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Quantification of biomass availability for wood harvesting and storage in the continental United States with a carbon cycle model

Henry Hausmann[1], Qixiang Cai[2] and Ning Zeng[1*]

Abstract

Background Wood Harvesting and Storage (WHS) is a form of Biomass Carbon Removal and Storage (BiCRS) that utilizes a combined natural and engineered process to harvest woody biomass and put it into long term storage, most frequently in the form of subterranean burial. This paper aims to quantify the availability of woody biomass for the purposes of WHS in the continental United States using a carbon cycle modeling approach. Using a regional version of the VEGAS terrestrial carbon cycle model at 10 km resolution, this paper calculates the annual woody net primary production in the continental United States. It then applies a series of constraints to exclude woody biomass that is unavailable for WHS. These constraints include fine woody biomass, current land use, current wood utilization, land conservation, and topographical limitations. These results were then split into state by state and regional totals.

Results In total, the model projects the continental United States could produce 1,274 $MtCO_2e$ (CO_2 equivalent) worth of coarse woody biomass annually in a scenario with no anthropogenic land use or constraints. In a scenario with anthropogenic land use and constraints on wood availability, the model projects that 415 $MtCO_2e$ of coarse woody biomass is available for WHS annually. This is enough to offset 8.5% of the United States' 2020 greenhouse gas emissions. Of this potential, 20 $MtCO_2e$ is from the Pacific region, 77 $MtCO_2e$ is from the Western Interior, 91 $MtCO_2e$ is from the Northeast region, and 228 $MtCO_2e$ is from the Southeast region.

Conclusion There is enough coarse woody biomass available in the continental United States to make WHS a viable form of carbon removal and storage in the country. There is coarse woody biomass available across the continental United States. All four primary regions analyzed have enough coarse woody biomass available to justify investment in WHS projects.

Keywords Carbon removal, Carbon storage, Forestry, Wood Harvesting and Storage, United States, Carbon cycle modeling

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Background

According to the United Nations' Intergovernmental Panel on Climate Change (IPCC) the planet has warmed by approximately 1 °C since the early 1800s as a direct result of anthropogenic emissions of greenhouse gasses, most notably carbon dioxide. A direct reduction in these emissions will likely not be enough to stave off potential catastrophe, so other solutions including carbon dioxide removal (CDR) are required as part of a complete response [1]. One potential avenue for climate change prevention is Biomass Carbon Removal and Storage (BiCRS), which refers to any technology or technique where carbon dioxide is removed directly from the atmosphere (Carbon Dioxide Removal or CDR) via biomass utilization and placed into long term storage [2]. While current applications of BiCRS are relatively limited, various techniques have the potential to offset significant portions of anthropogenic carbon dioxide emissions and sequester the carbon for a permanent duration [3].

In this paper we will focus a specific BiCRS technique, Wood Harvesting and Storage (WHS), attempting to quantify the sequestration potential of WHS in the continental United States. WHS is a hybrid natural and engineered form of CDR [4–6]. It is designed to take advantage of the natural photosynthesis. In photosynthesis a plant intakes water, sunlight, and CO_2 to create energy, release O_2, and store carbon in the plant's biomass. In WHS, plant material (specifically woody biomass (WB)) is harvested and placed into long term sequestration in an environment specially engineered to prevent decomposition [6].

Although there are several sequestration techniques that can be deployed for WHS the most common and well researched is WB burial in a specifically engineered Wood Vault [6]. This means WB is buried in an anoxic (O_2-depleted) environment below the active soil layer where decomposition is minimized. Archeological evidence has shown examples of buried WB surviving relatively intact on millennial or longer time scales when entombed in the correct conditions [6, 7].

There are several methods of harvesting WB for WHS. First one can create plantations specifically for the purposes of WHS: plant trees, harvest and sequester the grown WB, then reseed the original plot of land and wait for trees to regrow in order to repeat the process. The second method is to harvest dead and waste WB that would otherwise decompose and place it directly into long term sequestration. This WB can come from natural forest mortality or urban waste generation and requires minimal intervention. In both cases, only coarse woody biomass (CWB), which refers to trunks, main branches, and other large pieces of wood [8], is collected for sequestration. Fine wood, such as twigs, bark, roots, and other small woody material, has too high a ratio of surface area to volume to guarantee long term sequestration [6].

This analysis will quantify the total CWB available for WHS in the entirety of the continental United States. It will look at the nation as a whole, four broad geographic regions, and all 48 states in the continental United States.

The methodology is based Zeng et al. 2013 [5]. However, several key differences and advances justify this new endeavor. The 2013 paper was a global assessment of WHS availability, using grid points of 250 km by 250 km while this paper uses much more precise 10 km by 10 km grid points. Additionally, improvements in the Vegetation-Global-Atmosphere-Soil (VEGAS) carbon cycle model used by both papers have occurred between 2013 and 2022 [9, 10]. These improvements include the addition of anthropogenic land use constraints, wood utilization data, and general performance upgrades. In addition, this paper makes use of more current and accurate land conservation estimates.

Methods

This paper is a modeling analysis of the CWB (and thus carbon) available for WHS in the continental United States. It also quantifies the total unconstrained annual Net Primary Production (NPP) of CWB for the same region. This analysis uses a carbon cycle model to estimate the excess CWB generated in the region. In order to assess the potential availability of CWB for WHS and the unconstrained NPP of CWB, this analysis used two runs of the VEGAS Carbon Cycle Model Version 2.6 [9, 10]. The VEGAS model simulates global vegetation distribution and full terrestrial carbon cycle forced by observed climate data (precipitation, temperature), CO2 and land-use history following the international TRENDY carbon model intercomparison guideline [11] (CRU climate, NOAA/ice core CO2, HYDE land use history). This analysis used a regional run of the model with daily timesteps and a spatial resolution of 0.1 degree latitude by 0.1 degree longitude (about 10 km by 10 km). Every value analyzed was an average of quantities between the years 2010 and 2019. The first simulation was a spin up scenario with no constraints for human activities. The spin up run also lacked the carbon fertilization effect [10]. The second model run is a full run with considerations for anthropogenic land use (both agriculture and urbanization) as well as the impacts of anthropogenic climate change. Both model runs use wood death rates (from fire, stress, and background mortality) in forested areas as a proxy for WB NPP (see Eq. 1). This proxy assumes a steady state equilibrium in the forests of the United States. While this may not be accurate for an individual plot of forest, it holds true on the spatial scales of the modeling analysis employed by this paper.

$$NPP_{Wood} = \sum_{k=1,2} (D_F + D_{STR} + D_{BRM}) \quad (1)$$

Where NPP_{Wood} is Net Primary Production of Woody Biomass, D is death rate, F is fire, STR is stress, BRM is background mortality, and k is VEGAS plant functional type with k=1 corresponding to broadleaf trees, k=2 corresponding to needleleaf trees, and k>2 corresponding to grassland, cropland, and urban areas.

Going from woody NPP to CWB available for WHS is a matter of applying 5 constraints to available WB (see Fig. 1). These constraints are as follows:

1. Exclude fine wood.
2. Add current land use constraints to the model run.
3. Exclude current wood utilization.
4. Exclude land set aside for conservation.
5. Exclude difficult to access regions.

Once all of these constraints were applied, we were left with CWB that is usable for the purposes of WHS (see Fig. 2).

Fine woody biomass

The first constraint is that only CWB is suitable for burial in WHS. Fine woody biomass is a part of the total wood growth/death rate calculated by the VEGAS carbon cycle model and needs to be excluded. While a tree is mostly coarse wood by mass (trunk, main branch structures) the fine wood dies and regrows at a much faster rate. As such, we assumed that 59% of all WB produced is CWB, following Zeng et al. (2013) [5] where they simulated a global CWB production rate of 10 GtC (Gigatonne carbon) per year. This is consistent with a recent observation-based synthesis of 10.8 GtC per year world dead wood production rate [12]. We applied this factor to both the spinup run and the full forced run. This factor is all that is needed to calculate the unconstrained CWB NPP that is used as a baseline for further analysis. As such, it was the only constraint placed upon the spin up run of the VEGAS model. In total, there is 1,274 Mt of carbon dioxide equivalent (CO_2e) worth of CWB NPP in the continental United States annually.

Land use

The next constraint is anthropogenic land use. No WB can be harvested from land that is already being used for agriculture, human habitation, or some other anthropogenic use case. The VEGAS model already has built in parameters for land use and they were utilized for this analysis. As such, at this point we switch from the spin up model run which lacked anthropogenic forcing to the full model run with complete anthropogenic forcing. In total, once land already used by humans is taken out of consideration, there are 724 $MtCO_2e$ available for sequestration in the continental United States.

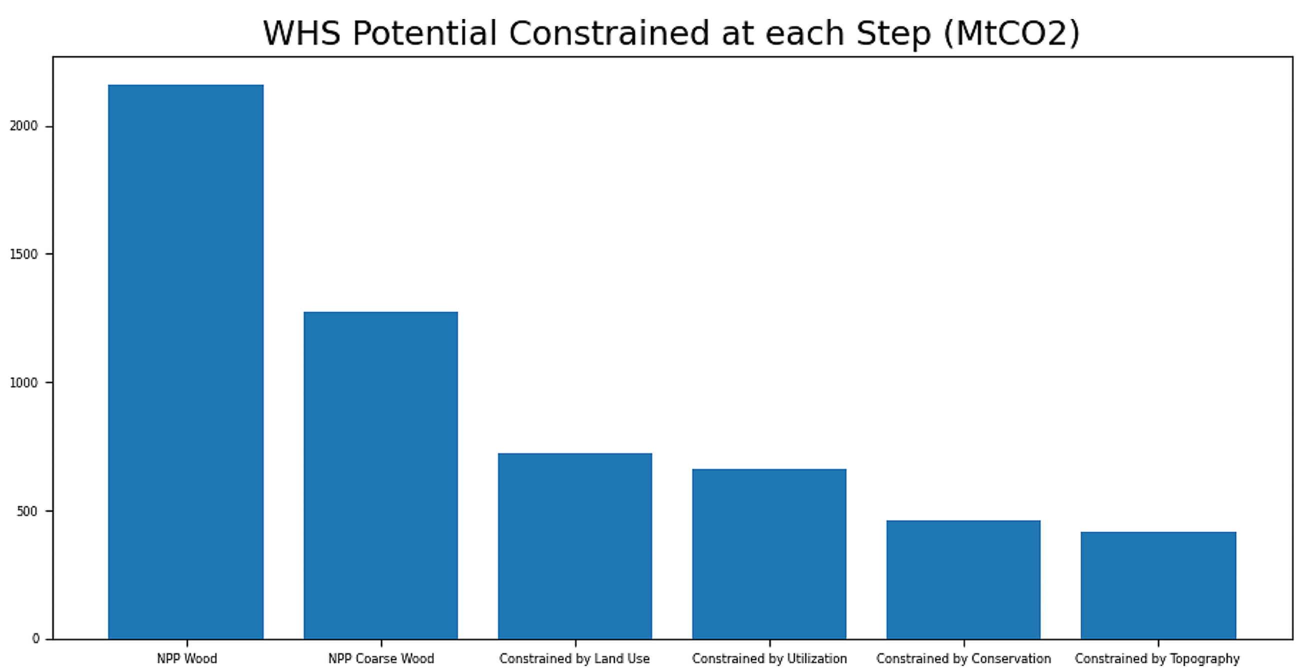

Fig. 1 The amount of wood (in $MtCO_2e$) available for the entire continental United States after each limit on sequestration is imposed. NPPwood (1st column) is the unrestricted potential from the spin up model run. The next column excludes all fine woody biomass. The third column switches to the full anthropogenically forced model run, excluding all CWB displaced by land use (agriculture and urbanization). The next column excludes all CWB already claimed for existing utilization. The next column excludes all CWB grown in land set aside for conservation. The final column excludes all CWB grown in land that is topographically difficult to access for harvest. All values are expressed in units of $MtCO_2e$

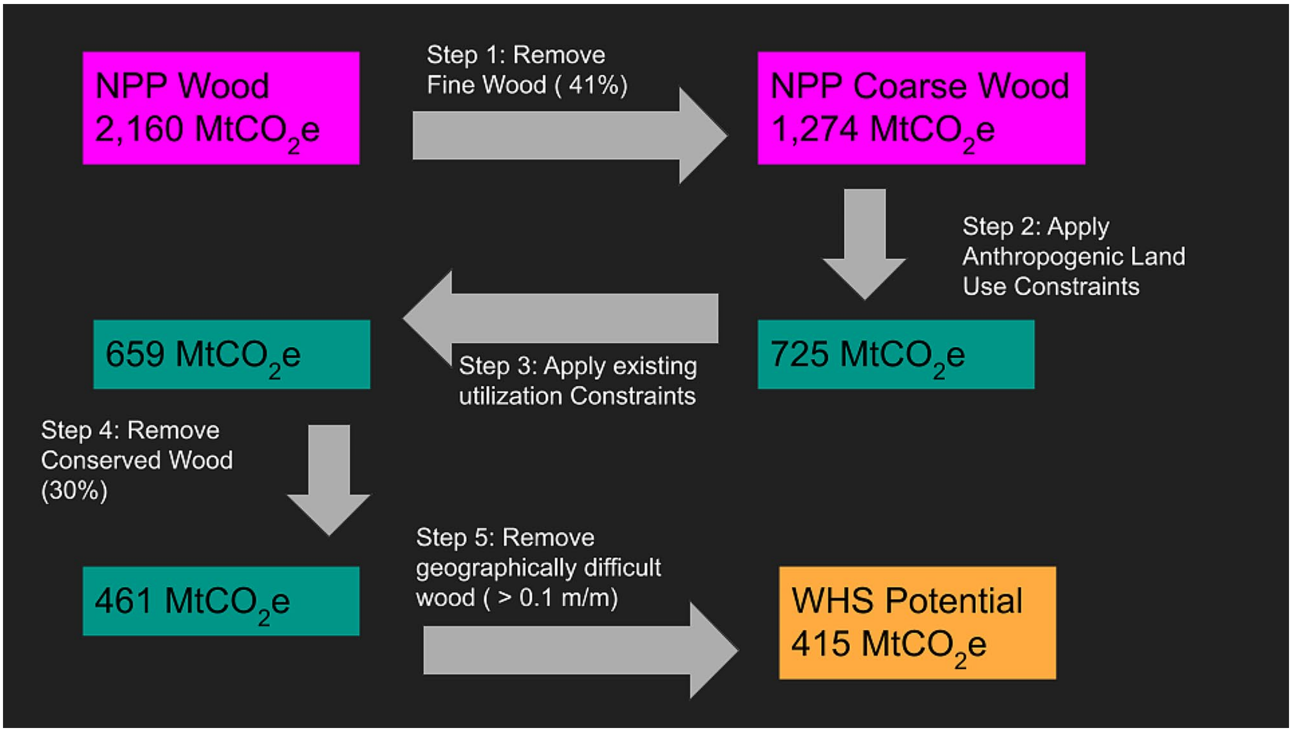

Fig. 2 Flow chart of the constraints placed on wood availability at each step of the methodology.[1]

[1] A Note on Units: This paper uses tCO_2e (tonnes of carbon dioxide equivalent) as the primary unit of carbon sequestration. This translates to the amount of CO_2 that would be released back into the atmosphere if the sequestered wood was allowed to burn or decompose. Converting this to the more physical metric of tonnes of carbon is a matter of simple stoichiometric conversion, as there is 1 tonne of carbon per 3.67 tonnes of carbon dioxide

Wood utilization

The next constraint is CWB already utilized by human activities. Hurtt et al. 2011) provides an analysis of wood harvested across the country for human utilization and consumption. This is simply excluded from the CWB at every grid point. This leaves a total of 659 $MtCO_2e$ available.

Conservation

Next, we exclude all CWB already set aside for conservation purposes. The Biden Administration has set a long-term goal of placing 30% of America's forestland under some form of conservation or protection. As such, we assume that 30% of remaining available CWB will be part of this conserved land and thus unavailable for utilization in WHS. This was done by a simple reduction if 30% in the per unit area availability. This approach is relatively crude, as not all regions of the country will be conserved equally. As more details of future conservation plans become available, it may become possible to mask out protected grid points instead of applying a 30% reduction to the yield of every grid point. In total, this conservation constraint leaves us with 461 $MtCO_2e$ of CWB for WHS.

Topographic gradient

Finally, we set aside all CWB grown on land that is difficult to reach and harvest from due to geographical limitations. Modern forestry machine operations can operate at 0.3 m/m slope without major difficulty, though the cost will be hire and more likely causing erosion. We thus conservatively selected a 0.1 m/m slope as a threshold. In the model, we assume that any grid point with a topographical gradient greater than 0.1 to be not harvested and has a CWB production of 0. This mask is applied based on the EROS HYDRO1K dataset. This leaves us with a final WHS potential for the continental United States of 415 $MtCO_2e$. See Fig. 3 for a detailed spatial distribution of the WB excluded by all of these constraints.

Results and discussion

In total, under the harvest assumptions made in this paper's methodology, the model predicts that the US can generate 415 $MtCO_2e$ worth of sequestration via WHS annually. Without any constraints (land use, conservation, existing utilization, and ease of access), the continental US could theoretically generate 1,274 $MtCO_2$ worth of sequestration annually. This means that only 32.5% of the CWB is actually available for sequestration.

We also split up the WHS potential by state to determine several geographic trends (see Fig. 4). The highest

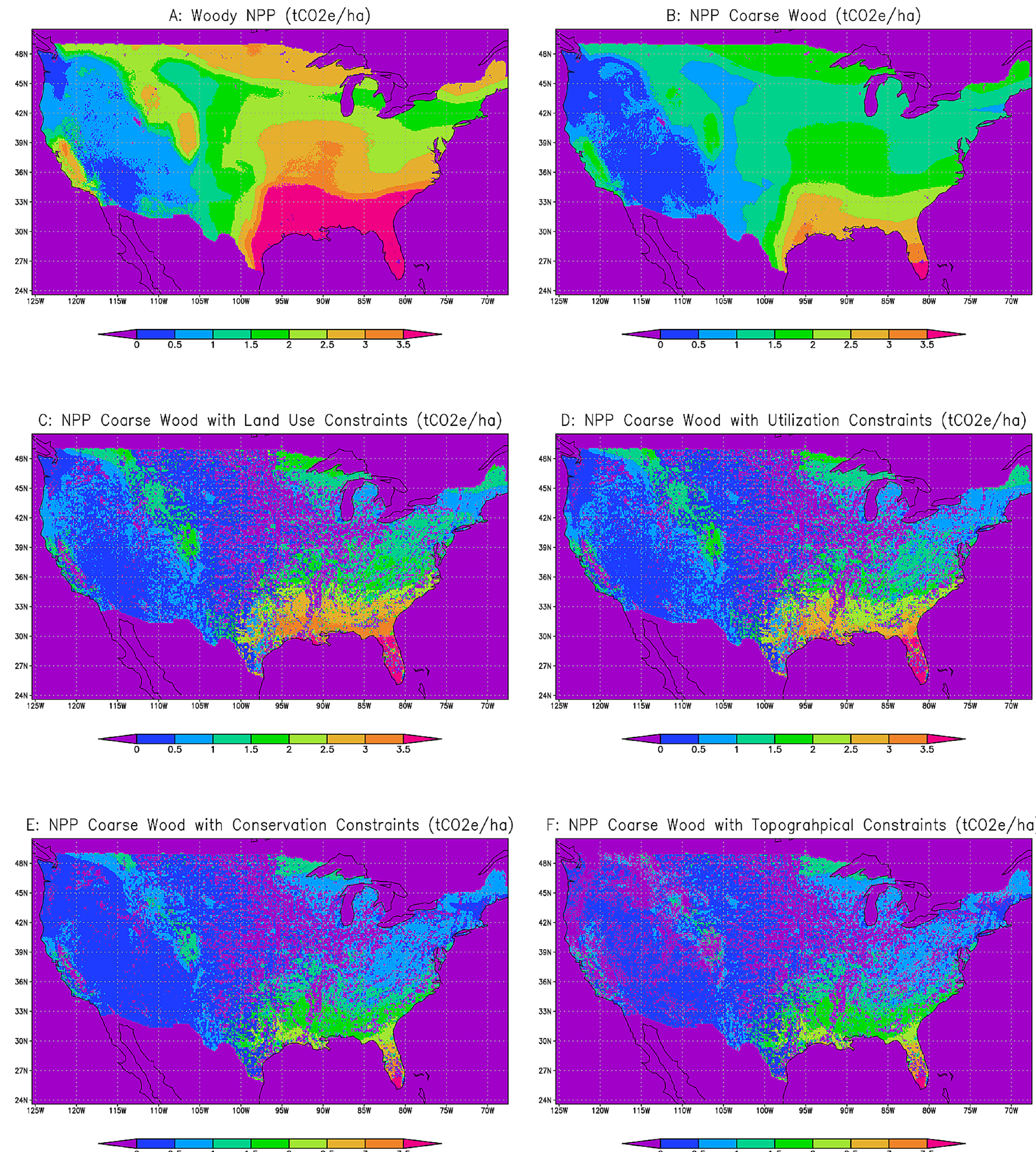

Fig. 3 Spatial distribution of wood availability under the constraints overviewed in this methodology, in units of tCO_2e/ha. Panel A: Unrestricted Woody NPP. Panel B: Coarse Wood NPP. Panel C: Coarse Wood NPP with anthropogenic land use constraints. Panel D: Coarse Wood NPP with current utilization constraints. Panel E: Coarse Wood NPP with conservation constraints. Panel F: Coarse Wood NPP with topographical constraint. This panel shows final WHS potential

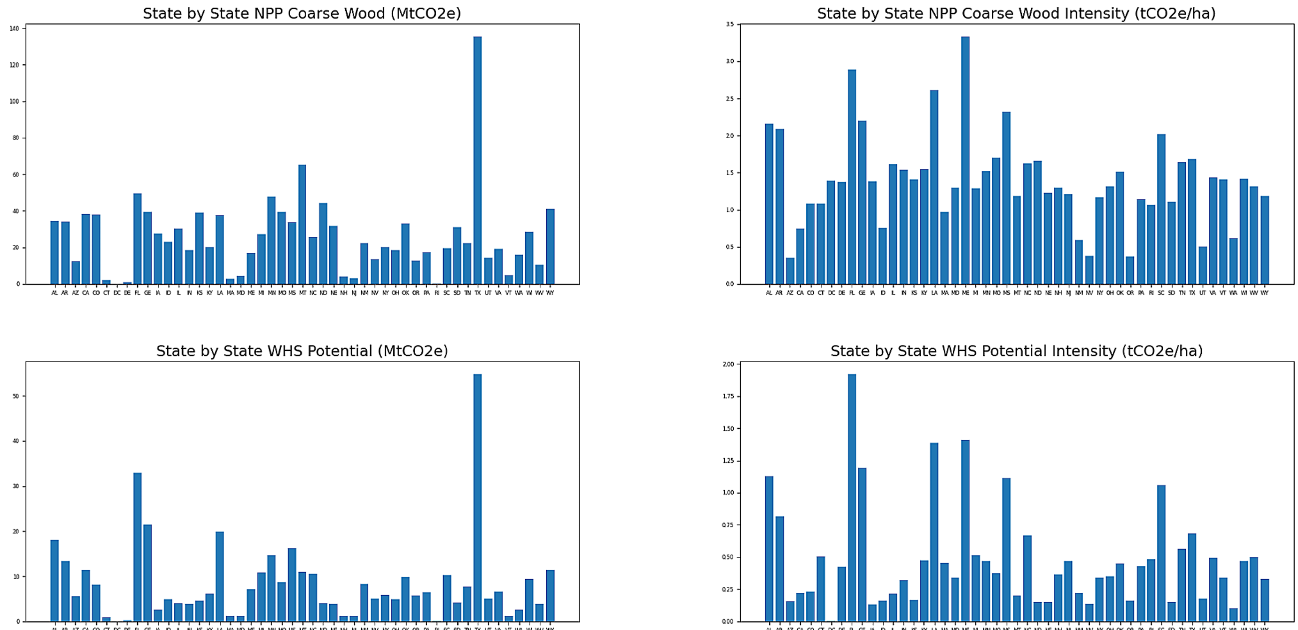

Fig. 4 State by state totals and intensities of both NPP Coarse Wood and WHS Potential Including all constraints. See Appendix A for the raw data used to generate these plots

potential for WHS comes from the gulf coast states (Alabama, Florida, Georgia, Louisiana, Mississippi Puerto Rico, and the East coast of Texas). All have WHS potentials well above 1.0 tCO_2/ha. The Gulf Coast region has warm temperatures, plentiful rainfall, plentiful sunlight, flat terrain, and a limited footprint of cropland. All of these factors combine for rapid and consistent wood growth, ideal for the production of available CWB necessary for WHS.

On the other hand, there are several categories of states that have very low potential for WHS. A few categories of states have geographical/climatological factors that severely limit the viability of WHS. Desert states with low rainfall (Arizona, New Mexico, Nevada, Utah) simply lack the capacity to produce the quantity of CWB required for WHS. Mountainous states (Colorado, Wyoming) are simply too difficult to effectively harvest CWB from, though future innovations and cost reductions could help make their CWB more easily available. Finally, there are agricultural states (California, Ohio, Illinois, Iowa, Kansas). These states have geographical/climatic conditions that could lead to high levels of CWB production, as shown in their CWB NPP totals and intensities. However, most of the productive land in these states is already claimed by agriculture. As such, any attempt to utilize these states for WHS will produce only limited sequestration without disrupting food production.

This analysis also split the continental United States into 4 regions, based on the regions set out by the US Forest Service (Forest Service, 2022). While the Forest Service had 9 regions, this analysis consolidated the smaller ones, creating four regions with similar properties in terms of forest type and geographic conditions (See Fig. 5 for detailed spatial plots of the CWB production of each of the regions and Fig. 6; Tables 1 and 2 for a detailed breakdown of the constrained CWB availability). The four regions are as follows:

1. Pacific Coast: CA, OR, WA.
2. Interior: AZ, CO, ID, KS, MT, NE ND, NM, NV, SD UT, WY.
3. Southeast: AL, AR, FL, GE, KY, LA, MS, NC, OK, SC, TN TX, VA.
4. Northeast: CT, DE, IA, IL, IN, MA, MD, ME, MI, MN, MO, NH, NJ, NY, OH, PA, RI, VT, WI, WV.

In general, the Southeast has the highest potential for WHS, with warm temperatures and plentiful rainfall spurring on significant productivity. It also lacks significant constraints, meaning a relatively high proportion of the region's CWB (45.2%) is actually available for WHS.

The Northeast has moderate production throughout, with some outliers in either direction. A few unbroken forests near the Canadian border (Maine, Northern Minnesota, and Michigan's Upper Peninsula) have CWB production values that rival the productive Gulf Coast. Combined with limited constraints and these regions are some of the most productive in the nation. The region is also heavily constrained by both agriculture and human habitation, meaning much land with high theoretical CWB production is actually unavailable.

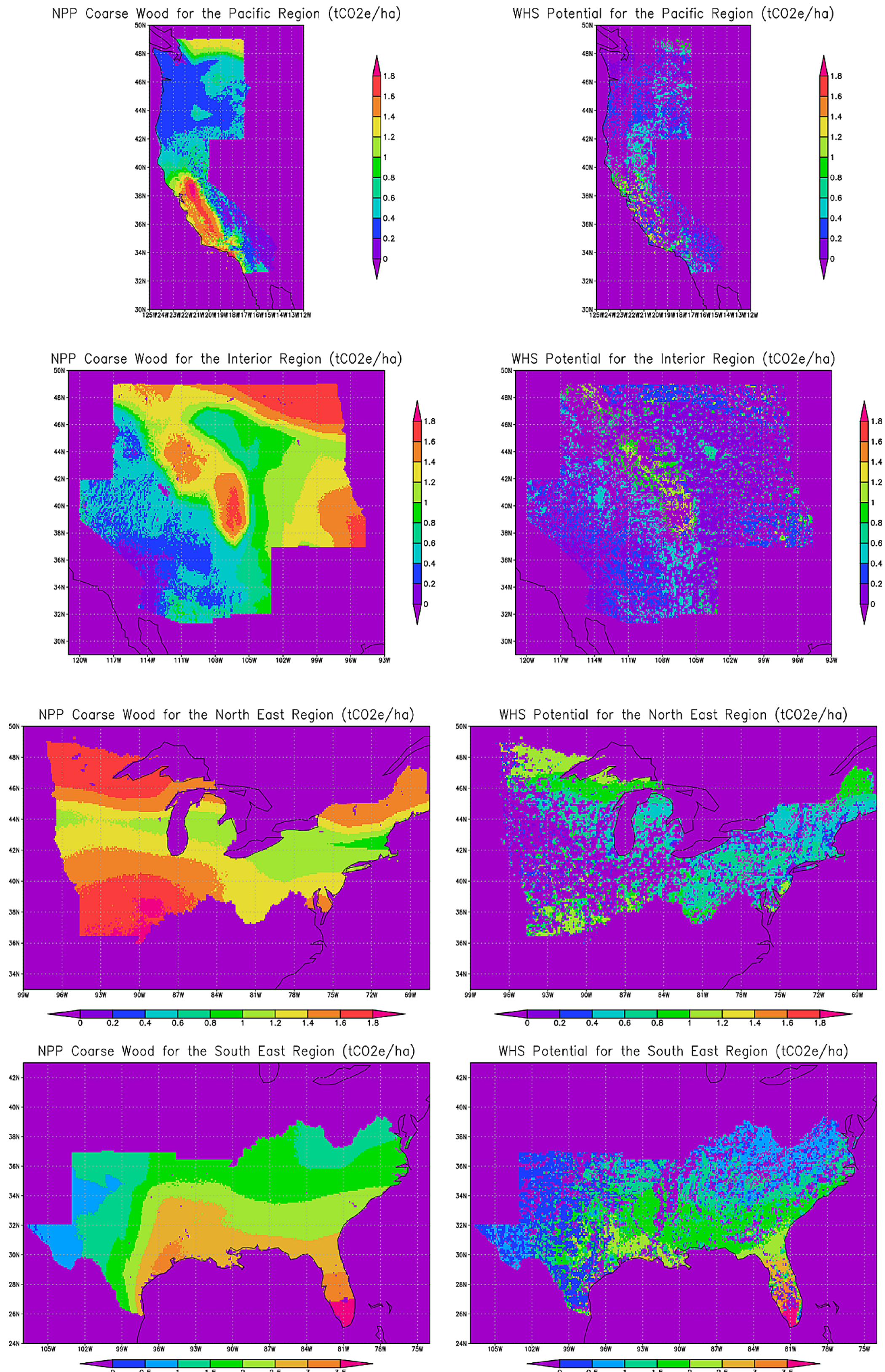

Fig. 5 Spatial plot of unconstrained and fully constrained woody NPP for each of the four primary regions of the continental United States

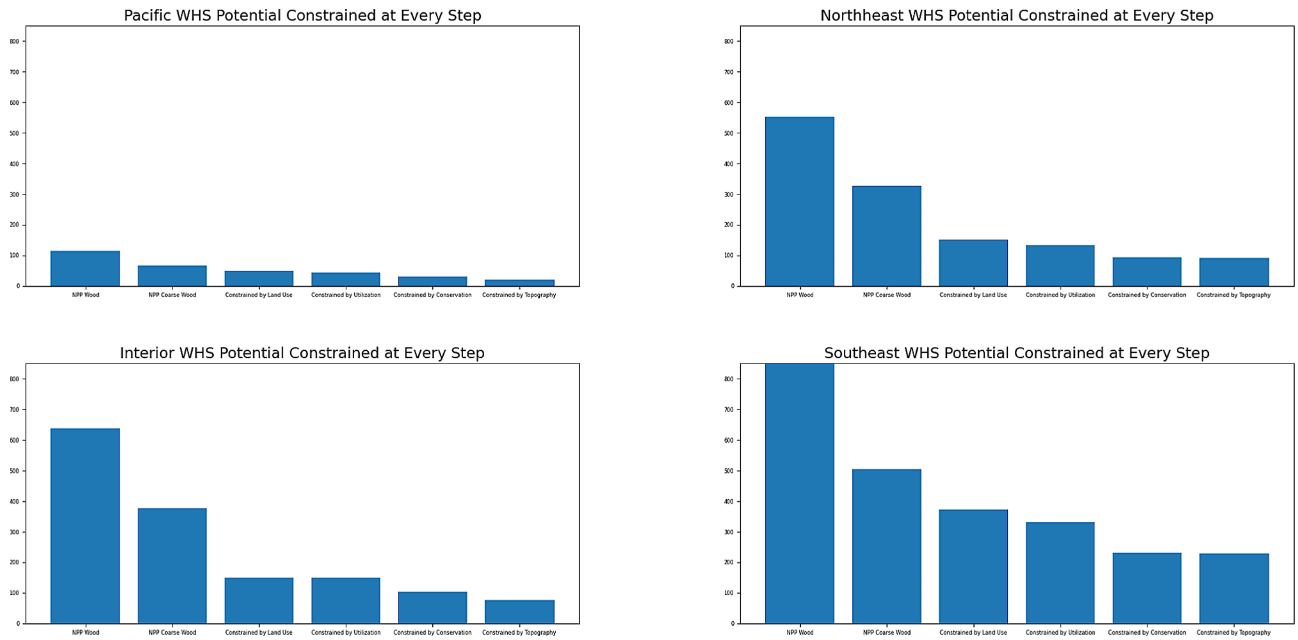

Fig. 6 Constraint Plot for each of the four defined regions of the continental United States, in $MtCO_2e$

Table 1 Regional WHS potential totals ($MtCO_2e$)

	Pacific	Interior	South East	North East
NPP Wood	113.992	637.913	855.434	553.058
NPP Coarse Wood	67.255	376.368	504.706	326.304
Constrained by Land Use	49.009	150.768	372.834	152.841
Constrained by Current Utilization	44.427	149.714	331.135	133.784
Constrained by Conservation	31.099	104.8	231.794	93.649
Constrained by Geography	19.841	76.549	228.112	90.505

Table 2 Regional WHS potential intensities (tCO_2e/ha)

	Pacific	Interior	South East	North East
NPP Wood	1.016	1.589	3.234	2.458
NPP Coarse Wood	0.6	0.938	1.908	1.45
Constrained by Land Use	0.437	0.376	1.409	0.679
Constrained by Current Utilization	0.396	0.373	1.252	0.595
Constrained by Conservation	0.277	0.261	0.876	0.416
Constrained by Geography	0.177	0.191	0.862	0.402
Coarse Wood Availability (%)	29.5	20.4	45.2	27.7

The Pacific region is constrained by large mountain ranges as well as a high proportion of land utilized for agriculture and human habitation. The Pacific Northwest (Washington, Oregon) also has a lower CWB production than what would be expected given the region's climate. This error persists throughout VEGAS's global and regional runs and should potentially be addressed in future versions of the model.

The Interior region is categorized by two primary constraints: desert and mountains. Desert regions simply lack any CWB production to begin with. And mountainous regions are excluded by the topographic constraints. As such, any potential WHS projects in the interior region must carefully select where to harvest CWB.

The closer look provided by Figs. 5 and 6 can also provide a clearer picture of overall national trends. Fertile and prosperous river banks (for example, the Mississippi River) are often entirely claimed by human activity, be it agriculture or dense settlement. This creates significant areas of limited to no potential for WHS. And it's not as simple as the further south a grid point is, the higher its WHS potential. While that trend holds mostly true for the Southeast, it is reversed for the Northeast. It's a more complicated calculus than how much sun and rain is available.

Here we present more detailed analysis of a few representative states (Fig. 7). For similarly detailed plots of any other state in the continental United States, contact this paper's corresponding author. The selected states are:

1. Arizona.
2. California.
3. Florida.
4. Illinois.
5. Michigan.
6. Texas.

Arizona is a fairly low intensity state for the purposes of CWB production. Across the entire state, there is only 0.159 tCO_2e/ha worth of CWB NPP available for

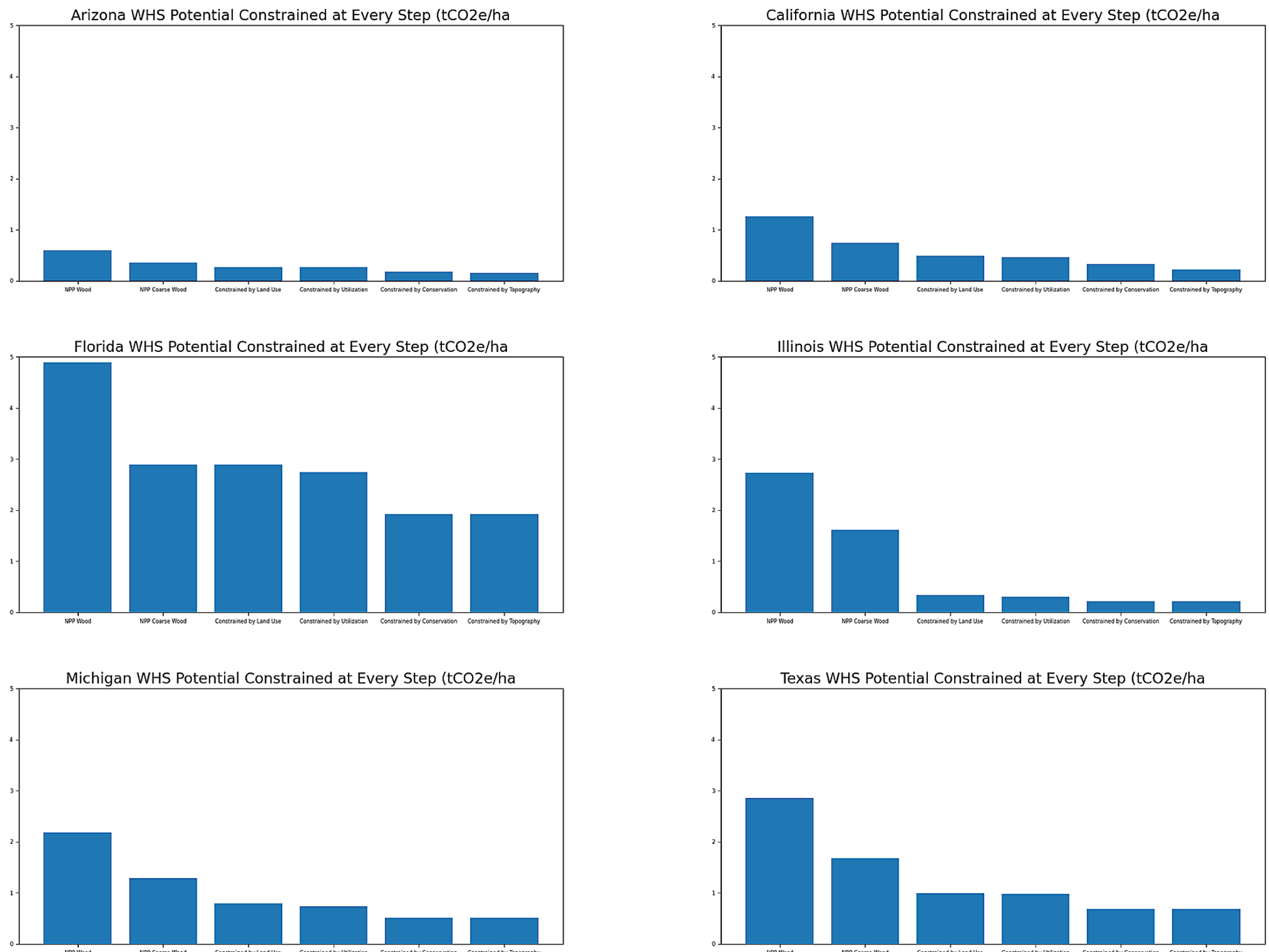

Fig. 7 Constraint Plot for each of the six selected states of the continental United States, in tCO_2e/ha

WHS. Given that much of the state is dominated by an arid climate, this is unsurprising. Although there is some mountainous terrain, Arizona has a relatively high ratio of available CWB to unconstrained CWB (45%). There is simply a low baseline CWB production in the state. Overall, there are very few regions of Arizona appropriate for WHS.

While California has high productivity of CWB in an unconstrained model run, several constraints severely limit the state's WHS potential. Anthropogenic land use, both agricultural and urban, take up much of the state's land area. And many undisturbed grid points are too mountainous for effective CWB harvesting. So, California's climate shows potential for CWB production, but in reality can only output 0.223 tCO_2e/ha worth of sequestration, only 30% of the state's unconstrained CWB production and not even double the intensity of desert states like Arizona and Utah.

With a potential WHS intensity of 1.922 tCO_2e/ha Florida is the single most productive state in the continental United States. Florida has very limited constraints on its CWB production, with 67% of its unconstrained CWB NPP available for WHS. Florida is the epitome of the high productivity characteristic of the warm and wet Gulf Coast Climate. However, a more granular and detailed analysis of land conservation may limit Florida's WHS potential. Its highest productivity region is the Everglades in the Southern portion of the state. As this is a popular National Park and a unique ecosystem, it is unlikely that this region will be accessible for intense CWB harvesting.

Illinois is a good example of the characteristics of many of the Midwestern states. It has relatively high unconstrained CWB NPP. Illinois' intensity of 1.614 tCO_2e/ha is about 70-80% of the unconstrained total for most of the high productivity Gulf Coast states. But the vast majority of Illinois's land area is occupied by agriculture. As such, Illinois has a constrained WHS potential 0.215 rCO_2e/ha, only 13% of the unconstrained potential. This intensity is less than the state of California, which has less than half of Illinois' unconstrained CWB NPP. Illinois has only a few scattered grid points available for WHS projects.

Michigan is divided into two regions. The main Southern region of the state is relatively standard for states in the Northeast region. A mixture of relatively productive forests with heavy land use produces a statewide WHS potential of 0.515 tCO_2e/ha, about average for the nation. But the Upper Peninsula is dominated by dense, unbroken forest. The peninsula, along with Northern Minnesota and Maine have WHS potentials above 1 tCO_2e/ha, the highest of any region outside of the Southeast region.

Texas, the largest state by area in the continental United States is a mix of a high NPP Gulf Coast climate and a less productive arid interior, much of which is set aside for ranching and other land use constraints. Texas has the single largest total WHS potential of any state, accounting for 13% of the WHS potential in the continental United States. This is a combination of the state's superlative size and above average WHS potential intensity of 0.681 tCO_2e/ha. Overall, Texas has ample opportunities for potential WHS projects.

Conclusions

Overall, the continental United States has a large potential for WHS. The US emitted about 5,200 $MtCO_2e$ in the year 2020 (EPA, 2022). This means that WHS in the continental United States can offset about 8.0% of the nation's annual emissions. This total can be increased by converting agricultural land, developing more cost-efficient ways to log mountainous terrain, discovering a way to permanently and cheaply sequester fine woody biomass, or harvesting at a higher (potentially unsustainable) intensity.

The results of this analysis are also relatively similar to a similar (if coarser) analysis conducted in Zeng et al. (2013) [5]. That analysis estimated the United States had a WHS potential of 513 $MtCO_2$, 98 $MtCO_2$ more than this analysis. The Zeng 2013 analysis used much coarser resolution (2.5-degree grid points), made different assumptions about land conservation (20% vs. 30% here) and did not include slope constraint explicitly. As such the difference in WHS totals makes sense.

The next step could be to repeat this analysis for other regions of the world. Many nations including Brazil, China, Canada, India, and Russia have large and productive forested regions. Analysis similar to that found in this paper could determine where WHS projects have the most potential to offset industrial emissions. Scaling WHS up to the Megatonne or Gigatonne scale required to make a significant impact will require many of these analyses. It could also be useful to compare the results of this paper to a study attempting to quantify the same quantities from a bottom-up approach. While doing this on the national scale may be prohibitively time consuming, a bottom-up analysis of the WHS potential of a few key states may prove enlightening.

Abbreviations

CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CO_2e	Carbon Dioxide Equivalent
BiCRS	Biomass Carbon Removal and Storage
CWB	Coarse Woody Biomass
FWB	Fine Woody Biomass
IPCC	Intergovernmental Panel on Climate Change
NPP	Net Primary Production
VEGAS	Vegetation-Global-Atmosphere-Soil carbon cycle model
WB	Woody Biomass
WHS	Wood Harvesting and Storage

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13021-024-00270-4.

Supplementary Material 1

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Author contributions

HH preformed the primary analysis, generated all figures, and wrote the manuscript. NZ conceived the idea, led the study, developed the VEGAS model, and helped to write the paper.QC set up and ran the VEGAS model simulations, created boundary conditions and datasets. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

NZ is a co-founder of Carbon Lockdown Project that implements WHS projects.

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