Baltic Blue Carbon Systems Under Global Change: Assessing Soil Reduction Potential

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ABSTRACT

As anthropogenic climate change increases in severity, carbon removal from the atmosphere is essential to mitigate global impacts. Blue carbon systems, coastal systems that are known for their high carbon sequestration potential, are key to mitigating global climate change. Coastal marshes, a type of blue carbon ecosystem, have a great potential for carbon sequestration and are particularly under-studied in Europe's Batic region. Five Northern European Universities founded the NordSalt experiment to better understand carbon fluctuations, plant biodiversity, and soil biogeochemistry of the Baltic coastal marshes of Denmark, Finland, and Sweden in response to climate change. This project specifically investigates the biogeochemistry of these soils using the Indicator for Reduction in Soils (IRIS) method to assess soil reduction potential and resulting oxygen availability. Using this reduction data we found no significant impact of warming on soil reduction potential with an ANOVA P-Value of 0.57750, indicating a degree of ecosystem resilience in the face of global change. We did find a significant impact of cattle grazing on soil oxygen availability (P-Value of 0.04233) as well as significant differences between soil country origin (P-Value of 0.00239). Our results indicate that Baltic blue carbon systems will likely demonstrate resilience to global temperature rise, but only if they are protected from land use practices such as cattle grazing.

KEYWORDS

coastal marshes, climate change, soil biogeochemistry, IRIS method, coastal land management

INTRODUCTION

Coastal marsh ecosystems are characterized by regular flooding from tidal or non-tidal sources of saline to brackish water (Adam 1990; Dijkema 1990). Due to this flooding, coastal marsh ecosystems have high salinity soils that limit plant communities. Coastal marsh vegetation must be highly resistant and adaptable to changing tidal conditions, soil chemistry, and land shifts (Adam, 1990). These species also face soil conditions with large water content and are even submerged for prolonged periods of time with limited access to sunlight (Adam, 1990). Blue carbon systems are coastal ecosystems of special interest in the climate crisis for their carbon sequestration capacity (Mcleod et al., 2011; Wang et al. 2019). Coastal marshes are a type of blue carbon ecosystem that play important roles in coastal dynamics and are notable for their nutrient cycling abilities. However, coastal marshes are declining globally at an estimated annual rate of 0.7% to 7% due to increasing sea levels and land use practices such as diking and agricultural grazing (Duarte et al., 2005; Mcleod et al., 2011; Spivak et al., 2019).

Assessing the ability of soils to maintain oxygen is key to better understanding how blue carbon ecosystems will respond to a warming climate. Oxygen in soils is required to support plant and microbial life and thus a healthy and functioning ecosystem (Mobilian and Craft 2022). Anaerobic soil conditions are characterized by lower oxygen levels while more aerobic conditions are characterized by higher oxygen values (Mobilian and Craft 2022). Oxygen availability is commonly assessed by measuring Reduction-Oxidation reactions in the soil. Analyzing reduction values will indicate the levels of oxygen in soils that will be able to support plant and microbial communities.

It is not yet well understood how Baltic blue carbon systems will respond to warming, specifically, how soil oxygen levels and resulting ecosystem health will be impacted. Rising global temperatures alter plant respiration, microbial activity, and soil moisture but these impacts have not yet been studied in Baltic systems (Mueller et al. 2018). It is also not fully understood how land management practices such as cattle grazing impact the soil biogeochemistry of these regions.

This project seeks to assess how the soil biogeochemistry of Baltic coastal marshes will respond to rising global temperatures by investigating differences in soil reduction potential due to temperature treatments, grazing treatments, and varied country of origin. Specifically I will be seeking to answer: How will the soil biogeochemistry of Baltic coastal marshes respond to rising global temperatures? I will investigate this question by addressing three sub-questions: How does soil reduction potential in Baltic coastal marshes respond to different temperature treatments? Do land use practices impact soil reduction potential in Baltic coastal marshes? How does soil reduction potential vary among the salt marsh ecosystems of Denmark, Finland, and Sweden? I hypothesize that soil reduction potential will be significantly different between all three treatment groups and thus reveal negative impacts of warming and grazing, as well as difference in soil reduction potential due to varied soil composition between countries.

METHODS

NordSalt experiment

The NordSalt experiment was founded in order to better understand coastal marsh ecosystem dynamics under climate change. For this experiment, teams from Aarhus University, the University of Hamburg, Southern Danish University, Stockholm University, and Turku University harvested coastal marsh plots from the Baltic coasts of Denmark, Finland, and Sweden in Fall of 2021 and constructed a mesocosm at the University of Hamburg in Northern Germany. In order to harvest these plots, sections of soil were removed and placed in crates for transport. The experiment began in June of 2022 and data regarding carbon fluctuation, soil biogeochemistry, and plant biodiversity were collected until the experiment's termination in November of 2023. The mesocosm consists of 30 plots from each region of both grazed and ungrazed land types (Figure 1). Warming treatments are randomly applied based on feedback control from the ambient plots, of temperatures +1.5°C, +3°C, +4.5°C, and +6°C (Figure 2).

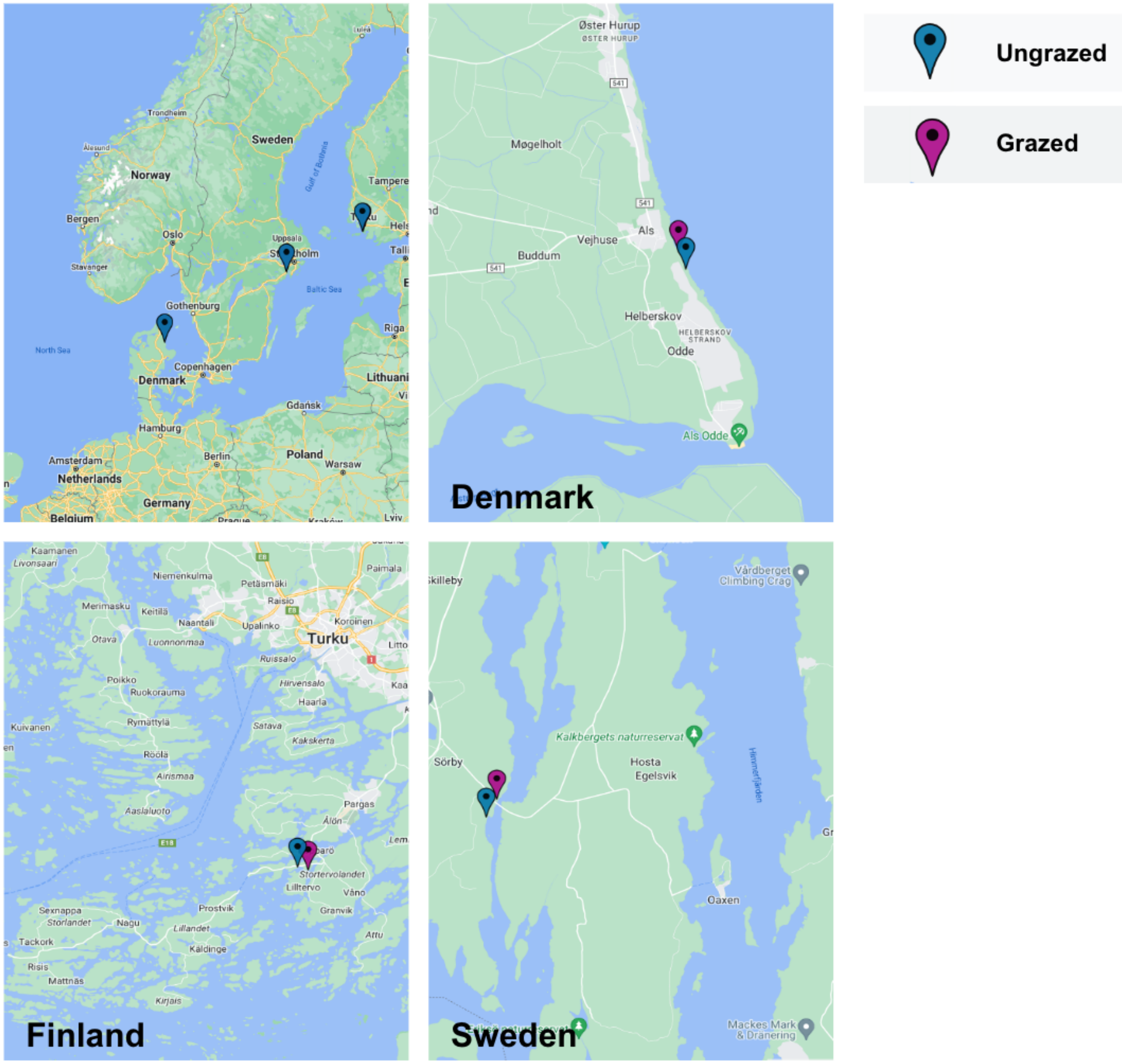

Figure 1. NordSalt Experiment Sample Sites. Denmark grazed 56°45'00.9"N 10°18'03.8"E and Denmark ungrazed 56°44'46.9"N 10°18'14.9"E; Sweden grazed 58°59'27.6"N 17°37'14.9"E, Sweden ungrazed 58°59'12.7"N 17°36'58.4"E; Finland grazed 60°14'26.6"N 22°12'54.7"E, Finland ungrazed 60°14'34.5"N 22°11'50.8"E (© NordSalt).

Figure 2. NordSalt Experiment Plot Layout including dispersal of country of origin, grazed and ungrazed plots, and warming treatments. Grazed plots are in light green and ungrazed plots in dark green. Box color corresponds to warming treatment. No color denotes ambient or no temperature treatment, dark blue denotes +1.5°C, orange +3°C, red +4.5°C, and purple +6°C.

IRIS method

In order to assess soil oxygen availability we measured soil reduction potential using Indicator for Reduction in Soils (IRIS) Sticks. These PVC sticks are coated in orange ferrihydrite $FeCl_3$ paint that indicates reduction in soils when the paint is depleted (Figure 3). The IRIS method provides visual insight into long-term redox dynamics in the soil and relies on the reduction of Fe(III) to Fe(II) in the absence of oxygen (Figure 4) (Jenkinson 2002). As iron is reduced in soils, the orange color of the IRIS sticks will be removed leaving the white PVC background (Reddy and DeLaune 2008). This method follows that of Jenkinson (2002) and Castenson and Rabenhorst (2006). Other methods for soil reduction potential measurements utilize running a current between two electrodes placed in the soil (Vaughan and Rabenhorst 2006). However, this method only captures a small data set at a specific time point across approximately 1 mm of soil. It is also more costly and time consuming (Vaughan and Rabenhorst 2006). The IRIS method allows for long-term soil redox assessment across greater soil depths with lower cost and simpler deployment. I placed these IRIS sticks in each of the 90 coastal marsh plots so that the entirety of the paint is submerged in the soil. After 6 weeks, I removed the sticks and gently washed them with tap water before leaving them to dry overnight. I repeated this for a total of 3 stick cycles over a 12 week period during the 2023 Summer season.

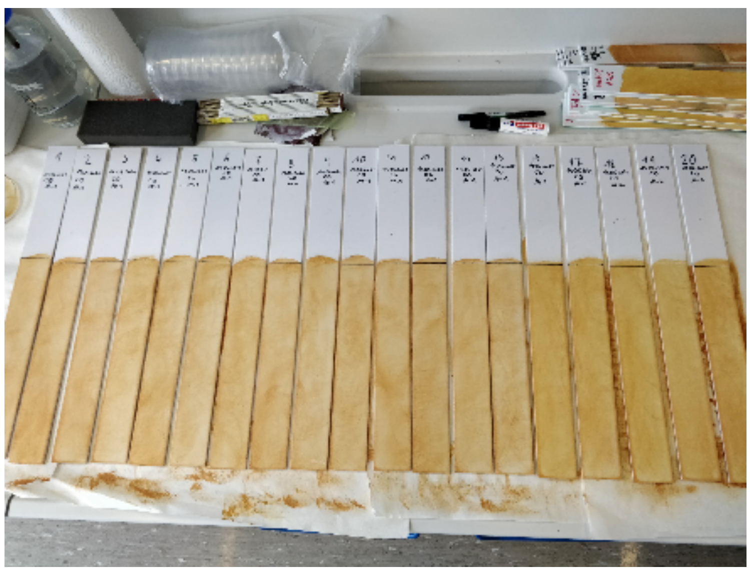

Figure 3. Freshly painted IRIS sticks (© Mittmann-Götsch).

Figure 4. IRIS sticks after 6 weeks of placement in the NordSalt Experiment.

I then scanned the IRIS sticks (Figure 5) and processed the resulting images in ImageJ.

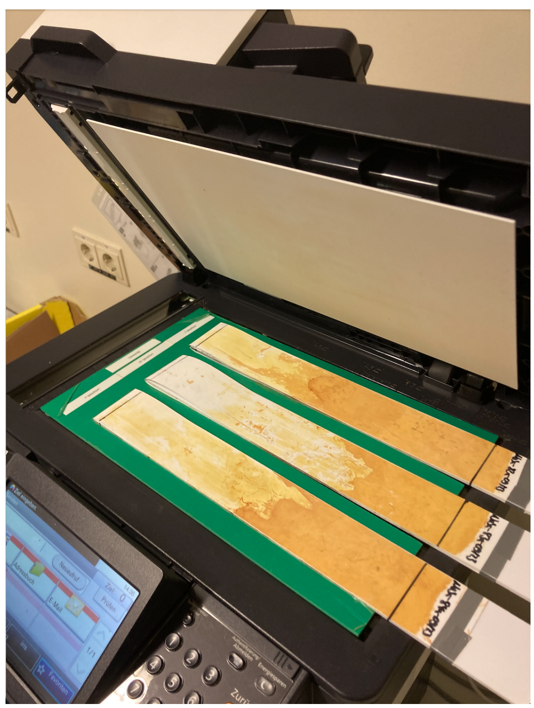

Figure 5. IRIS stick scanning process.

Data analysis

To analyze the reduction index data, I ran ANOVA statistical tests to determine any statistically significant differences between the warming and grazing treatments as well as plot origin. Using ANOVA testing I investigated whether there was a statistical difference in the reduction index values of the plots among the different warming treatments. I also investigated significant differences in reduction index value by grazing treatment (grazed and ungrazed) and plot origin (Denmark, Sweden, Finland). All analyses were performed in R version 2023.09.1+494.

RESULTS

Impact of warming treatments on oxygen availability

We found that the warming treatments did not significantly alter oxygen availability in plot soils. Using the Reduction Index value data we generated P-values upon completing a three-way ANOVA statistical test in RStudio (Table 1). These values revealed no significant difference in the reduction index values by warming treatment (Figure 5). This indicates that the warming treatments did not significantly impact oxygen availability in the NordSalt plots.

Table 1. Three-way ANOVA results.

Condition	dF	F	P
Country	2	6.073	0.00239
Grazing	1	4.132	0.04233
Warming	4	0.721	0.57750
Country:Grazing	2	0.992	0.37102
Country:Warming	8	1.853	0.06399
Grazing:Warming	4	0.749	0.55886

Country:Grazing:Warming	8	2.428	0.01336

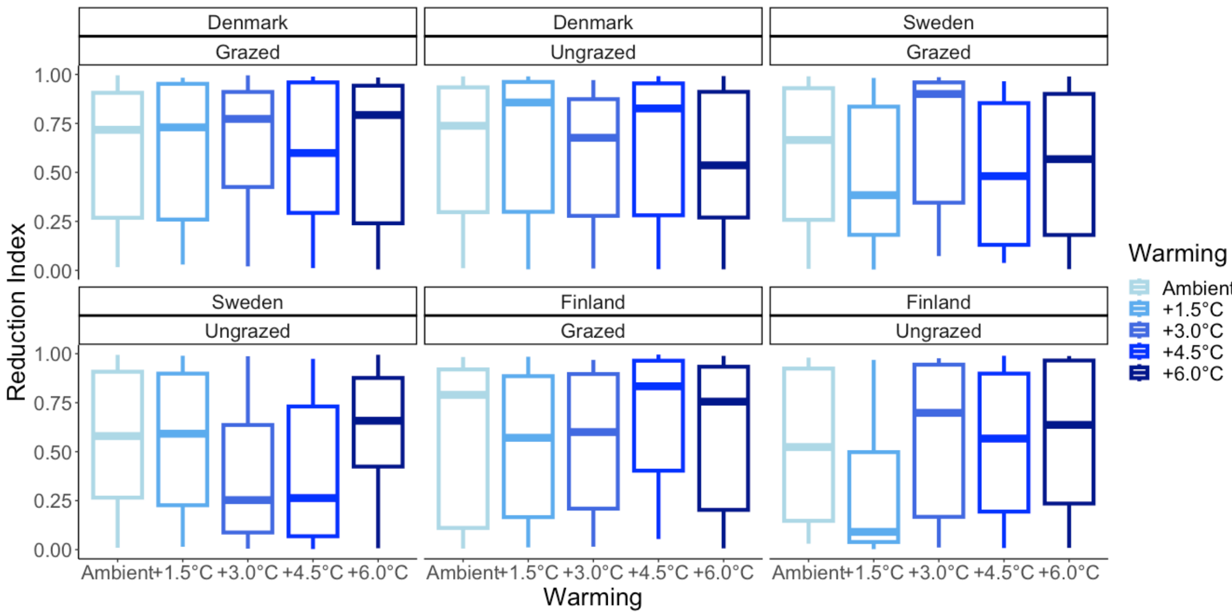

Figure 5. Three-way plot of warming treatments, grazing treatments, and plot origins.

Impact of cattle grazing on oxygen availability

We found that the cattle grazing plot treatment did significantly alter oxygen availability in the soil (Figure 6). The grazed plots had significantly higher reduction index values indicating a greater degree of paint reduction on the IRIS sticks in grazed plots (Table 1). As paint is reduced from the IRIS sticks in the absence of oxygen, we can conclude that grazed plots feature less available oxygen than ungrazed plots. Thus, we found more anoxic soil conditions in plots that have received the grazing treatment in comparison to plots that did not receive the grazing treatment.

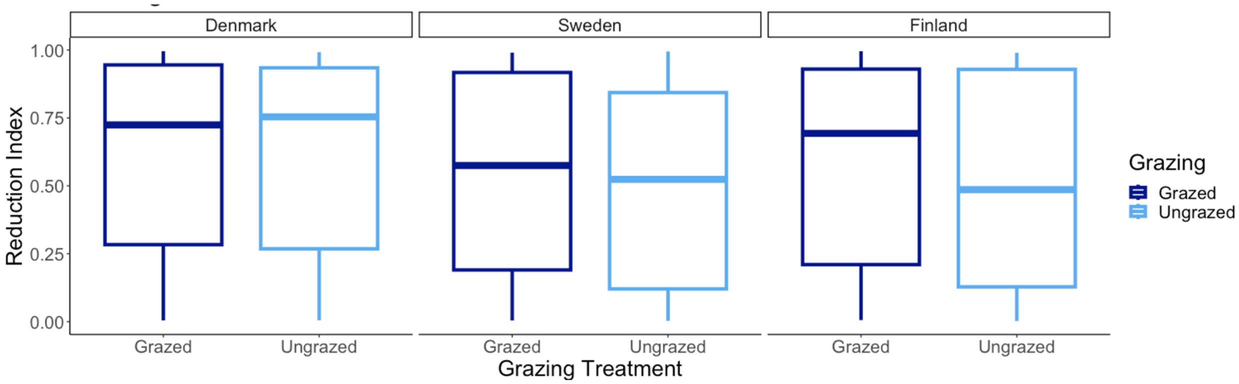

Figure 6. Reduction index values plotted with grazing treatment by country.

Impact of plot origin on oxygen availability

We found that plot country of origin revealed significantly different oxygen availability between soils (Figure 5). This indicates differences in soil content and composition and resulting variance in Reduction-Oxidation potential and oxygen availability between plots. We found that Denmark varied from Sweden and Finland, and that Sweden and Finland were similar to each other (Table 1).

DISCUSSION

Our results illustrate the role of both environmental temperature increase and land management practices in soil oxygen availability and resulting ecosystem health of Baltic coastal systems. We investigated the impacts to soil geochemistry of temperature increases ranging from +1.5°C to +6°C as well as cattle grazing land management practices. The data also confirms our understanding of differences between soils from each plot origin in terms of their soil organic matter compositions.

Impact of warming treatments on oxygen availability

We found that as plot temperature treatments increased, there was no significant change in reduction index value demonstrating a consistent level of oxygen in plot soil. The soil's ability to maintain oxygen levels is key to sustaining plant and microbial life and speaks to the system's capacity for resilience in the face of global climate change. We did not anticipate that temperature treatments would show no significant impact to soil reduction potential based on prior findings that warming altered soil moisture and plant respiration rates (Mueller et al. 2018). As soil moisture and plant respiration rates have the potential to alter soil oxygen levels we anticipated to discover a significant difference in the soil reduction data. However, we are optimistic that these results indicate a greater degree of resilience of Baltic systems to global temperature increase.

Impact of cattle grazing on oxygen availability

Plots that underwent the grazing treatment showed a significant decrease in reduction index value compared to non-grazed plots. This indicates that grazed soils have lower oxygen availability than ungrazed soils. This change in oxygen availability would decrease the soils ability to support plant and microbial life and may impact the soils capacity for carbon sequestration. When these systems are subjected to cattle grazing, the oxygen depletion noted in soils makes them more vulnerable to change. With the growing need for carbon sequestration, and mounting global changes, these systems will need to be protected from land management practices such as cattle grazing in order to exhibit their maximum degree of resilience.

Impact of plot origin on oxygen availability

We found that reduction potential significantly varied among plot origins. Upon further analysis we found that the reduction index values for Danish plots were significantly different than that of Sweden and Finland, but that Sweden and Finland were not significantly different from each other. We hypothesize that this is due to plot soil contents. Danish soils have greater organic matter content than Swedish and Finish soils (Hauschild, 2022). Sweden and Finland coastal marshes also sit higher in the Baltic region and experience a different degree of salinity from Baltic Sea waters than Denmark. Denmark is closer to the entrance of ocean water to the Sea and thus experiences a greater degree of salinity than Swedish and Finnish coastal soils (Adam 1990;

Dijkema 1990). These differences in soil salinity and organic matter content will result in differing degrees of carbon sequestration and methane emission by plot soils (Wang et al. 2019). This may indicate that Danish soils emit greater degrees of methane due to their lessened soil reduction capacity in comparison to Sweden and Finland which will limit the ability of these soils to play key roles in reducing greenhouse gas concentrations in the atmosphere (Wang et al. 2019).

Limitations and future directions

This study is limited by its sample sites in specific regions of the Baltic coast. The data serves as an indicator for how the Swedish, Danish, and Finnish coasts will respond to climate change, but is limited to the specific sample sites. The data also thus cannot be applied to coastal marsh systems elsewhere around the globe as the sites are all in the Baltic region. The project is also limited by the grazing treatment applied to the grazed plots. Grazed plots continued to be periodically cut/trimmed after their collection from the sample site. However, when cattle graze marshlands they both consume grass, therefore managing the grass height, and compact the soils. After being transported to the University of Hamburg, the soils ceased to be compacted. We hypothesize that we would see an even greater difference in oxygen availability in grazed soils had the plots continued to be periodically compacted throughout their time in the NordSalt experiment.

To further investigate Baltic coastal marsh response to warming, soil reduction should be compared to greenhouse gas fluctuation data to determine whether soil reduction is correlated to carbon dioxide or methane flux in Baltic systems. The impact of grazing should also be further investigated by applying the experimental conditions to plots that have been grazed, plots where the grass has been cut short but the soil not compacted, and plots where the soil has been compacted but the grass not cut. This will determine whether it is the soil compaction or grass height that influences the oxygen availability in Baltic soils.

Broader implications

Cattle grazing demonstrated greater reduction index values indicating a significant decrease in oxygen availability in the soil. This poses impacts to plant and microbial life and may impact the soils capacity for carbon sequestration. Blue carbon coastal systems, specifically Baltic coastal marshes, will play important roles in mitigating changes to the global climate. Their ability to resist increasing temperatures and support highly adaptable biota while sequestering carbon makes them significantly important in the conversation around global atmospheric carbon removal. Their restoration and protection from harmful land-use practices must be made paramount in order to maintain these ecosystem services.

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