Global net primary production	Carbon uptake/Net primary productivity	Biomes or land cover groups
Surface water (Hydroecology)	Basins or river networks (%) within flow limits	Aquatic biosphere integrity	Basins or river networks
Groundwater (Hydroecology)	Basins (%) with low enough flows	Biosphere integrity, terrestrial or aquatic	Regional aquifers
Frozen water (Storage)	Volume of ice melt	Sea level rise	Global

4.3 Spatial and temporal scales

Reyer et al. (2015) explain that forest changes reach across both spatial and temporal scales. Tipping points can involve interactions across scales. Spatial and temporal scales are used to evaluate forest resilience and potential tipping points. When a forest changes it is important to understand if and how much change could lead to a reduced resilience and if there are any potential tipping points. Comprehension of underlying mechanics could help during evaluation of risks, restoration of ecosystems or forest management. For the temporal scale they propose: “Short term” implying less than 10 years and capturing tree mortality processes as well as “Long term” implying more than 10 years and capturing species replacement. For spatial scale they propose “Local scale” implying less than 10 km^2, “Regional scale” implying more than 10 km^2 up to continental scale and “Global scale” (Reyer et al., 2015).

5. Method

This section will explain the method used to answer the four research questions in the aims. A literature review has been selected as method design.

5.1 Method design

Forest and Savannah conditions: In order to find out what controlling environmental conditions define the forest and savannah stable states, five scientific articles in total have been selected that couple climate data with tree cover data and describe the conditions at which the different possible states exist in the Amazon River basin.

Feedbacks: In order to find out what kind of feedbacks that the anthropogenic perturbations in the form of deforestation, global warming and fire spread might provoke and what consequences they have on the tipping element, eight scientific articles have been selected that well describe expected positive feedbacks from anthropogenic perturbations.

Projections 21st century: In order to find out what impact that current scientific studies project that anthropogenic perturbation will have on the Amazon tipping element during 21st, three scientific articles have been selected for each of the anthropogenic perturbations: deforestation, global warming and fire. The selected studies evaluate the effect that these anthropogenic perturbations will have on the identified controlling environmental conditions during the 21st century.

Local safe operating space framework: The results from the three first sections were put together and fitted into a local safe operating space framework. This was done by using the Local safe operating space framework (Zipper et al., 2020), the Hydrological framework (Gleeson et al., 2020A&B) as well as the framework for Spatial and Temporal scales (Reyer et al., 2015). For each driver of change the following was identified: type of feedbacks, control variable, response variable, potential limits or thresholds as well as temporal and spatial scales.

5.2 Selection criteria

All references in this paper are from scientific articles. Scientific articles were found by searches using the research platform EBSCOhost. All references in this paper were peer-reviewed which validate their credibility. Due to the high number of scientific articles focusing on different aspects and potential futures of the Amazonian tipping points, the number of selected articles had to be limited.

The articles were selected firstly for relevance and secondly for being the most current papers attending to different parts of significant aspects and will represent an overview of current estimations of the effect of anthropogenic perturbations. Newer studies were favoured. The reason for this is that more recent research is more likely to have better accuracy in projections over the future. Moreover, science builds on older science, which makes newer articles more likely to contain more important discoveries in the research field.

Forest and Savannah conditions: Hirota et al. (2011), Malhi et al. (2009), Staal et al. (2016), Staver et al. (2011) and Wuyts et al. (2017). These five scientific articles were all selected because they have investigated at what environmental conditions in the Amazon River basin that the forest and savannah biome exist. As tree cover satellite data sources all but one used tree cover satellite data from MODIS. Malhi et al. (2009) instead used the Global Land Cover 2000 map. As climate data source Malhi et al. (2009), Staver et al. (2011) and Wuyts et al. (2017) used Tropical Rainfall Measuring Mission, TRMM, while Hirota et al. (2011) and Staal et al. (2016) instead used Climatic Research Unit, CRU. This similar method facilitates comparison. The studies from Hirota et al. (2011), Malhi et al. (2009) and Staal et al. (2016) have been identified as ground breaking in this specific area and was therefore included. The newer studies from Staal et al. (2016) and Wuyts et al. (2017) both highlight the effect of human perturbations and calculate conditions for equal probability of forest and savannah state, which make their contribution valuable.

Positive feedbacks: Boers et al. (2017), Betts et al. (2004), Cox et al. (2004), Latif and Keenlyside (2009), Staal et al. (2015), Staal et al. (2020), Staver and Levin (2012) and Zemp et al., (2017). Boers et al. (2017) were selected to explain feedbacks due to land cover change because they explained it clearly and in a way that was supported by previous studies. Staal et al. (2020) suggested a deforestation feedback that has not yet been put forward and therefore had no other studies to choose from. Betts et al. (2004) and Cox et al. (2004) were selected because they explain the feedbacks from global warming very well. Their results have been put forward and referred to in many other studies. Since these articles are from 2004, they are complemented by Zemp et al., (2017). This allows for new discoveries to be included. Latif and Keenlyside (2009) was added as a complement for the missing knowledge gap concerning changes to the ENSO. Staver and Levin (2012) was selected because they have analysed the fire feedback, which has had very little focus in other studies. Finally, Staal et al. (2015) was selected because they combined the feedback effects from all three perturbations: deforestation, precipitation reduction and fire, in order to get a complete picture of interactions.

Projections 21st century - Global warming: Duffy et al. (2015), Duque-Villegas et al. (2019) and Malhi et al., (2009). Duffy et al. (2015) and Duque-Villegas et al. (2019) were selected because they both investigated what impact the anthropogenic perturbation in the form of high emission global warming will have on the Amazon tipping element during 21st. Duffy et al. (2015) have simulated a high emission scenario, RCP8.5, until year 2100 in 35 global climate models from the Coupled Model Intercomparison Project Phase 5, CMIP5. Malhi et al., (2009) have used 19 different Global Climate Models from IPCC fourth assessment report, where they have simulated an intermediate-high emission for 2070-2099 from IPCC's Special Report about emissions scenarios. By comparing a wide range of models and also being from CMIP5 and IPCC, provides credibility that they represent currently used models, which are accepted by the scientific community. Duque-Villegas et al. (2019) was selected because they simulated what consequences a permanent El Niño would have on climate and land eco systems by the year 2100. Duque-Villegas et al. (2019) simulated the same sea surface temperature data that was measured during the warm period of the particularly strong ENSO in June 2015-May 2016. As mentioned in the background, Lenton (2008) identified ENSO as one of the tipping elements on Earth with a possibility of crossing a threshold due to global warming. Insight about how changes to the ENSO affected the climate in the Amazon River basin was lacking in the two first studies. Duque-Villegas et al. (2019) introduce a way to fill this knowledge gap.

Projections 21st century - Deforestation: Guimberteau et al. (2017), Pires and Costa (2013) and Spracklen and Garcia-Carreras (2015). Spracklen and Garcia-Carreras (2015) was selected because they have compiled the projections from 44 peer-reviewed studies with a total of 96 simulations of how deforestation will affect precipitation in the Amazon. The simulated deforestation areas varied in the different studies between 10-100% and the time period was mostly between 1-50 years (Spracklen & Garcia-Carreras, 2015). Therefore, they represent a wide range of studies. To complement this already wide range of results, Pires and Costa (2013) was selected because they simulated different levels of deforestation up to 70% by using a climate-biosphere model and compared selected sub-regions of the basin as well as the Amazon River basin as a whole. Guimberteau et al. (2017) further complement these results by simulating three scenarios of deforestation in combination with IPCC's A2 scenario of intermediate climate change. The low deforestation scenario implicate a slow downward trend of 3900 km^2/year until year 2025 and thereafter less than 1000 km^2/year which means a total of 7% deforestation by 2100. The high deforestation scenario implicates an increase of deforestation with 19500 km^2/year after 2020, which means a total of 34% deforestation by 2100 (Guimberteau et al., 2017).

Projections 21st century - Fire: Brando et al. (2020), Fonseca et al. (2019) and Le Page et al. (2017). These three articles were selected because they have analysed the impact from climate change and deforestation on the Amazonian fire regime during a simulated 21st century using two different deforestation scenarios and two different emission scenarios. This made the findings very easy and straightforward to compare. The scenarios in all three studies match scenarios from the IPCC, which make them considered to be fully possible scenarios by the scientific community. It also makes them easier to compare. Brando et al. (2020) and Le Page et al. (2017) changes in burned area during the intervals of 2041-2050 and 2071-2100 respectively. They complement each other's results by contributing to different parts of the 21st century. Fonseca et al. (2019) instead simulate changes in area with a fire relative probability, FRP≥0.3 for different months separately. In this way they manage to include changes to the fire season.

6. Result

6.1 Forest and savannah conditions

This section presents the results of five scientific articles, which have investigated at what environmental conditions in the Amazon River basin that the forest and savannah biome exist.

6.1.1 Precipitation

All five studies found an evident coupling between biome distribution and precipitation and they presented the biome distribution as a function of precipitation. All studies except for Hirota et al. (2011) found that the relationship was dependent on both MAP as well as seasonality. Hirota et al. (2011) did not analyse a potential relationship with seasonality but focused instead on MAP. Table 2 presents an overview of the findings concerning quantified precipitation range of biome distribution as well as potential estimated limits. Whereas MAP conditions were presented as fairly straightforward mm/year, seasonality was quantified using different methods. Staver et al. (2011) use the length of the dry season in months. Staal et al. (2016) and Wuyts et al. (2017) use Markham's Seasonality Index, MSI. Malhi et al., (2009) instead use the Maximum Climatological Water Deficit, MCWD. Climatological Water deficit is here assumed to be zero during the wettest period of a year. MCWD is the lowest measured water deficit during the same one-year period (Malhi et al., 2009).

Staal et al. (2016) and Wuyts et al. (2017) calculated Maxwell points for the biome distributions. Maxwell points are points where conditions between the two different states are equally stable (Staal et al., 2016). Therefore they are presented here as an identified potential limit in the forest-savannah stability. The point for equal stability of the forest and savannah state in the Amazon from Hirota et al. (2011) is taken from the graph in Figure S2 where the probability for the forest and savannah state are equal and therefore is estimated to have equal probability. Staal et al. (2016) conclude that higher seasonality means lower stability for the forest biome and dry season length limited the forest distribution. Staver et al. (2011) explained that seasonality affect both tree physiology by limiting tree growth and the possibility for fire spread since long periods of drought enables fire to spread more easily.

Table 2. Results from the literature review of five scientific articles where the scientists have coupled climate data with tree cover distributions. MAP stands for Mean Annual Precipitation. MCWD stands for Maximum Climatological Water Deficit. MSI stands for Markham's Seasonality Index.

Reference	Data sources	Quantified distribution	Estimated limits or thresholds
Hirota et al., 2011	MODIS: 35°S-15°N CRU: 1996-2002	ND	Equal probability. Forest-savannah-treeless: MAP≈1900mm & 500mm
Malhi et al., 2009	Global Land Cover 2000 map: 45°W-70°W, 0°-20°S TRMM: 1998-2005	Forest: MAP>1500mm + MCWD>-200mm Savannah: MAP<1500mm, MCWD<-400mm Transition: -400< MCDW<-200mm	Approximate limit: MAP≈1500mm + MCWD≈ -300 mm
Staal et al., 2016	MODIS: 35°S-15°N. CRU: 1961-2002	Bistability:1100-2000mm. Higher probability at 1300-2000 mm. Bimodal at MSI: 12-55%	Maxwell point: 1760 mm, MSI: 50%
Staver et al., 2011	MODIS. TRMM: 1998-2010	Bimodal at MAP: 1000-2500 mm + dry season <7 months. Seasonality limited forest but did not affect savannah	Forest only exists when MAP >1000mm + dry season <7 months
Wuyts et al., 2017	MODIS: 12,5°N-23°S, 81,5°-24°W TRMM: 1998-2010	Bimodality at MAP = 1400-1900mm & MSI = 45-62% Bimodality exists near cultivated areas only	Maxwell point: 1500mm. MSI: 42% when distance from agriculture >2km

Hirota et al. (2011) conclude that biome resilience is dependent on precipitation. They set up a resilience map as a function of MAP. Staver et al. (2011) noted that a large portion of the Amazon that is currently in a forest state has precipitation patterns with intermediate MAP and mild seasonality that could support both biomes. Staver et al. (2011, Fig. 4) presented a map of areas of estimated bistability based on precipitation, which in agrees well with the forest resilience map based on precipitation showed in Hirota et al. (2011, Fig 4).

All articles except Malhi et al. (2009) choose to present their biome identification in the form of tree cover percentage. Biome definition varied between studies but tree cover for a forest state was considered approximately 80%. Hirota et al. (2011) noted that a tree cover around 60% and 5% was scarse in their observations. Staver et al. (2011) noted the same scarcity in their tree cover estimates for the interval 50-55%. The distribution figures presented in Staal et al. (2016, Fig. 3 & 4) and Wuyts et al. (2017, Fig. 3) show the same patterns. Hirota et al. (2011) identify these tree cover scarcities as unstable thresholds where the biome could shift to a forest or savannah state depending on environmental conditions. They suggest positive feedbacks such as fire as an explanation for the 60% tree cover instability. These findings suggest that deforestation toward these unstable thresholds of 60% tree cover could enable a transition to savannah. Meanwhile, particularly wet periods could also shift a savannah state here to a forest state. Hirota et al. (2011) conclude that these unstable tree covers and positive feedbacks imply double hysteresis.

6.1.2 Fire

Staver et al. (2011), who included fire distribution in their study, conclude that fire only exists until a certain threshold, which was estimated at a tree cover of 45 or 50%. They explain that trees behave as a barrier preventing fire from spreading when tree cover is high enough (Staver et al., 2011). Wuyts et al. (2017) found a similar pattern and stated that fire in their study was prevalent when 5<Tree cover<40% and with a water deficit of 400-800 mm/year. Staver et al. (2011) conclude that fire is a positive feedback enabling open canopies, which in turn promote fire spread. These patterns for fire distribution were not as sharp in South America as on other continents in their study. Fire was present in South American forests at a greater degree. Staver et al. (2011) suggest that this could indicate changes in biome states in South America. Changes in biome distribution, either through fragmentation or climate is harder to reverse due to fire acting as a positive feedback (Staver et al., 2011).

6.1.3 Anthropogenic perturbations

Hirota et al. (2011) and Wuyts et al. (2017) noted that areas with a dryer climate and thereby a lower resilience are situated in the eastern and south-eastern parts of the Amazon River basin. These are the same areas that have been exposed to the highest deforestation and other anthropogenic perturbations (Hirota et al., 2011; Wuyts et al., 2017). These areas have the highest risk for drought (Hirota et al., 2011). Staal et al. (2016) noted a local coexistence of forest and savannah along the edges of the Amazon. The probability of coexistence was not only evenly distributed throughout the climatic interval but also existed along edges. They concluded that climate does not solely determine savannah distribution (Staal et al., 2016). Wuyts et al. (2017) compared tree cover data for areas near cultivated areas with areas not subject to anthropogenic perturbations and came to the same conclusions. Their results showed that bimodality only existed near cultivated areas. Anthropogenic edge effects such as increased fire spread, land cover changes into agriculture as well as natural spatial heterogeneity were offered as explanations. Their presented relationship between precipitation, biome and distance from agriculture (Fig. 6a) display an apparent impact on the precipitation-biome relationship at distances less than two km. Calculated Maxwell points for MAP and Markham's Seasonality Index in the savannah-forest stability relationship was increased exponentially with reduced distance to agriculture (Wuyts et al., 2017). Staal et al. (2016) point out that logging can create savannah conditions in a forest because it opens up the canopy and reduces tree cover. They also suggest that coexistence could implicate spatial interactions between neighbouring patches. For example, a forest patch can increase tree cover in a neighbouring savannah patch by seed dispersal. On the contrary, a savannah patch could reduce tree cover in neighbouring forest patches through fire spread. If the least stable state is dominant, a local invasion could in theory create a domino effect through spatial interactions (Staal et al., 2016).

6.2 Feedbacks due to anthropogenic perturbations

This section will present the findings of what kind of feedbacks that anthropogenic perturbations in the form of deforestation, global warming as well as fire spread and what consequences they have. An overview over the different feedbacks is presented as a casual loop diagram in Figure 1.

6.2.1. Feedbacks caused by deforestation

Boers et al. (2017) identified release of condensational latent heat over the Amazon forest as the physical mechanism behind the collapse of the moisture feedback. They describe how atmospheric moisture inflow from the Atlantic Ocean results in rainfall where it travels by winds across the Amazon and then southwards after being blocked by the Andes. Precipitation increases the heat gradient between the Atlantic Ocean and South America because of latent heat. This leads to a two to three time increase in atmospheric moisture inflow during the monsoon periods. Evapotranspiration from the Amazon contribute with new atmospheric moisture that can become rainfall down-wind. High precipitation and condensational latent heat is important in order to maintain this important evapotranspiration. Condensational latent heating over the Amazon River basin has a vital role in intensifying the inflow of atmospheric moisture from the Atlantic and further across the Amazon. During deforestation and land cover change to agriculture, albedo increases while evapotranspiration decreases. This leads to a reduction in surface net radiation and total surface heat flux. Total surface heat flux is energy from the land surface to the atmosphere associated with evaporation and transpiration, which later becomes condensate and clouds in the troposphere. Because of this land cover change, the atmospheric moisture can no longer trigger enough latent heat to maintain moisture feedback. Less condensate reduces total atmospheric heating across the Amazon, resulting in reduced precipitation. In their analysis of deforestation's impact on atmospheric moisture traffic, Boers et al. (2017) find a threshold with bifurcation and hysteresis. The cause is identified as a breakdown of the latent heat feedback. When the transpiration has reduced to a certain limit, there is not enough atmospheric moisture to release latent heat. Crossing this threshold lead to a 40% reduction in precipitation for non-deforested parts of the basin to the west as well as further down wind. The reduction is approximately the same for different tested values of evaporation, the amplification factor as well as heating of the Atlantic Ocean. The simulations also shows a reduction in wind speed in the climate regime, which could lead to further reductions in precipitation further down wind. These areas include large cities in the south-eastern parts of South America. Because these feedbacks have non-linear responses, deforestation could have an impact on the atmospheric circulation and thereby affect climate at different places (Boers et al. 2017).

Staal et al. (2020) suggest that there is also a drought-deforestation feedback. Deforestation reduces forest area, which means less recycled water. This leads to reduced rainfall and the dry season becomes more intense. Drought facilitates deforestation. Deforestation rates increase during dry seasons. The correlation from Staal et al. (2020) between drought in the form of MCWD and deforestation rates shows a clear relationship between increased deforestation rated during more intense droughts. When examining the reason behind the recent increase in drying observed in the form of reduced MCWD, Staal et al. (2020) estimates that less than 4% of the reduction is due to deforestation where mainly the south-western part of the Amazon River basin has been affected. The main driving force and reason behind remaining drying was identified as global warming. The observed drought-deforestation feedback is therefore now small but is expected to heighten with increased deforestation (Staal et al., 2020).

6.2.2. Feedbacks caused by global warming

Betts et al. (2004) propose that there are three mechanisms in the interaction between the vegetation in the Amazon River basin and climate under increased carbon concentration in the atmosphere: Biogeophysical feedbacks, carbon cycle feedbacks and the physiological forcing of climate and vegetation by increased carbon concentration in comparison to radiative forcing (Betts et al., 2004).

Increased atmospheric carbon concentrations is, according to Betts et al. (2004) and Cox et al. (2004), expected to result in reduced precipitation across the Amazon due to two effects of the increased carbon concentration: radiative and physiological forcing.

Physiological forcing: Betts et al. (2004) estimate that physiological forcing is the reason for approximately 20% of the predicted precipitation reduction. The mechanism involves modification of near surface temperature, which results in reduced moisture supply for precipitation. The increased carbon concentration affects plant function by increasing water efficiency and photosynthesis. The plant stomata open less at high carbon, which reduces moisture flux from the land surface to the atmosphere. This warms the near surface air temperatures and increases the ratio between sensible heat flux and latent heat flux. Reduced stomatal opening could therefore lead to reduced moisture recycling, which leads to reduced precipitation. Therefore physiological forcing acts directly by reducing moisture recycling by evaporation and indirectly by warming the land-surface impacting atmospheric circulation patterns. However, the physiological forcing by increased atmospheric carbon concentrations also acts like a fertilizer on vegetation and increases water use efficiency. This could slow down the rate of forest dieback (Betts et al., 2004).

Radiative forcing: The effect of radiative forcing is estimated by Betts et al. (2004) to be the driver behind the remaining, approximately 80%, of the predicted precipitations. Radiative forcing involves modification of atmospheric circulation pattern. Betts et al. (2004) and Cox et al. (2004) predict an ocean surface warming in the tropical Pacific that are similar to El Niño patterns, associated with periods of dry season and therefore a reduced ocean moisture inflow and reduced precipitation across the Amazon. The modelling predictions from Cox et al. (2004) all produced a larger warming of the East tropic Pacific than in the west, which coincide with El Niño mean SST patterns leading to a precipitation reduction in north-eastern Amazon. Cox et al. (2004) suggest that mechanisms behind these SST patterns are related to cloud feedbacks in the east and west Pacific and interactions between ocean and the atmosphere. However, the models in CMIP2, Coupled Model Intercomparison Project 2, did not show the same clear result of SST pattern. The results were varied for the different models (Cox et al., 2004). The same point was highlighted in Latif and Keenlyside (2009) who have analysed how ENSO could be affected by global warming. They conclude that the ENSO's response to global warming varies greatly by different models and in different studies and is therefore highly uncertain with our current knowledge of ENSO responses. Some models predict increase, some decrease while some show no difference in amplitude of the ENSO. No conclusions of future changes to the ENSO could therefore be made with confidence. A warming trend has been observed in SSTs in the Equatorial Pacific during the last 50 years that coincide with the global warming trend. The trend has El Niño patterns. A small regime shift of the ENSO was also observed during the 1970s. Based on the observed changes, Latif and Keenlyside (2009) conclude that there is no indication of tipping point behaviour in ENSO during the near future. Late 21st century or later would be more probable. Nonetheless, Latif and Keenlyside (2009) point out that lack of evidence for a tipping point in a physical system does not mean that there does not exist tipping points in other parts of the Earth system that affects the climate in the tropical Pacific. If a slow change towards an El Niño-like state leads to reduced precipitation across the Amazon leading to forest dieback like suggested by Cox et al. (2004), the carbon released from a potential rainforest collapse could accelerate global warming (Latif & Keenlyside, 2009).

Zemp et al., (2017) highlight that the dry season might become longer and more intense with these changes. The risk of self-amplified Amazon forest loss increases linearly with dry season intensity of reduced inflow of oceanic moisture. Low MAP and MCWD result in lower forest resilience and increased probability of state shift during exposure to perturbations such as drought and fire. An increase in extreme drought events could therefore affect the stability of the forest state and lead to a state with lower tree cover (Zemp et al., 2017).

Moreover, reduced precipitation increases the risk of forest dieback and could have a cascading effect (Zemp et al., 2017; Betts et al., 2004; Cox et al., 2004). Betts et al. (2004) suggest that forest dieback cause two positive feedbacks with impact on the climate: a biogeophysical feedback resulting in a 20% further reduction in precipitation and a biogeochemical feedback by a carbon cycle feedback resulting in a 5% further reduction in precipitation estimated by Betts et al. (2004). The biogeochemical feedback is the carbon cycle feedback, which implicates a carbon release to the atmosphere during forest dieback. The excess carbon to the atmosphere accelerates the global warming and its effect, leading to further climate change (Betts et al., 2004; Cox et al., 2004). The mechanics for the biophysical feedback induced by forest dieback are the same as described for land cover change due to deforestation above. Furthermore, Betts et al. (2004) share that the biogeophysical feedback depends on the relationship between global mean surface temperature and the precipitation patterns across the Amazon River basin. A reduced land cover by forest cover results in reduced evapotranspiration and water recycling (Betts et al., 2004; Zemp et al., 2017).

Furthermore, Zemp et al., (2017) suggest that there is a decreased risk of forest dieback with increased heterogeneity. Spatial heterogeneity arises from the response of forest patches to the reduced precipitation and could theoretically have a stabilizing effect on the ecosystem. Forest patches could adapt to drought by giving rise to differences in land surface properties that controls water availability for trees and disturbances in forest patches. If individual forest patches shifts at different critical rainfall regimes, propagation of the cascading effect could be hindered at an early stage. They conclude that such heterogeneity could in theory reduce frequency of large cascade effects with over 50% (Zemp et al., 2017).

What consequences these feedbacks will have on the future of the Amazon River basin by 2100 vary somewhat between Cox et al. (2004) and Zemp et al. (2017). Simulating a high emission scenario, Cox et al. (2004) predict a 10°C warming by 2100 and a precipitation reduction across the Amazon River basin with over 60%. They conclude that extreme drought and warming will lead to forest dieback

(Cox et al., 2004). Betts et al. (2004) explain that drought and warming reduces Net Primary Production, NPP, which they expect will reduce tree cover from 80% towards below 10%. They predict that half of the Amazon River basin will become savannah and the other half desert by 2100 (Betts et al., 2004). However, Zemp et al. (2017) argue that the result does not indicate a complete Amazon dieback by 2100. They agree that more frequent extreme drought events could destabilize large parts of the forest. They conclude that the changes in vegetation-atmosphere feedback would lead to a 25-38% forest dieback, depending on thresholds (Zemp et al., 2017).

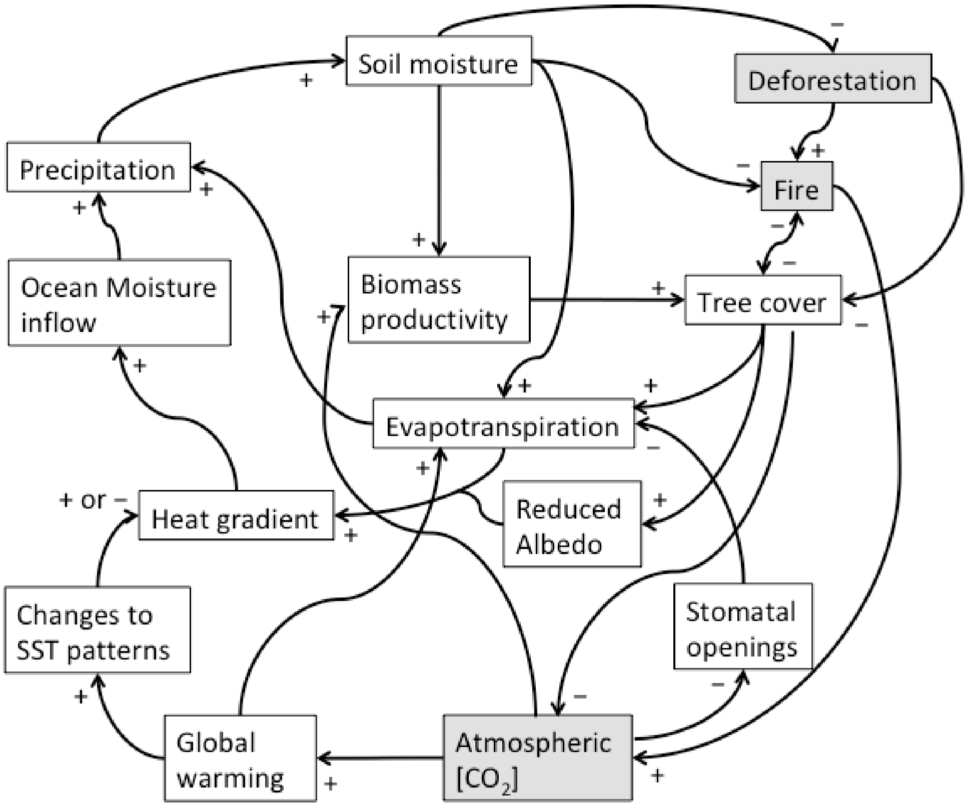

Figure 1. This casual loop diagram shows an overview over the different feedbacks. The biogeochemical feedback caused by land cover change, the drought-deforestation feedback, the vegetation-fire feedback and the carbon feedback due to physiological forcing are all positive feedbacks with reinforcing loops. The carbon feedback promoting biomass production is a negative feedback with balancing loops. The radiative forcing due to global warming is either a positive or negative feedback depending of what type of changes they would induce in SST patterns. Grey boxes are directly increased by humans, affecting the entire loops.

6.2.3. Vegetation-fire feedback

Staver and Levin (2012) have analysed the mechanism behind fire feedback. They suggest that both climate and fire determine tree cover and biome distribution at intermediate rainfall. They conclude that the impact of fire spread and fires on tree demography both have an impact on stability and dynamics of savannah and forest. Savannah trees and forest trees are different. Savannah tree saplings die from fire. However, if they get the opportunity to grow up, full-grown savannah trees do survive fires. Forest trees on the contrary, die from fires both as full-grown and as forest tree saplings. While savannah tree saplings can only grow in areas covered by grass, forest tree saplings can grow in areas covered by grass, savannah samplings or trees. Forest trees are highest in the competitive hierarchy, followed by savannah trees followed by grass. Rainfall increases the opportunity for trees to establish while it reduces tree mortality, resulting in higher tree cover. Forest trees dominate. Meanwhile, frequent droughts are associated with tree mortality. At intermediate rainfall, savannah has a competitive advantage only in the presence of frequent fires. Fire spread is dependent on grass cover. Fire affects savannah trees by inhibiting them from establishing, and forest trees by increasing tree mortality. Therefore, fire leads to lower tree cover and a possibility for grass to not be outcompeted. The presence of grass in turn enables further fire spread with the presence of grass. The fire-vegetation feedback therefore implicates that fire limits establishment of trees and induces tree mortality to forest trees. Absence of trees promotes further fire, which prevent trees to establish and so on. Staver and Levin (2012) suggest that the fire-vegetation feedback could explain the observed bimodality in tree cover at intermediate rainfall. If climate change leads to changes in fire frequency, the rainforest in the Amazon River basin could be degraded. Changes are expected to be sudden and include hysteresis (Staver & Levin, 2012).

6.2.4. Combined effect of deforestation, precipitation reduction and the fire feedback

Staal et al. (2015) have used a tree cover model from Van Nes et al. (2014) to examine the combined effect of both reduced precipitation and deforestation, where they included the vegetation-fire feedback. Separately, precipitation reduction of 40% without deforestation lead to state shift in 19% of the simulated cells. Meanwhile, deforestation of 20% without a precipitation reduction lead to state shift in 22% of the simulated cells. They concluded that a reduction in precipitation in combination with deforestation lead to 6,6 times as many local state shifts then they did separately. The largest reduction took place during the combination of 32% precipitation reduction and 14% deforestation. 80% of regime shifts occurred at around 15% deforestation and 30-35% precipitation reduction. This combination also resulted in increased fire probability (Staal et al., 2015).

6.3 Amazon 21st century predictions

Evident from the result in section 6.1 above, the studies have found that biome integrity is dependent on MAP and drought occorrence. Meanwhile, fire could also act as a positive feedback promoting the savannah state. This section will present an overview of what consequences that recent research estimates that anthropogenic perturbations in the form of deforestation as well as global warming will have on the climate and fire regimes in the Amazon River basin during the 21st century.

6.3.1. Predicted changes to the climate regime during 21st century due to deforestation

This second section presents the findings from three studies projecting how anthropogenic perturbations in the form of deforestation will impact precipitation across the Amazon River basin.

Changes to MAP: The simulated effects from deforestation vary between studies where some showed an increase while others showed a MAP decrease in response to deforestation. This was apparent in the peer-review results from Spracklen and Garcia-Carreras (2015) where the results from the 44 studies varies greatly from an expected increase in precipitation of 15% to a reduction of 57%. The mean value for the 44 studies was however a reduction of 12%±11% (Spracklen & Garcia-Carreras, 2015). The simulation by Guimberteau et al. (2017) without deforestation projects a temperature increase by 3,3°C by 2100. This temperature rise leads to an increase in evapotranspiration of 5,0%, which in turn leads to an increase in precipitation of 8,5% (190mm/year) and an increase in runoff of 14%. The projections of precipitation varies between the three used global climate models from a 4,5% reduction to a 16,2% increase. Guimberteau et al. (2017) shares that that the effect of climate change is partly offset by the effect from deforestation. The combination with climate change and deforestation therefore gives a result of only 2,6% reduction in evapotranspiration and a 2,2% increase in runoff. The western and northern parts of the Amazon River basin are expected to become wetter while the south-eastern parts are expected to either be unchanged or become dryer depending on model used (Guimberteau et al., 2017). When Pires and Cosca (2013) simulates a 70% deforestation scenario of the Amazon, the MAP decreases from 2255 to 1799 mm/year in the basin as a whole, which is a 20% reduction. When they compared the projections of the sub-regions they noticed that precipitation responded different to deforestation in different areas. One region exhibit a constant rate of reduction, one region shows fast reduction event at low deforestation levels while a third shows a reduction first after intermediate deforestation levels (Pires & Cosca, 2013).

Seasonality: Only Guimberteau et al. (2017) analysed differences in seasonality. Towards the end of the dry season, August-October, their simulations showed a reduction in precipitation in south-eastern parts of the Amazon of 10-14%. Meanwhile, in western and northern parts of the basin an increase of 16-30% is projected.

Identified causes: Pires and Costa (2013) who used a coupled climate-biosphere model identified the cause behind reduction in precipitation to be a reduction in regional moisture budget where deforestation had resulted in changes to evapotranspiration and moisture convergence (Pires & Cosca, 2013). Moreover, Spracklen and Garcia-Carreras (2015) noted that all of the studies whose results showed an increase in precipitation had simulated only a small area size of deforestation. Simulations of larger areas of deforesstation always projected a reduction. They found a negative linear relationship between rainfall and deforestation with 92% of simulations projecting reduced precipitation in response to deforestation where every 10% deforestation corresponded to a 1.6% reduction in precipitation. However, they also noted that individual studies often found the relationship to be nonlinear. The studies that had used models with coupled ocean-atmosphere interactions more often predicted larger reductions in comparison with those who used atmosphere models (Spracklen & Garcia-Carreras, 2015).

6.3.2. Predicted changes to the climate regime during 21st century due to climate change

This first section presents the findings from three studies projecting how anthropogenic perturbations in the form of climate change will have an impact on precipitation across the Amazon River basin.

Changes to MAP: The studies shows different results of the impact on MAP due to expected global warming. Duffy et al. (2015) suggest that there will be a reduction of the MAP in eastern parts of the Amazon while an increase in western parts, leading to no overall change in MAP for the basin as a whole. In the simulations from Malhi et al. (2009), the results varies greatly between the 19 different models resulting in their conclusion that as a group, no significant change in precipitation in response to global warming could be seen. When Duque-Villegas et al. (2019) simulated what effect a permanent El Niño condition would have on the climate, they projects a reduction of precipitation across the whole basin with highest decrease projected in central parts of the basin.

Seasonality: All three studies project an increase of drought in eastern parts of the Amazon River basin. In their high emission scenario RCP8.5, Duffy et al. (2015) projects dry periods to become dryer, wet periods to become wetter and the time in between to become dryer. They predict extreme events will have higher probability, which could lead to forest degradation or change. Areas affected by severe drought are expected to double or triple by 2100. Areas of unusual wetness are expected to increase in frequency as well as area after the year 2040. By 2100, drought is expected to increase in frequency and area distribution in eastern parts of the Amazon River basin while decrease in the western parts. Some areas with projected reduced MAP are projected a ten-fold increase in drought (Duffy et al., 2015). The simulations of the intermediate-high emission scenario in Malhi et al. (2009) show that eastern Amazonia is expected to receive dryer dry seasons. MCWD could go below -200 during El Niño droughts and experience increased water stress to the forest. Malhi et al. (2009) estimate a 20-50% probability that rain forest in the eastern part of the Amazon River basin will become seasonal forest. While western parts of the basin are expected to experience more seasonality, they estimate only a 10% probability of the forest changing to seasonal forest here. They argue that while seasonal forest could be resilient to some degree of drought, long-term drought would lead to at state transition. Fire could trigger such a transition to a savannah state (Malhi et al., 2009).

Duque-Villegas et al. (2019) shares that global warming due to emissions can lead to a higher frequency of El Niño events because it reduces temperature gradients in the East equatorial Pacific Ocean, which create the changes in convection zones that take place during El Niño events. Their permanent El Niño simulation projects an increase in MCWD in the whole basin while decreasing gross primary production. Greatest increase in MCWD is expected in eastern parts. Duque-Villegas et al. (2019) projections of permanent El Niño conditions simulate large-scale changes to climate patterns including changes to global energy and water balance, reduced wind speed towards the west as well as gross primary production which, according to Duque-Villegas et al. (2019), could lead to state transitions and forest dieback in the Amazon River basin.

Evapotranspiration and the carbon effect: Malhi et al., (2009) point out that increased temperature due to global warming results in higher transpiration as well as water stress even without a change in precipitation. Meanwhile, elevated carbon concentrations in the atmosphere could theoretically result in higher production of biomass as well as more efficient water use. To test this, they simulated a 4,7°C temperature increase combined with 850 ppm in atmospheric carbon concentration. The temperature increase resulted in an increase in evapotranspiration by 55% while the carbon increase reduced evapotranspiration with 17% leaving a total effect of a 37% increase. Higher carbon concentrations could therefore to some extent suppress the effect of global warming (Malhi et al., 2009).

Identified causes: Duffy et al. (2015) found couplings between the simulated sea surface temperatures in the Pacific and the expected precipitation over eastern parts of the Amazon River basin while the sea surface temperatures in the North Atlantic coincide with precipitation over the northern part of the basin. The simulations predict a rapid warming of the sea surface temperatures of the Pacific and a slow warming of the North Atlantic sea surface temperatures. They conclude that it is the warming of the sea surface temperatures that causes the projected change in drought and wetting in the global warming changes (Duffy et al., 2015).

6.3.3. Predicted changes to the fire regime during 21st century

This last section of projections presents the findings from three studies, which have analysed the impact from climate change and deforestation on the Amazonian fire regime during a simulated 21st century. An overview of the predicted changes of extent of the fire regime is presented in Table 3 below. As seen in Table 3, the results from all three studies show significant interaction and impact from both climate change and deforestation on the Amazonian fire regime. All future scenarios with either simulated deforestation, global warming or the combination show an increase in the Amazonian fire regime.

All three studies connect land use or land cover changes as sources of ignition for simulated fires to explain the fire increase. Brando et al. (2020) conclude that scenarios without deforestation result in fewer sources of ignition, which in turn result in lower projected burned area. According to Le Page et al. (2017), the number of fire ignitions in the models can be set up as a function of land use. Prevention of further deforestation could therefore supress fire spread (Brando et al., 2020, Le Page et al., 2017, Fonseca et al., 2019). Brando et al. (2020) conclude that efforts are needed to eliminate sources of ignition and to supress fire spread in order to conserve the forest in southern part of the Amazonas. Both Brando et al. (2020) and Le Page et al. (2017) independently suggest that the techniques that now use fire in agriculture should be replaced.

Brando et al. (2020) test the hypotheses that there are more ignition sources along forest edges. The results showed that fire occurred along forest edges in arc of deforestation, which is consistent with fire occurrence the last decades (Brando et al., 2020). Fonseca et al. (2019) also noted that closeness to agriculture or secondary vegetation cover resulted in higher fire risk. There was also a slight shift in geography for fire distribution. Brando et al. (2020) noted that previous areas for fire hot spots showed a decrease while an increase was noted in new edges. The same pattern was shown in the simulations from Fonseca et al. (2019, Fig. 5b) where scenarios of high deforestation showed that areas of previous fire hot spots had a somewhat decreased fire risk while areas north of these old fire frontiers had an increase in fire risk. The scenario of low deforestation did not simulate this geography change (Fonseca et al., 2019, Fig. 5a). The same pattern can be seen in the simulations in Le page et al. (2017, Fig. 4b). The average annual maximum shows fire duration where a low deforestation scenario simulate a decrease in south eastern frontiers while a high deforestation scenario simulate an increase in areas north of these old frontiers. The simulations in average burned area on the contrary have the southeast parts as a fire hot spot regardless of simulated deforestation scenario (Le page et al., 2017, Fig. 5).

Table 3. Results from the literature review of three scientific articles where the scientists have analysed the impact from climate change as well as deforestation on the Amazonian fire regime during a simulated 21st century. RCP are potential future pathways of climate and land cover change during the 21st century developed by the IPCC (Pachauri et al., 2014) described in section 3.3.1. FRP stands for fire relative probability. The deforestation scenarios used by Fonesca et al. (2019) are the same used in Guimberteau et al. (2017)

Reference	Simulation interval	Simulated ΔClimate	Simulated ΔLand-cover	Result ΔFire distribution
Brando et al., 2020	2041-2050	RCP 2.6	None	3.6 Mha burned 2001-2010 ➔ 5.3 MHa 2041-2050
		RCP 2.6	Deforestation	3.6 Mha burned 2001-2010 ➔ 6.0 MHa 2041-2050
		RCP 8.5	None	3.6 Mha burned 2001-2010 ➔ 5.9 MHa 2041-2050
		RCP 8.5	Deforestation	3.6 Mha burned 2001-2010 ➔ 6.8 MHa 2041-2050
Fonseca et al., 2019	2071-2100	None	IPCC’s SSP1	+10.6% area with FRP>0.3
		None	IPCC’s SSP3	+73.2% area with FRP>0.3
		RCP 4.5	None	+6.9% area with FRP>0.3 in October
		RCP 8.5	None	+27.7% area with FRP>0.3 in October
		RCP 4.5	IPCC’s SSP1	+21.3% area with FRP>0.3 in October
		RCP 8.5	IPCC’s SSP1	+39.1% area with FRP>0.3 in October
		RCP 4.5	IPCC’s SSP3	+90.9% area with FRP>0.3 in October
		RCP 8.5	IPCC’s SSP3	+113.5% area with FRP>0.3 in October
Le Page et al., 2017	2080-2100	Today	Today	5400 km^2 area burned and 67% fire-free”
		RCP 8.5	None	+48% burned area & 75% fire-free” forest.
		None	RCP 8.5	+18% burned area & 47% fire-free” forest.
		RCP 4.5	RCP 4.5	+165% burned area & 56% ”fire-free” forest
		RCP 8.5	RCP 8.5	+850% burned area & 35% ”fire-free” forest

All three studies connect climate change with fire spread. Brando et al. (2020) noted that their model was sensitive to vapour pressure deficiency as well as drought, simulated in their model in the form of maximum climatic water deficit, MCWD. Le Page et al. (2017) noted that the fire spread rate in their model was dependent on weather, soil moisture and fuel structure. Fonseca et al. (2019) noted that precipitation in their simulations had a great impact on fire probability where high precipitation resulted in low fire probability while drought years resulted in high fire risk. Increased maximal temperature also resulted in increased fire risk (Fonseca et al., 2019). Brando et al. (2020) concluded that drought controlled the results of how much area that was simulated to be burned as well as the amount of emissions released. Projected regional warming also played an important role. Primary forest became flammable and burned during dry and warm conditions only. These conditions were mainly common after 2030. Their results indicate a doubling of burned area due to climate change by 2050. Fires will mainly occur in the arc of deforestation during climatic warm and dry years (Brando et al., 2020). Fonseca et al. (2019) explain that the relatively small increase in fire relative probability in their combined low climate change and low land use change scenario is caused by the relatively small change in precipitation and evaporation in the combination with scarce ignition sources. Le Page et al., (2017) stress the importance of maintaining a climate with enough moisture to keep away fire spread and to avoid human ignitions and disturbances.

Regarding seasonality, Fonseca et al. (2019) share that the dry season in the Amazon run July-September during years without drought and the fire season follows the same interval. Contrariwise, the part of the rainforest that is located on the northern hemisphere has its dry season January-March with fire season December-March. Fire season is extended in their simulations with a displaced peak. The largest change in fire probability was the large increase during the month of October. Therefore they present the results for October. Fonseca et al. (2019) point out that their simulations display a 30-year average. Years with extreme El Niño drought events could result in much higher fire probability (Fonseca et al., 2019). Particularly large fire events have in fact taken place during drought event of 2005, 2010 and 2015 (Brando et al., 2020). Warm periods of ENSO could lead to drought in the whole basin, which could lead to large fire events since probability of fire spread is larger during longer dry seasons (Le Page et al., 2017). Flammability could also increase if climate change leads to more frequent, intensive and extensive drought events (Brando et al., 2020).

6.4 The Amazonian tipping element in the local safe operating space framework

This section will present the findings in the form of a local safe operating framework. The information from the other sections has been used to identify potential control and response variables for the system changes as well as at what spatial and temporal scales they act. Potential limits or thresholds that have been identified in reviewed studies are listed for the purpose of trying to locate a potential boundary for a local safe operating space. The results of the findings are presented in Table 4 below.

Table 4. Overview of the findings on changes to the three feedbacks identified as vital in determining the future state of the Amazonian tipping element.

Human driver of change	Deforestation	Global warming	Fire: Ignition or creating savannah conditions
Type of feedback	Biogeophysical feedback	1. Biogeophysical feedback 2. Biogeochemical/Carbon feedback	1. Biogeophysical feedback 2. Vegetation-fire feedback
Control variable	Percentage of land area with a change in evapotranspiration within the range of simulated future	1. Percentage of land area with a change in evapotranspiration within the range of simulated future 2. Maintenance over Global net primary productivity	Percentage of land area with a change in precipitation within the range of simulated future
Response variable	Stability of climate pattern and land-atmosphere coupling (MAP, mm/yr)	1. Stability of climate pattern and land-atmosphere coupling (MAP, mm/yr) 2. Carbon uptake (Pg C)	Biosphere integrity (Tree cover, %)
Limit/Threshold	- 30-50% deforestation (Boers et al., 2017), - 10% of Amazonia or 60% of Cerrado (Pires & Costa, 2013) - Combination 32% deforestation + 14% precipitation reduction (Staal et al., 2015) - 40% deforestation (Nobre & Borma, 2009)	- 3-4°C Global warming (Nobre & Borma, 2009)	1. Water deficit: 400 mm/yr (Wuyts et al., 2017) 2. Tree cover ≈ 40-45% (Staver et al., 2011) -
Spatial Scale	Regional scale	Regional scale	Regional scale or Local scale
Temporal scale	Long term scale>10 years	Long term scale>10 years	Short term scale<10years

7. Discussion

This section discusses the result of what controlling environmental conditions define the forest and savannah stable states as well as predicted impact from global warming and deforestation. The results from the fire regime is integrated into these parts.

7.1 Controlling environmental conditions

This section discusses what controlling environmental conditions define the forest and savannah stable states.

Precipitation: From the five scientific article reviews, it is clear that precipitation in the form of both MAP as well as drought has been identified as a controlling variable in determining biome integrity. This agrees well with previous studies. For example, Brovkin et al. (1998) explain vegetation-precipitation interactions, which enable the multiple states to be stable. They showed that climate and precipitation influence what type of biome and vegetation that is able to thrive and that vegetation is linearly dependent on precipitation. Considering the key aspects of the water sub-boundaries presented in Gleeson et al. (2020A & B), this agrees perfectly with the findings of the Atmospheric water – hydroecology sub-boundary, who also concludes that precipitation over a certain land area is the controlling variable of terrestrial biosphere integrity.

At exactly what rainfall regime that the forest and savannah state are stable at varied somewhat between different studies. Since we are looking for the entire range, the highest interval should be included. In Table 1, we see that Staver et al. (2009) found forest state as low as at a MAP of 1000 mm/year. They also found the highest MAP that the savannah state had, which was 2500 mm/year. However, at what location they found the exceptionally high and the low MAP interval for these savannah and forest patches is not specified in Staver et al. (2009). Both Staal et al. (2016) and Wuyts et al. (2017) pointed out that areas close to perturbations, such as edges of the Amazon and agriculture were the areas in their studies that showed coexistence and bimodality of savannah state and forest state. This edge theory is further supported by the results from Brando et al. (2020), which showed that fire occurred along forest edges in arc of deforestation, which is consistent with fire occurrence during the last decades. Fonseca et al. (2019) also noted that closeness to agriculture or secondary vegetation cover resulted in higher fire risk, which further support this theory. According to Wuyts et al. (2017) the precipitation-biome relationship was disturbed at distances less than two kilometers from human perturbations where both MAP and Markham's Seasonality Index in the savannah-forest stability relationship was increased exponentially with reduced distance to agriculture. If for example the savannah patches that Staver et al. (2009) found at MAP of 2500 mm/year were near such edges, then these direct perturbations might be what hindered a forest state to flourish. If the results from Staver et al. (2009) have been influenced by areas very close to anthropogenic perturbations, the results from Staal et al. (2016) of 1100-2000 mm/year, which has taken such effects into consideration, would be a more accurate result. In the absence of such insight, we can conclude that the widest rainfall regime in which both the forest state and savannah state are stable according to the findings of these five studies therefore was found between 1000-2500 mm/year. With the forest stability relationship increasing exponentially with reduced distance to agriculture found by Wuyts et al. (2017), we can also conclude that close distance to human perturbations affects the possibility for a forest state to be stable. The findings in section 6.3.3 support this theory; Brando et al. (2020), Le Page et al. (2017), Fonseca et al. (2019) associated deforestation and agriculture with sources of fire ignition and partly the reason behind the predicted increase in fire regime during the 21st century. Fire promotes savannah state and forest tree mortality (Staver & Levin, 2012), which then could explain why savannah patches are more common close to agriculture. Theoretically, it would make sense to suggest that deforestation should be steered towards patterns that limits edge effects. Deforesting areas next to already deforested areas rather than untouched areas surrounded by forest at all sides. How such different locations ideally affect the rainfall regime to minimize changes is not clear. Also, feedbacks from edge effects have not been a focus in this thesis. If the edge effect has such a large impact as Wuyts et al. (2017) suggest, a focus on its potential feedbacks and spatial interactions would be interesting to include in further research. Avoiding deforestation completely is obviously to be preferred. As highlighted in the limitation section, social, economic or political aspects will not be analysed. However, it is important to note that these aspects are driving deforestation in the Amazon River basin. Wheather the benefits of deforestation overcome the further consequences they might have on the stability of the rainforest is a vital discussion that must be tackled.

Another interesting point is that Hirota et al. (2011) and Wuyts et al. (2017) noted that areas with a dryer climate and thereby a lower resilience are situated in eastern and south-eastern parts of the Amazon River basin. These are the same areas that have been exposed to the highest deforestation and other anthropogenic perturbations (Hirota et al., 2011; Wuyts et al., 2017). These areas have the highest risk for drought (Hirota et al., 2011). Something that is not clear is whether these areas already had low MAP and low resilience from the start or if the deforestation has made these areas dryer? Brovkin et al. (1998) explain that there is a moist entropy gradient between the land area and the ocean, a main factor in precipitation dynamics. Precipitation is non-linearly dependent on vegetation, where vegetation impacts the climate and precipitation through surface albedo as well as surface roughness. A land cover change that means a change in albedo like in this case deforestation and agriculture could therefore lead to a state shift of the system (Brovkin et al., 1998). Weather the low resilience in the eastern parts of the Amazon River basin is only due to deforestation and human perturbation or if it is also due to previous climate patterns has not been examined in this thesis but would be an interesting aspect to look at in further research in order to fully determine the effect of deforestation and add to the debate.

Concerning limits or thresholds, the five different studies showed no clear limits in precipitation. As seen in Table 1, Hirota et al. (2011), Staal et al. (2016) and Wuyts et al. (2017) found equal probability of an area to have a forest or savannah state at 1900, 1760 and 1500 mm/year respectively. Either, it is because they have had slightly different data, different interpretation methods or if there are other controlling environmental conditions also affecting probability has not fully been explained. It has already been noted that fire and closeness to anthropogenic perturbations have a great impact on forest stability. The wide range of bistability as well as uncertain limits for the forest and savannah state support the theory from Staver and Levin (2012), that the fire-vegetation feedback could explain the observed bimodality in tree cover at intermediate rainfall. They suggest that both climate and fire determine tree cover and biome distribution at intermediate rainfall.

Drought and fire: Regarding drought, three very different forms of measurements were used between four studies, which make them difficult to compare. What can be concluded is that drought limits forest stability. Staver and Levin (2012), who analysed the vegetation-fire feedback, explained in section 6.2.3 that drought results in higher tree mortality while rainfall increases the opportunity for trees to establish while it reduces tree mortality. Drought could also facilitate spread of fire as was identified in section 6.3.3 where predicted changes in the fire regime during the 21st century was increased with climate change for all three studies (Brando et al., 2020, Le Page et al., 2017, Fonseca et al., 2019). Fonseca et al. (2019) noted that precipitation in their simulations had a great impact on fire probability while high precipitation resulted in low fire probability and drought resulted in high fire risk. One could therefore argue that precipitation or lack thereof is a controlling variable of possibility for fire to exist. The findings from Wuyts et al. (2017) that fire was prevalent in places with water deficit of 400-800 mm/year further support this theory.

Wuyts et al. (2017) also found that fire in their study was prevalent when 5<Tree cover<40%. This agrees with the findings of Staver et al. (2011) who estimated that fire only existed until a certain threshold, a tree cover of 45 or 50%. This support the theory of Staver and Levin (2012) who suggested that fire spread is dependent on grass cover. With higher tree cover, forest cover leading to closed canopies are highest in the competitive hierarchy and outcompete grass. Moreover, Staal et al. (2016) points out that logging can create savannah conditions in a forest because it opens up the canopy and reduces tree cover. This means that humans disturb the competitive hierarchy. With lower tree cover and grass presence, fire spread is possible.

Meanwhile, as mentioned in the background, the vegetation-precipitation relationship illustrate potential equilibria for the system where the two relationships coincide (Brovkin et al., 1998). Could these vegetation-precipitation relationship equilibria coincide with the stable and instable tree covers percentages? Theoretically, if the vegetation-precipitation relationship coincides for the Amazon River basin at around 80% tree cover and around 10% tree cover and divert at around 50-60% and 5 % tree cover, this could possibly suggest an additional explanation to the conclusion from Hirota et al. (2011) that the instability was due to positive feedbacks such as fire. However, such a vegetation-precipitation relationship would have to be set up in order to offer this as a valid explanation. The instability does suggest rapid transitions.

Moreover, something that is important to note is that Staver et al. (2011) suggested there are signs of changes between states in South America because the fire distribution were not as sharp in South America as on other studied continents in their study. This change is also supported by the results for the predictions in section 6.3. The predictions show that some areas are in fact predicted to get a changed climate regime. This is supported by the results from Brando et al. (2020), Le Page et al. (2017) and Fonseca et al. (2019) who conclude that global warming will lead to an increase in the fire regime. The different fire distribution patterns could however also reflect the patterns of anthropogenic ignitions sources in South America where both deforestation and fire techniques in agriculture according to Brando et al. (2020), Le Page et al. (2017) and Fonseca et al. (2019) are associated with fire spread. Staver et al. (2011) noted that a large portion of the Amazon that is currently in a forest state has precipitation patterns with intermediate MAP and mild seasonality that could support both biomes. This could mean that even without changes in the rainfall regime, these large areas with intermediate MAP could transition under changes to the fire regime or closeness to other anthropogenic perturbation.

7.2 The Amazon during the 21st century

This section discusses the combined results of what effect that current scientific studies project that anthropogenic perturbation in the form of deforestation, global warming and fire will have on the Amazonian tipping element during 21st century. In this part, the result for each investigated perturbation in the form of feedbacks, projections as well as potential boundaries for a local safe operating space is discussed.

7.2.1. Effects of deforestation

In this second part, the impact on the Amazonian tipping element during 21st century of deforestation is discussed.

Changes to MAP: The simulated effects from deforestation varied between studies where some showed an increase while others showed a decrease in precipitation in response to deforestation. This was apparent in the peer-review results from Spracklen and Garcia-Carreras (2015) where the results from the 44 studies varied greatly from an expected increase in precipitation of 15% to a reduction of 57%. This indicates that there are differences in perception within the scientific community about what impact the deforestation will have on the rainfall regime during the 21st century. This makes it more difficult to conclude with good confidence what will happen. However, there are five arguments that back up an expected decreased MAP in response to deforestation. Firstly, a large majority of the projections did predict a decreased MAP in response to deforestation: Pires and Costa (2013), Guimberteau et al. (2017) as well as 92% of the simulations in Spracklen and Garcia-Carreras (2015) concluded that deforestation would have a reduced effect on MAP. Secondly, Brovkin et al. (1998) argue that vegetation impacts the climate and precipitation through surface albedo as well as surface roughness. A land cover change to lower tree cover, would in theory lead to lower precipitation

(Brovkin et al., 1998). Thirdly, Boers et al. (2017) explain the feedback theory behind what land-atmosphere interaction that takes place during deforestation in the Amazon River basin. The land cover change to agriculture leads to an increased albedo and a decreased evapotranspiration. Simplified, these changes in energy fluxes prevent the moisture feedback to be maintained, which results in reduced precipitation. Moreover, Staal et al. (2020), who suggested a drought-deforestation feedback coupled 4% of recent drought has occurred due to the effect of deforestation as evidence of deforestation is actually causing lower MWCD in practice. Lastly, Spracklen and Garcia-Carreras (2015) noted that all of the studies whose results showed an increase in precipitation had simulated only a small area of deforestation. These five arguments together make a stronger argument to a rainfall regime with reduced MAP in response to deforestation in the Amazon during the 21st century.

Limit/Threshold: Boers et al. (2017) identified that there is a threshold situated between 30-50% deforestation. This goes well with previous estimations of a threshold at around 40% deforestation from Nobre and Borma (2009). The threshold identified from Staal et al. (2015) at 32% deforestation in combination with 14% precipitation reduction also align with the same interval. They also conclude the fire-feedback in their modelling, which excludes a large uncertainty. The estimated threshold from Pires and Costa (2013) at 70% deforestation of the Amazon River basin or 10% deforestation of Cerrado does not fit as well with the others. From this we can conclude that an exact threshold is uncertain but most studies have identified the threshold somewhere between 30-50%. Since the boundary is placed in the lower range of uncertainty as a precaution (Gleeson et al., 2020B), the results suggest setting the boundary for a local safe operating space boundary at 30% deforestation. However, what must be highlighted when communicating such a boundary is that deforestation is not the only reason behind land-cover change that give rise to these changes in atmospheric water hydroclimate. As mentioned in the background, Bullock et al. (2020) mapped deforestation, degradation and natural disturbances in the Amazon River basin during 1995-2017 and concluded that degradation and natural disturbances has had affected approximately the same area of the rainforest as deforestation during the interval. Largest impacts took place during periods connected to severe drought events of 1998, 2005, 2010 and 2015-2016 (Bullock et al., 2020). Furthermore, global warming could cause forest dieback and therefore further land cover changes (Cox et al., 2004; Betts et al., 2004; Zemp et al., 2017). Meanwhile, increased fire regime due to climate change induced drought and increased ignition sources from deforestation and agriculture (Brando et al., 2020; Fonseca et al., 2019; Le Page et al., 2017) also promote land cover changes into reduced tree cover. The boundary for setting a local safe operating space boundary of 30% land cover change instead of deforestation might better reflect the feedbacks.

Furthermore, the high deforestation scenario described and used by both Guimberteau et al. (2017) and Fonesca et al. (2019) corresponded to the high land cover change from IPCC's SSP3 (Fonesca et al., 2019) is therefore considered a probable scenario. This scenario shows a deforestation of 19500 km^2/year after 2020 resulting in a total of 34% deforestation by 2100 (Guimberteau et al., 2017). Such a scenario, would then cross into the danger zone risking a tipping of the Amazonian climate system.

How would this affect the biome integrity? Considering the possible future stable state and biosphere integrity from the results in section 6.1 in combination of the key aspects of the water sub-boundaries presented in Gleeson et al. (2020A & B), we can expect precipitation over a certain land area to be the controlling variable of terrestrial biosphere integrity. How MAP would change across the Amazon River basin would vary greatly for different location because of local and regional climate patterns as well as topological differences. If we make a grave approximation and take the MAP in the Amazon River basin is varying between over 3000 mm/year in north-western parts of the basin to less than 1500 mm/year in the transition zones (Malhi et al., 2009), then solely based on these very approximate values a 40% reduction in MAP would mean a transition in eastern part. With a 40% reduction, the eastern parts would receive an approximate MAP of 900 mm/year. This is below the interval of intermediate rainfall of 1000-2500 mm/year where both forest and savannah was found to be stable in section 6.1. The western parts would receive a MAP of 1800 mm/year. Compared to the same interval of bistability, places western the Amazon River basin in the intermediate rainfall range, meaning that both forest and savannah are possible stable states. Changes to the fire regime would then also be a determining factor for the future of the rainforest in western parts of the Amazon River basin in such a scenario of bistability based on the findings from Staver and Levin (2012). The results from Brando et al. (2020), Fonseca et al. (2019) and Le Page et al. (2017) all indicate that deforestation would lead to an increase in the fire regime by providing sources of ignition. Moreover, what kind of impact the transition in easthern the Amazon River basin with potential cascading effects described from Zemp et al. (2017) would have on the western parts of the basin is even more difficult to quantify.

7.2.2. Effects global warming

In this second part, the impact on the Amazonian tipping element during 21st century of global warming is discussed.

Changes to MAP: Combining the results from the MAP predictions and the predicted feedback consequences from global warming, the result is uncertain and highlight a gap in knowledge. The simulated consequences from global warming varied between the 35 and 19 models used by Duffy et al. (2015) and Malhi et al. (2009) respectively. As a group for the Amazon River basin as a whole, neither of the two studies showed any differences in MAP. This agrees well with was highlighted in Latif and Keenlyside (2009), that some models predict increase, some decrease while some show no difference in amplitude of the ENSO. Latif and Keenlyside (2009) concluded that ENSO's response to global warming is highly uncertain with our current knowledge of ENSO responses. These results of no significant change in MAP does not reflect the major changes in feedbacks and impacts proposed by Betts et al. (2004), Cox et al. (2004) and Zemp et al. (2017). With these feedbacks as a starting point, Cox et al. (2004) predicted a reduction in MAP of more than 60% by 2100. Meanwhile, the multi-scale model simulations from Guimberteau et al. (2017) without deforestation projected a temperature increase by 3,3°C and an increase in precipitation of 8,5% by 2100 and not a decrease. This means that either the estimation of the impacts of these feedbacks are in fact greatly exaggerated or current global climate models fail to account for these feedbacks. Since these major feedback consequences were proposed already in 2004, the many years until the newer studies allowed time for these effects to be integrated into updated models. Duffy et al. (2015) used 35 global climate models from the Coupled Model Intercomparison Project Phase 5, CMIP5, which should represent currently used models in a wide range with credibility in the research community. Malhi et al., (2009) used 19 different Global Climate Models from IPCC's forth assessment report, which should also represent Global Climate Models with credibility in the research community. Latif and Keenlyside (2009) also highlighted lack of knowledge and difference in opinion in the scientific community. They concluded that since ENSO's response to global warming varies greatly by different models and in different studies, it is therefore highly uncertain with our current knowledge of ENSO responses. Seeing that these newer studies from Duffy et al. (2015) and Malhi et al. (2009) also exhibit the same uncertainty, we can conclude that there is still a need for research to find out what ENSO's response to global warming will be like in order to be able to draw any conclusions of future changes to the ENSO with confidence. Considering that these radiative forcing effects on SST patterns represented 80% of the predicted initial precipitation reductions from Betts et al. (2004) and the reason for forest dieback leading to cascading effects, if ENSO's response to global warming will not lead to SST pattern resulting precipitation reduction, the differences in predicted forest dieback is huge. This suggest a continued uncertainty and difference in opinion within the scientific community about how SST patterns will be affected by increased atmospheric carbon concentrations and how this will affect the climate over the Amazon River basin. Further research is needed in order to be able to make conclusions especially since these could have a cascading effect as suggested by Zemp et al. (2017), Betts et al. (2004) and Cox et al. (2004).

Moreover, there is also a gap in knowledge of the effects on biomass productivity from increased atmospheric carbon concentrations. As mentioned in the background research, elevated levels of carbon in the atmosphere due to anthropogenic emissions could in theory give a positive effect on biomass productivity and increased precipitation (Nobre & Borma, 2009; Malhi et al., 2008). Brovkin et al. (1998) also suggested that enhanced carbon concentrations in the atmosphere shift the relationship so that given vegetation cover results in higher MAP than for lower carbon values. Little attention was given to this potential effect in the studies. The only one examining this effect was Malhi et al. (2009) who concluded that the effect of carbon offset the effect of temperature rise in evapotranspiration. However, they did not integrate this effect in their model simulations. Meanwhile, Betts et al. (2004) suggest that reduced stomatal opening due to increased atmospheric carbon concentrations could instead lead to reduced moisture recycling, which leads to reduced precipitation. Further research is needed to evaluate the net effect of these physiological forcings. What can be concluded regarding the carbon cycle however is that with forest loss and fire, carbon emission would increase and providing even higher carbon concentration to the atmosphere.

Seasonality: Regarding seasonality, all three studies project an increase of drought in eastern parts of the Amazon River basin in response to global warming. Duque-Villegas et al. (2019) suggested that global warming due to emissions could lead to a higher frequency in El Niño events because it reduces temperature gradients in the East equatorial Pacific Ocean, which create the changes in convection zones that take place during El Niño events. This agrees with Zemp et al., (2017) who suggested that the dry season might become longer and more intense with these changes in SST. Fonseca et al. (2019) also support this by predicting an extended drought and fire season. This also agrees with predictions of higher frequency of both extreme flooding and drought from Duffy et al. (2015). Observed trend agrees with these predictions. Firstly, Latif and Keenlyside (2009) highlighted that a warming trend has been observed in SSTs in the Equatorial Pacific during the last 50 years that coincide with the global warming trend. The trend does have El Niño patterns (Latif & Keenlyside, 2009). Secondly, the increase in frequency of mega-events of drought and flooding highlighted by Marengo et al. (2018) made them suggest that there is already an increase in frequency and intensity of drought and flooding events. Increased seasonality could have a huge impact on biosphere integrity because drought could lead to tree mortality resulting in forest degradation as well as increased risk for fire as described by Staver and Levin (2012). Both Malhi et al. (2009) and Duffy et al. (2015) predict more droughts in eastern parts of the basin. This agrees with observations already seen with more droughts in eastern parts of the Amazon River basin (Marengo et al., 2018). It also has the same outcome as the consequences for deforestation. It is also where fire has been most common (Brando et al., 2020).

Limit/Threshold: The only identified limit or threshold found was estimation from the earlier literature review made from Norma and Borma (2009) at 3-4°C. Using these results, the boundary for a local safe operating space boundary at 3°C increase in global warming. However, there are many uncertainties in this suggested threshold. Further research about the effect of global warming on both the ENSO's response to global warming and the effects on the Amazon is needed to be able to set a boundary for a local safe operating space with confidence.

How would this affect the biome integrity? Considering that there is a big difference in opinion about what impacts global warming will have on MAP, no conclusions could be made with high confidence about the effects on biome integrity. The stronger arguments for an increased seasonality however, with increased drought in especially the eastern parts of the basin, points to a possible state transition towards lower tree cover. Especially in the areas near deforested areas since Brando et al. (2020), Le Page et al. (2017), Fonseca et al. (2019) all predicted an increase in fire regime in eastern Amazonia and associated deforestation and agriculture with sources of fire ignition and part reason behind predicted increase in fire regime during the 21st century. All studies did indicate a decreased resilience for forest cover in eastern parts of the basin with the possibility of change. For western parts of the basin, with results varying between studies, the future is more uncertain.

7.2.3. Effects of fire

The effects on fire due to deforestation and global warming are discussed under 7.2.2 and 7.2.1 respectively. In this section the setting of a potential boundary for a safe operating space framework is discussed.

Limit/Threshold: As mentioned in section 6.1.2 Wuyts et al. (2017) found that fire in their study was prevalent with a water deficit of 400-800 mm/year. This agrees with the savannah conditions concluded by Malhi et al. (2009) of MCWD being less that -400mm. Therefore, a boundary for a local safe operating space framework regarding logging, fragmentation or deforestation should be set at a water deficit of 400 mm.

Furthermore, as pointed out by Staal et al. (2016), human perturbations in the form of logging can create savannah conditions in a forest because it opens up the canopy and reduces tree cover and therefore have direct impact on forest instability and possibility for fire spread. Staal et al. (2016) also suggest that coexistence could implicate spatial interactions between neighbouring patches. Staver et al. (2011), suggested that fire was only prelevant until a certain threshold, which was estimated at a tree cover of 45 or 50%. Setting a boundary for logging could hence be needed. Hirota et al. (2011) identified conditions of already 60% tree cover to be unstable where a forest could shift towards a savannah state during perturbations. A boundary for a local safe operating space framework regarding logging, fragmentation or deforestation should therefore be set above 60%. At least at 65% tree cover but higher would be preferred. Ideally logging should be stopped in order to keep higher resilient to meet the increase in drought that is predicted. Agriculture should also move to other techniques not including fire, in order to limit fire ignition as concluded by Brando et al. (2020) and Le Page et al. (2017).

8. Conclusion

What controlling environmental conditions define the forest state and savannah stable states?

Studies show that precipitation in the form of both MAP as well as seasonality is the main controlling variable for biosphere integrity. There is however, no sharp limit in rainfall regime between the forest state and savannah state. Fire can spread at an intermediate rainfall regime or during periods with low water deficits. Fire therefore has an impact on what type of biome that can grow under intermediate rainfall only. Tree covers of around 60% are found to be unstable. Deforestation, fragmentation or logging could therefore make a forest unstable and more prone to a state transition. Forest areas close to agriculture or edges are subject to perturbations and therefore have lower resilience. Area close to agriculture and deforestation coincide with areas of low rainfall, high fire regime and drought.

What kind of positive feedbacks do anthropogenic perturbations in the form of deforestation, global warming and fire spread provoke and what consequences do they have on the tipping element?

Deforestation is expected to involve a biogeophysical feedback and impact on the climate system. The land-cover change increases albedo and decrease evapotranspiration. This impacts the moisture inflow from the ocean, resulting in decreased precipitation across the Amazon River basin. Global warming is expected to involve both biogeophysical feedbacks as well as a biogeochemical feedback in the form of a carbon feedback. More research is needed to conclude as to how global warming will affect the ENSO and the net effect of the carbon feedback. Under intermediate rainfall, a fire-vegetation feedback could maintain savannah conditions and hinder forest to re-establish once burned.

What impact do current scientific studies project that anthropogenic perturbation will have on the Amazonian tipping element during 21st century?

The results show that further deforestation is expected to result in a decrease in MAP during the 21st century. The impact on MAP of increased carbon emissions and global warming during the 21st century is currently uncertain. Seasonality is however expected to increase in response to global warming. The eastern parts of the basin are expected to suffer from more intense drought with both higher frequency and amplitude of dry seasons. Increased deforestation and carbon emissions are expected to lead to an increase in the fire regime with increasing areas affected by fire. Deforestation contributes to the increase by providing more ignition sources. Deforestation further into the Amazon River basin would result in a slight shift in geography for forest fire frontiers and distribution. Global warming is expecting to contribute to the increase by providing dryer conditions and higher temperatures with increased emission scenarios. The fire season is expected to become prolonged with the extended drought.

Could current research focusing on the Amazonian tipping element be used to set boundaries for a local safe operating space framework?

The result suggests a boundary for land cover change to be set at 30% for the local safe operating space. Crossing such a threshold of land cover change could have great impact on the stability for land-atmosphere coupling and climate. This could lead to state transitions in eastern Amazonia and a possibility for transitions in western parts of the basin.

Concerning global warming, further research is needed in order to determine a boundary for a local safe operating space. Regarding a possible safe operating space for fire spread, results indicate that water deficits need to be kept under 400 mm/year. Logging, fragmentation and deforestation leading to reduced tree cover and instable limits, should be avoided. Furthermore, agriculture should be steered towards techniques without using fire in order to reduce ignition sources.

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