SOIL CARBON MODELING OF VERMONT FARMLAND: EVALUATING THE STEADY STATE SPIN UP ASSUMPTION

Presented by Sarah Grobe
to the Faculty of the College of
Engineering and Mathematical Sciences
of the University of Vermont

In Partial Fulfillment of the Requirements
of the University of Vermont Honors College
and Bachelor of Science in Data Science

Spring 2022

Brian Beckage, Ph.D.
Jeffrey Buzas, Ph.D.
Serge Wiltshire, Ph.D.

ABSTRACT

Many environmental models depend upon an initial spin up to obtain the initial conditions for the simulation. The spin up occurs prior to the model in order to obtain values for time t = 0 in the simulation run, meaning that ultimately the results of the environmental model are sensitive to the results of the spin up. Here we examine the role of the spin up in the RothC soil carbon model. The spin up process typically used assumes carbon levels are in equilibrium at the end of the spinup run, which we refer to as the steady state assumption. In taking a more historical approach to this spin up, particularly in regards to forest cover over the state of Vermont, this project aims to determine the validity of this steady state assumption, primarily acting as a proof of concept for a more in-depth investigation of this type. By developing a timeline of forest cover over time in Vermont and comparing this historically based spin up to a more traditional steady state one, it was determined that soil carbon stocks in Vermont appear to be decreasing, thereby violating the steady state assumption. Further analysis is required to make a definitive claim with respect to the steady state assumption, however this result indicates potential oversimplification from the assumption, which could ultimately have significant effects on the models which depend upon these spin up results.

INTRODUCTION

It has been well established in the literature that anthropogenic climate change is occurring, in large part due to the consumption of fossil fuels which contribute to high levels of CO_2 in the atmosphere (Dhanwantri et al. 2014). These higher concentrations of CO_2 then lead to rising temperatures as a result of the greenhouse effect, in which the increased carbon dioxide traps and reflects increased levels of heat back to the Earth’s surface (Dewar & Cannell 1992).

As such, many methods for mitigating anthropogenic climate change involve reducing this high concentration of carbon dioxide in the atmosphere. One such proposed method is through increasing carbon sequestration in the soil, in which plants capture the gas through the process of photosynthesis and store the carbon itself in the soil (Ontl & Schulte 2012).

Carbon Sequestration

Carbon sequestration occurs through photosynthesis, as plants take in carbon in the form of carbon dioxide in the atmosphere, and release it into the soil as soil organic carbon, or SOC (Blanco-Canqui & Lal 2004, Dhanwantri et al. 2014). Carbon that is released into the soil can be divided into five pools: inert organic matter (IOM), decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM) (Coleman & Jenkinson 2004). This carbon then transfers between these pools at varying rates through decomposition; DPM, for instance, tends to decompose very quickly, while HUM is highly resistant and therefore remains in the soil longer than other carbon pools (Ontl & Schulte 2012). The rate and volume at which carbon is sequestered in this manner is therefore dependent upon a number of factors, including soil conditions, climate, the type of plant in a given area, and how many plants are present (e.g., if an area is a thickly covered forest, or a sparse pasture). In this way, land management practices such as afforestation or clearing land for pasture use can have a significant impact on the rise and fall of carbon content in the soil (Blanco-Canqui & Lal 2004). It is also important to note that these changes in the rate of carbon sequestration are not constant. The changes are most noticeable shortly after the land use change occurs, and slowly level off as they reach an equilibrium; for instance, deforestation over a large plot of land in order to plant crops would initially show a steep reduction in the amount of SOC, before leveling off to a more constant rate over the course of several decades (Benbi & Brar 2008).

As alluded to above, increasing the amount of carbon sequestered in the soil through various land uses can help combat anthropogenic climate change by ultimately helping reduce the amount of carbon dioxide in the atmosphere. It has been suggested that being able to mitigate the resulting increase in the greenhouse effect and thereby slow the warming of the planet through something like carbon sequestration and land use management could slow climate change enough to essentially "buy us time" to incorporate other strategies which could work in tandem to slow or even ultimately stop anthropogenic climate change (Lal 2003). This is precisely why this type of research is so important: it is vital that we understand the various effects of these different land use practices as they relate to climate change.

The Steady State Assumption

Wiltshire & Beckage (2022) utilize this type of modeling, specifically the RothC model, to evaluate carbon sequestration levels under various conditions of forest and agricultural land uses for Vermont farmland. This model is used to analyze the effects on carbon sequestration of five different regenerative agriculture practices against business as usual, projecting 100 years into the future. The model used in the Wiltshire & Beckage (2022) study, and indeed many environmental models of this type, require what is known as a "spin up" in order to obtain carbon levels matching the empirical data for the present, which corresponds to time $t = 0$ in the simulation runs. This spin up method then assumes a steady state, meaning that at the time the model begins, the carbon levels are at equilibrium, and the soil is neither gaining nor losing carbon overall. The accuracy of these results depends in large part on this steady state assumption commonly used in environmental models, which we hope to evaluate in this project (Hanan et al. 2018).

But while this assumption of a steady state at time t = 0 seems to be a bold one, it remains the current "best practice" for environmental models of this type. The spin up is run in order to initialize carbon levels which match the empirical data for the beginning of the model run, and in accordance to the steady state assumption, the carbon levels are assumed not to be in flux at the time that the environmental model running begins (Nemo et al. 2016). This implies that if the model were to continue without making any land use changes, changes to climatic conditions, or other alterations to carbon sequestration, these values would remain stagnant forever. However, by taking a look at the history of land use in Vermont alone, we can see that this is almost certainly not the case; land uses such as forests, pastures, and agriculture have been constantly changing across the landscape of the state, and as mentioned above, these changes will have powerful impacts on the ability of the soil to sequester carbon. This is where this analysis will prove useful, as it will help evaluate how significant the effect of this steady state assumption is, and how far it seems to be from the reality of carbon sequestration.

Evaluating This Assumption

This method is currently considered to be the best practice for this type of environmental model (Nemo et al. 2016). However, this steady state assumption fails to take into account any historical changes in land use which certainly have an impact on overall carbon sequestration. In other words, it makes the assumption that the current conditions of the land use have been stagnant throughout, at the very least, several centuries prior to time t = 0 in the model, allowing carbon levels to stabilize (Hanan et al. 2018).

This project therefore aims to evaluate the validity of this steady-state assumption by taking a historical approach to the spin up method for the state of Vermont. By analyzing trends in land use changes over time, we aim to take a closer and more accurate approach to the spin up. Ultimately, this model will be able to tell us whether or not the carbon levels truly are in a steady state, and if they are not, how different the trend is from this steady state assumption. These results could then be utilized in a project like Wiltshire and Beckage's (2022), in order to see by how much, if at all, the results are impacted by a violation of this assumption.

The analysis conducted by Wiltshire and Beckage (2022) centers around the use of the Rothamsted Carbon model, or RothC model, which was created for the purpose of modeling carbon content in soil. This model takes in a variety of environmental factors in order to tailor these estimates, including but not limited to monthly rainfall, clay content in the soil, depth of soil, and monthly mean air temperature. Using these inputs, the model is then able to return the total organic carbon content (Coleman & Jenkinson 2014). This is precisely the kind of study which could benefit from a historically based approach to the spin up as is proposed here, since it would provide more accurate and robust results by ensuring the starting conditions for the model are as accurate as possible to the real-world conditions they are designed to emulate.

Environmental models of this type are highly sensitive to the results of the spin up, as it determines how the starting conditions are initialized (Hanan et al. 2018). The goal of this project is to use a historical approach to evaluate how accurate a steady state assumption for soil carbon is in the state of Vermont, and what kind of effect this could have on the spin up and subsequent starting conditions for the model. Ultimately, we hope to determine if Vermont truly is in a steady state, and if not, whether it is gaining or losing carbon as of the year 2022. As a follow up to these results, the goal is to then be able to evaluate what kind of effect this has on a model run like that used in Beckage and Wiltshire's project, should the soil carbon levels be found to not be in a steady state.

METHODS

The first step in taking this historical approach to the spin up was to construct an approximate timeline of Vermont's forest cover over time. Unfortunately, there were not many concrete figures available for this type of data; even from government sources, much of what was available was simply approximate percentages of forest cover at an approximate point in time. For those timeframes in which only percentage data was available, this percentage was then multiplied by the total land area of Vermont in order to approximate the forest cover in acres. The results of this timeline are included in Table 1 below, with a visual representation of the change in forest cover shown in Figure 1.

Year	**Area (millions of acres)**	**Percentage of Land Cover**	**Reference**
1620	5.605	95.00%	(Klyza & Trombulak 2015)
1790	4.838	82.00%	(Klyza & Trombulak 2015)
1820	3.422	58.00%	(Klyza & Trombulak 2015)
1850	2.773	47.00%	(Klyza & Trombulak 2015)
1870	1.475	25.00%	(Merck 2019)
1890	1.18	20.00%	(Bushnell 2018)

1903	1.175	19.92%	(*History of Forestry in Vermont* n.d.)
1908	1.159	19.64%	(*History of Forestry in Vermont* n.d.)
1925	1.77	30.00%	(Dabritz, n.d.)
2005	4.661	79.00%	(*History of Forestry in Vermont* n.d.)
2007	4.425	75.00%	(*History of Forestry in Vermont* n.d.)
2012	4.596	77.90%	(Morin et al. 2017)
2016	4.509	76.42%	(Morin et al. 2017)
2017	4.494	76.17%	(Morin 2018)

Table 1. Estimates of Vermont forest cover over time from the arrival of the Europeans to the present.

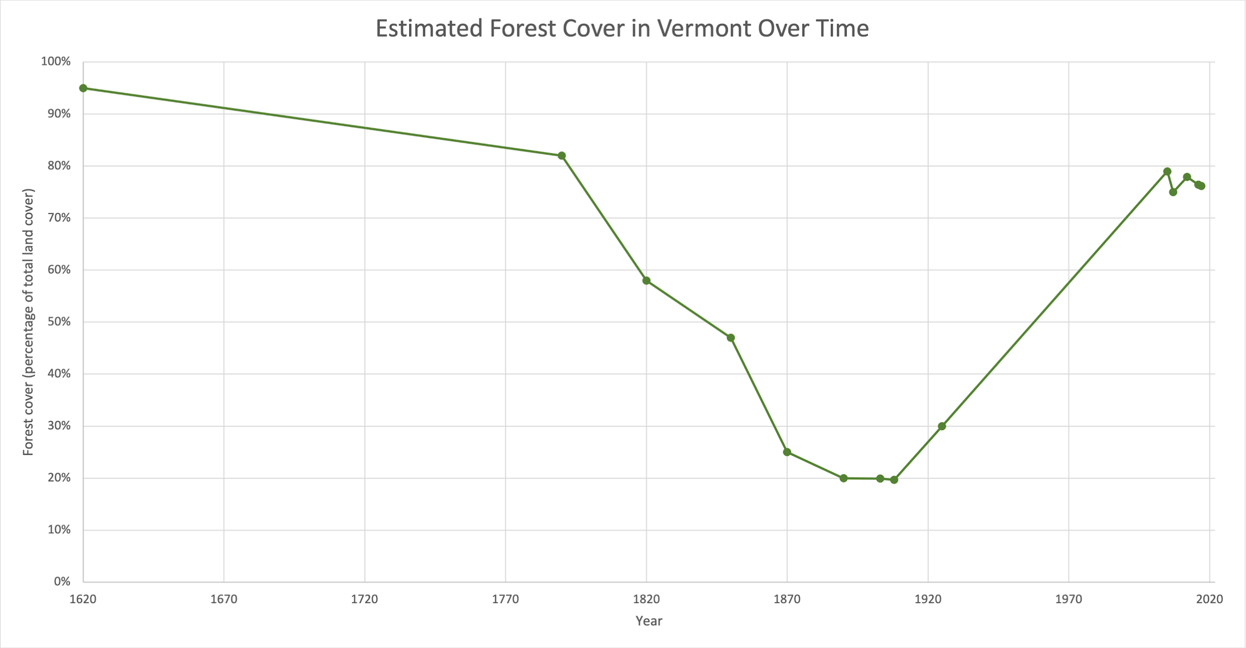


Figure 1. A graphical representation of the change in Vermont forest cover over time using the data found in Table 1.

To further facilitate incorporating this into the spin up, the above timeline was further boiled down to its overarching trends. The first trend, running for about 750 years, ends in the year 1760. At this point, the forest cover in Vermont was considered to be essentially stagnant, and marks the time before the settlers began significantly deforesting the landscape in favor of pastures (Klyza & Trombulak 2015). The next segment, running from roughly 1760 to 1895, marks this mass reduction in forest cover across the state (Merck 2019). The final segment shows afforestation as large-scale pasturing fell out of favor, alongside efforts to regrow the state's forests, and runs from 1895 to 2022 (*History of Forestry in Vermont* n.d., Morin et al. 2017, Morin 2018). These trends were compared with the data collected, and overlaid with the plot in Figure 1. The results are displayed below, in Figure 2.

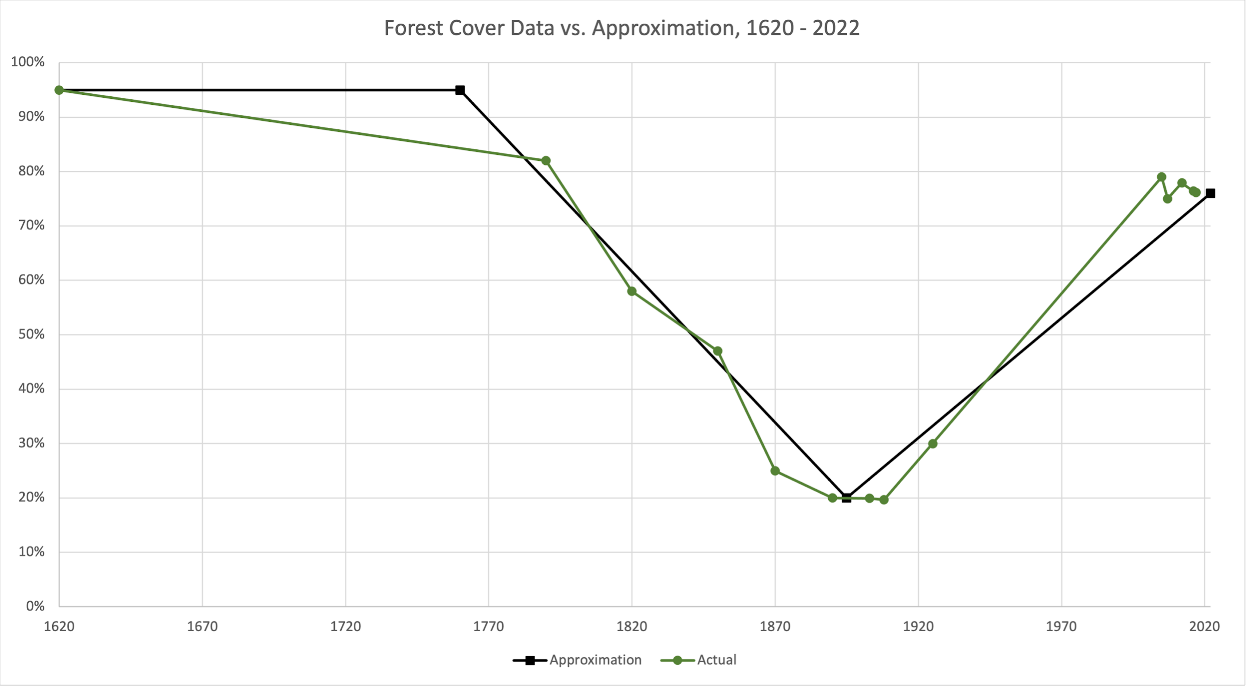
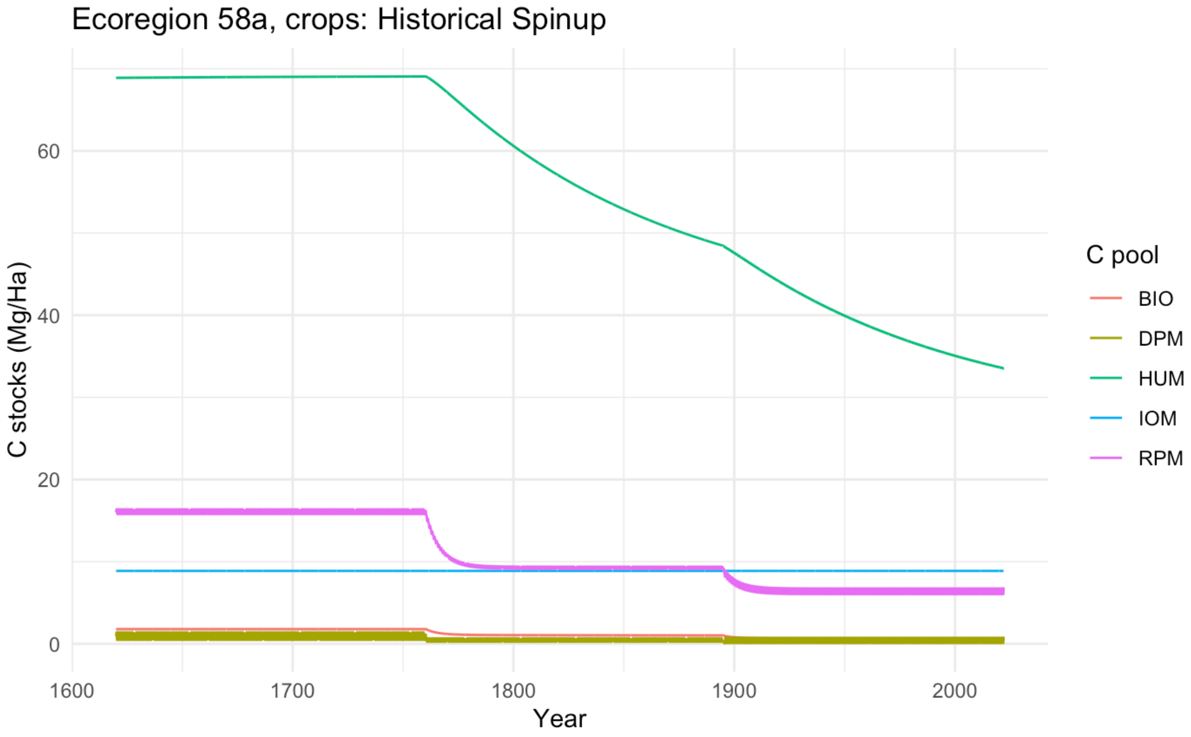


Figure 2. A plot of the historical data as shown in Figure 1, shown here in green, along with the trend approximations that will be entered into the model spin up, shown in black.

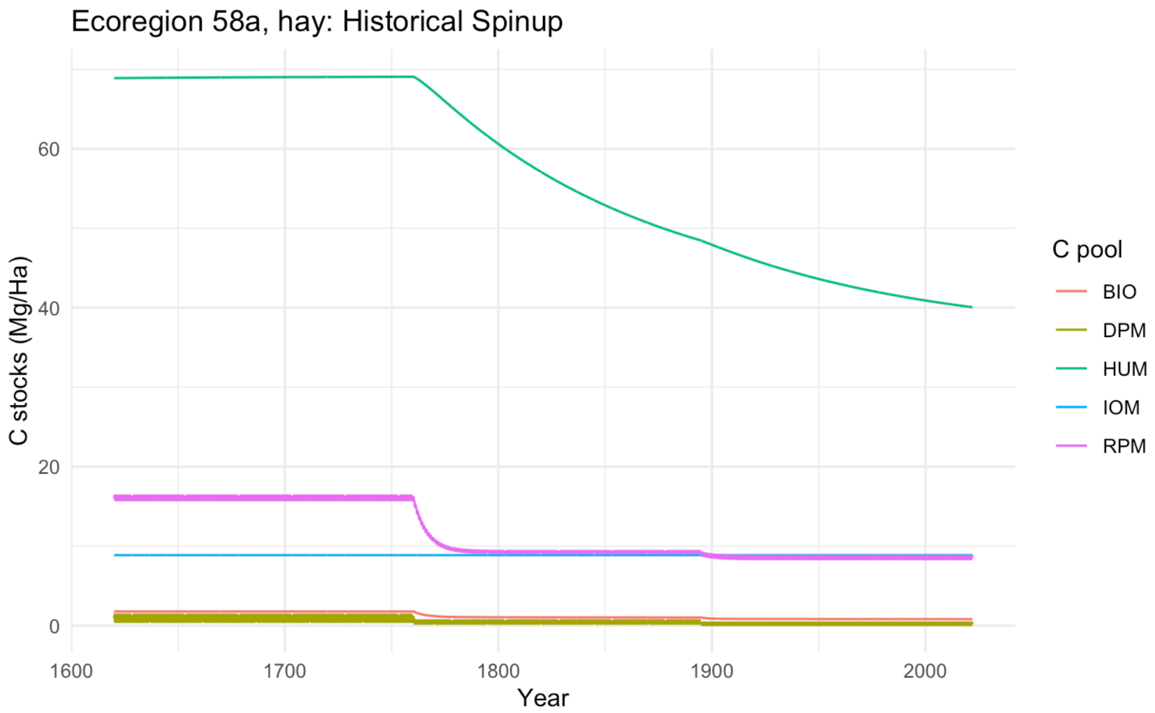
Once this timeline had been created, the next step was to run it in the spin up model to analyze the results. The spin up procedure begins by conducting the 750 year spin up to forest, sufficient for the carbon levels to stabilize. These levels are then the initial carbon stocks for the second spin up phase, which we're calling a "spin-down", reflecting the state's transition over 135 years to pasture. As before, the carbon stocks at this point are then the initial stocks for the final spin down as the state underwent the transition to current less extensive agricultural land uses, reflected by the 127 year afforestation trend. The primary difference between the initial spin up to forest and the second two "spin down" phases is that the 135 years of spinning down to pasture and 127 years of final spin down were not sufficient for the carbon levels to stabilize. This model was run on a subset of land in Vermont, which may be generalized to the state as a whole by analyzing the density of the carbon stocks, in this case using the units of megagrams per hectare.

RESULTS

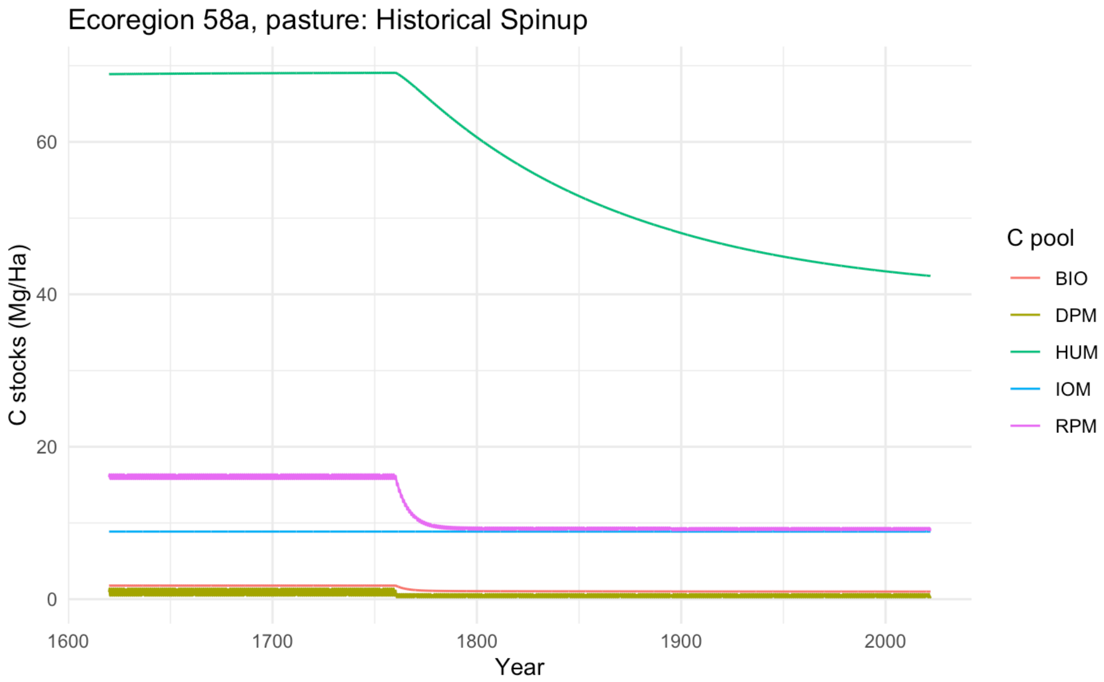
The first run of the model was conducted using above the figures for an initial spin up to forest, spin down to pasture, and a final spin up to the current land uses. The duration associated with each phase of the spin up corresponds to the time periods associated with the historical land use data described above. Results are shown below. This spin up procedure will be referred to as the "historical spin up."



a.



b.



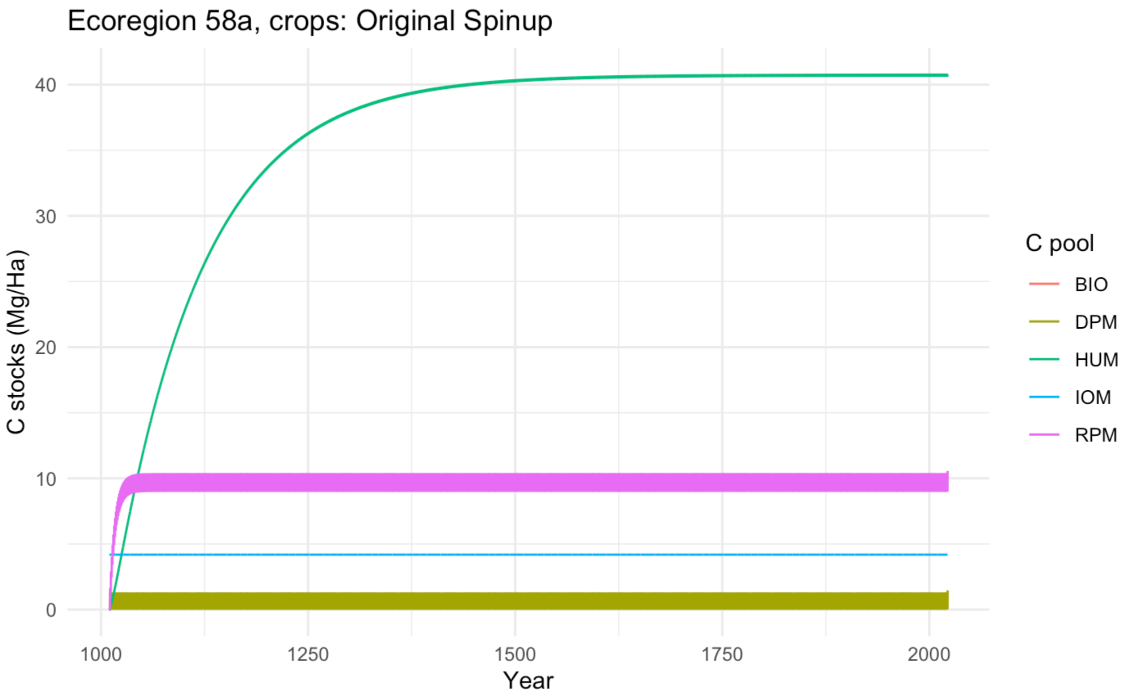
c.

Figure 3. The subplots a through c show the results of the spin up for current land uses of crops, hay, and pasture respectively using the historically calculated parameters. Each of these

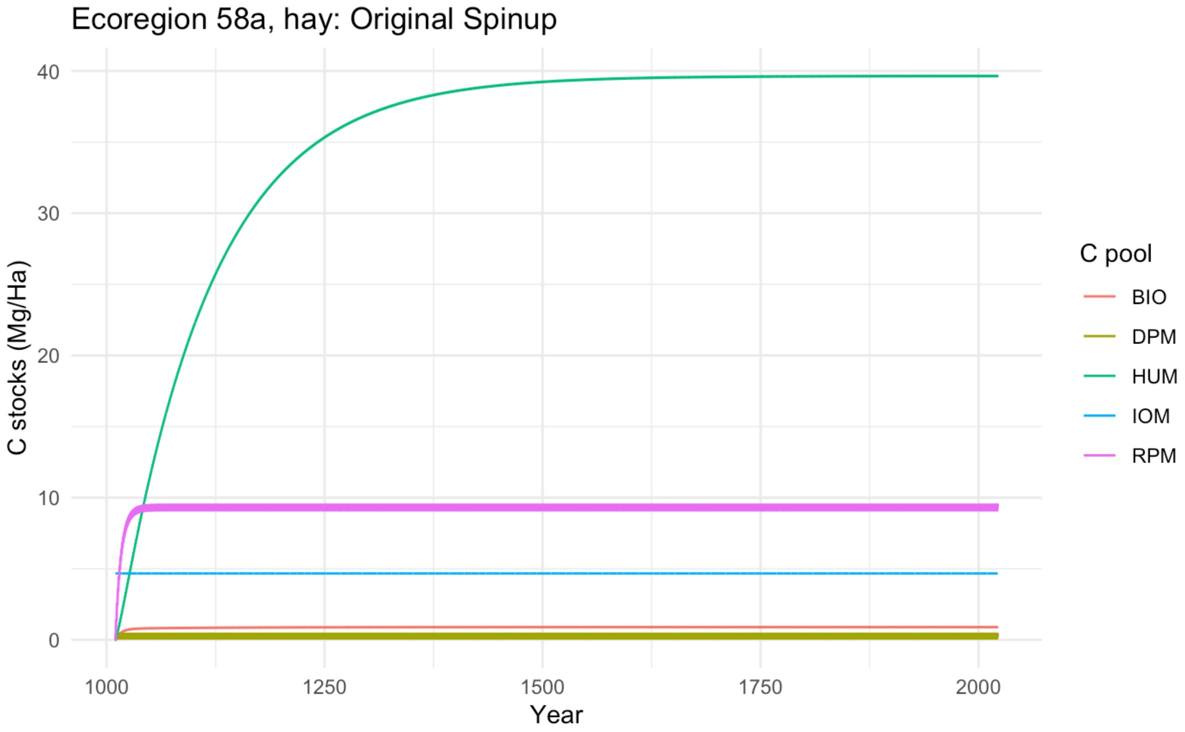
subplots shows the distribution of the carbon stocks over the five carbon pools from 1620 to 2022.

The plots in Figure 3 can be broken up into three sections, with each one corresponding to the three phases of the historical spin up described above. The first portion of this spin up, running from the year 1010 until 1760, shows the carbon stocks reaching an equilibrium, as land use and forest cover specifically was assumed to be largely undisturbed at this point, in accordance to the timeline of forest cover in Figure 2. The next portion of the plots, from 1760 to 1895, show a decline in all five of the carbon pools, triggered by the spin down to pasture as much of the land in Vermont was deforested. The third and final portion takes place from 1895 to 2022, and represents the change from pasture to the current agricultural land use, either crops, hay, or pasture. Figure 3a and 3b, illustrating crops and hay respectively, show an additional decline in carbon stocks at this point in time. Pasture lands, however, do not undergo any change beyond the 1760 spin down to pasture, however, and therefore do not experience this additional decline, as shown in Figure 3c.

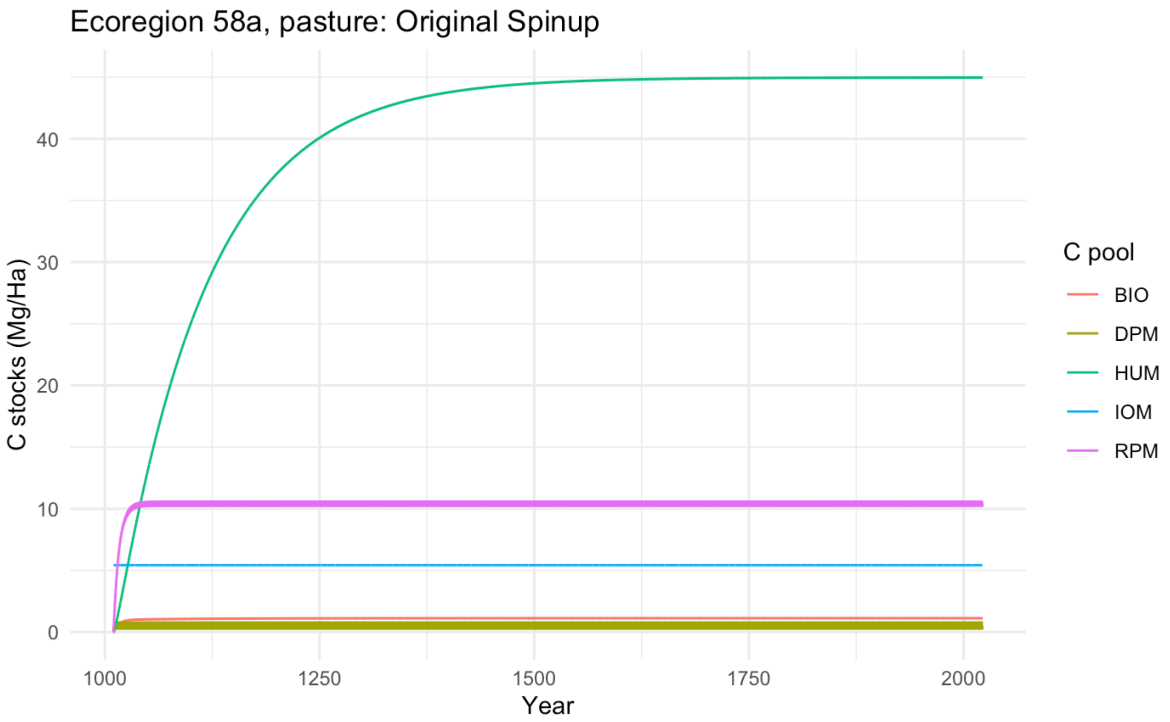
Next, the model was run using the steady state spinup, in which carbon levels are spun up to the current land use and assumed to be in a steady state by the end of the simulation, which in this case is the year 2022. This will be referred to as the “original spin up” or the “steady state spin up,” and mirrors the procedure used in Wiltshire and Beckage (2022).


Ecoregion 58a, crops: Original Spinup
C stocks (Mg/Ha)
0
10
20
30
40
1000
1250
1500
1750
2000
Year
C pool
BIO
DPM
HUM
IOM
RPM

a.


Ecoregion 58a, hay: Original Spinup
C stocks (Mg/Ha)
0
10
20
30
40
1000
1250
1500
1750
2000
Year
C pool
BIO
DPM
HUM
IOM
RPM

b.

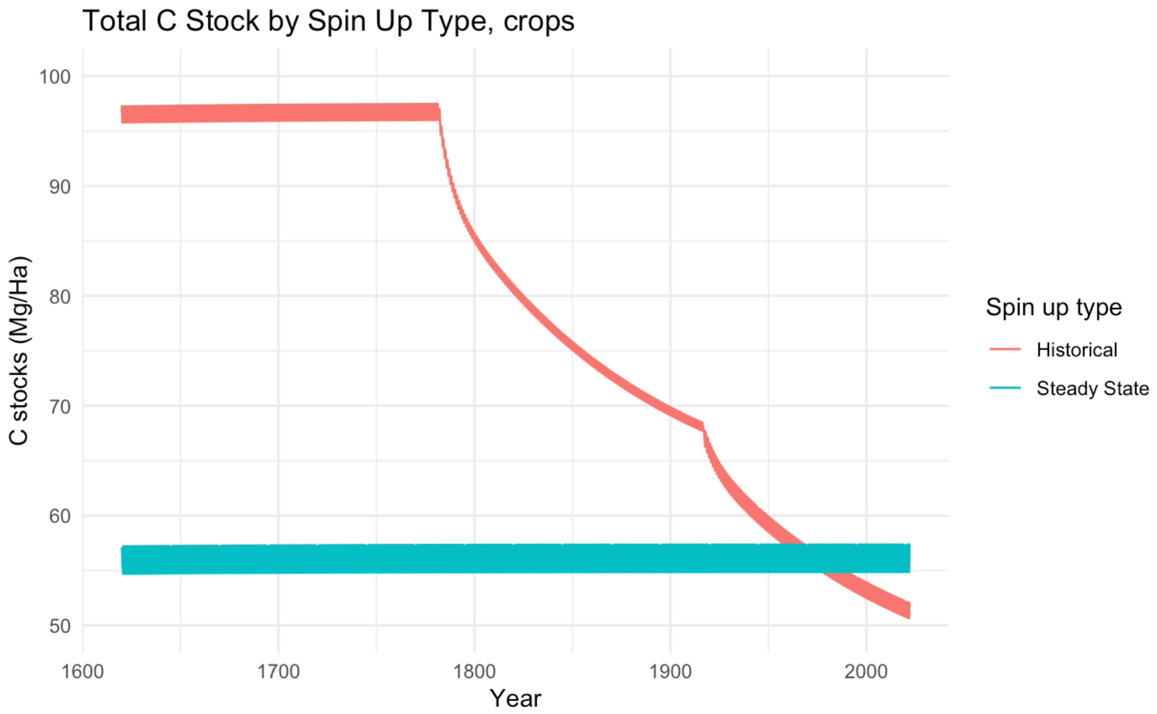


c.

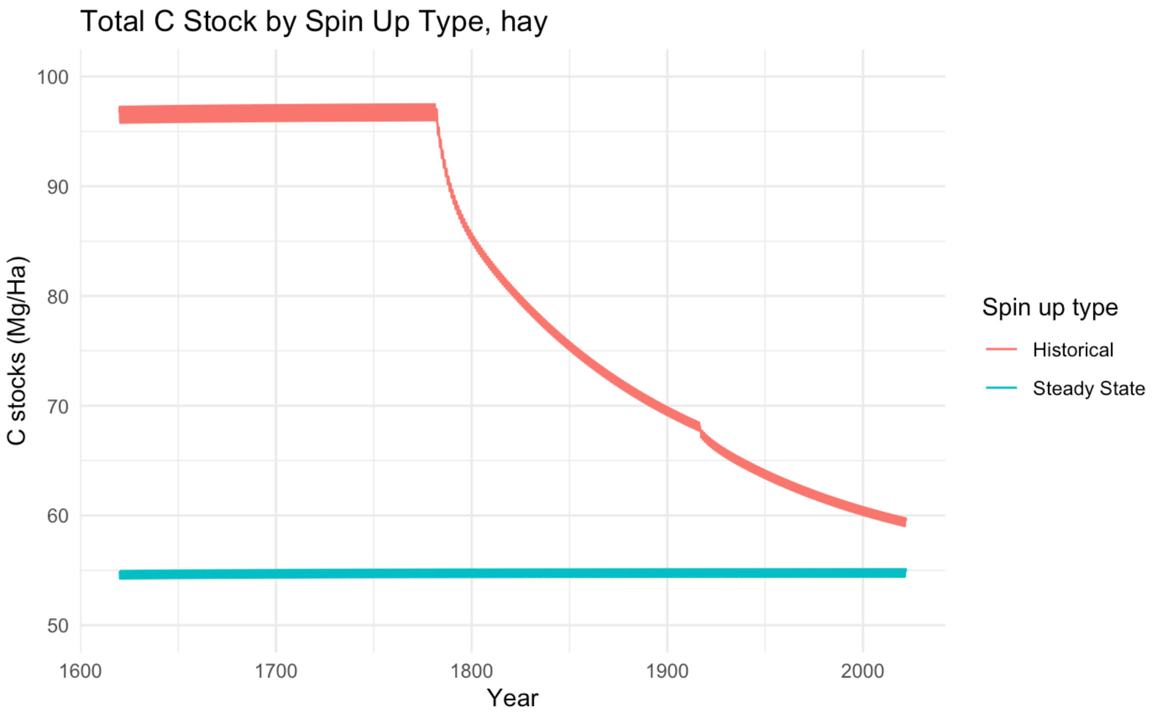
Figure 4. The subplots a through c show the results of the spin up for current land uses of crops, hay, and pasture respectively assuming a steady state at the present. Each of these subplots shows the distribution of the carbon stocks over the five carbon pools from 1012 to 2022, sufficient for the carbon pools to stabilize.

We overall see very little difference across the three subplots for the steady state spin up in Figure 4, unlike the historical spin up results from Figure 3. While all five carbon pools vary in the length of time they take to reach an asymptote, they all have essentially stabilized by the year 1760, at which point the historical spin up begins to undergo changes. Most notable is the stability of the carbon stocks across all five pools at the end of the steady state spin up in the year 2022, whereas the historical spin up above showed a distinct downward trend in all three subplots.

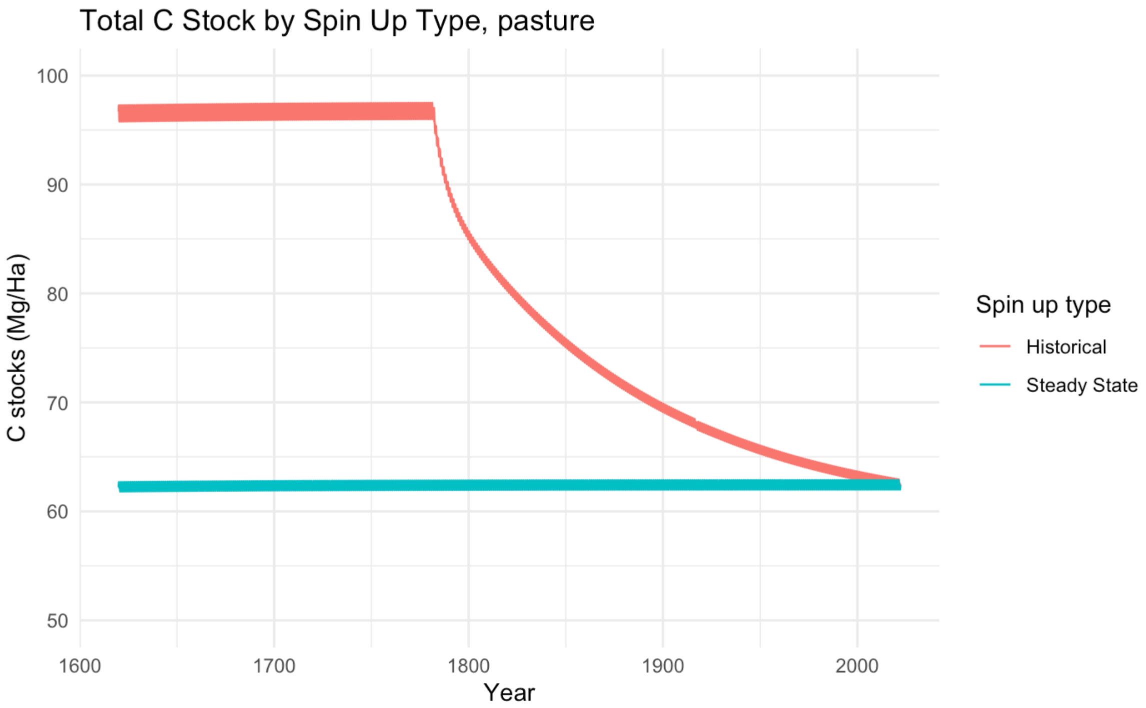
In order to evaluate the validity of the steady state assumption, it is necessary to evaluate the differences between these plots, specifically in terms of the trends between the two types of spin ups. In order to do this, the five carbon pools were summed to obtain the total carbon stock. The total stock for each of the spin up types within the three land uses were then plotted against each other over the 402 year period of 1620-2022, representing the period for which we have historical data on Vermont land use trends



a.



b.



c.

Figure 5. The total carbon stock for the historical spin up vs. the steady state (original) spin up. These were calculated for the three land uses, crops, hay, and pasture, and plotted from 1620 to 2022.

Initially, the historical spin up shows stable carbon levels, similar to the steady state spin up, in all three subplots of Figure 5. The trends of the historical spin up deviate from the steady state spin up, however, upon the spin down to pasture in the year 1760. At this point, there is a sharp decline in the total carbon stock across all three land uses, while the steady state spin up remains stable. This decline continues for the remainder of the spin up, and is still apparent by the year 2022; while present in all three land uses, the decline the sharpest for crops, as shown in Figure 5a.

DISCUSSION

Initial comparisons of the three corresponding subplots in Figures 3 and 4 clearly show different trends in the carbon stocks over time, which are catalyzed by the changes in land uses over the different periods within the historical spin up. These fluctuations show that soil carbon in the state of Vermont has likely been much more dynamic over the past few centuries than would be indicated by the steady state model.

The most important part of these results, however, are the trends shown in the plots of Figure 5. In all three subplots, the historical spin up carbon stocks are following a clear downward trend; this trend is present in all three land use cases, but is the most prominent in the case of crops, as shown in Figure 5a. These downward trends contrast with what is essentially a zero slope in the steady state spin ups, and indicate that the system is, overall, losing carbon at the end of the simulation run. Therefore, the steady state assumption appears to be an oversimplification of the soil carbon levels for Vermont at the present. This doesn’t imply that models which operate under the steady state assumption are wrong or inaccurate, but rather shows that simulations utilizing a historical spin up like the one proposed here will likely yield results that are more representative of the current state of soil carbon than models which operate under the steady state assumption.

It should be noted that this model has its own share of generalizations and assumptions. In particular, the historical data focus only on forest cover over time, and not on the changes in other land uses, such as the changes in pasture or cropland. Additionally, these figures were generalized for the entire state of Vermont, in particular that forest cover fluctuated homogeneously across all regions of the state, which is almost certainly not the case. The addition of more locationally precise data, especially data related to land uses other than simply forest cover, would provide much more conclusive and robust results by providing more precise and accurate data regarding soil carbon content and its corresponding trends. Further, much of the data that comprises the timeline of forest cover in Vermont is more or less anecdotal; it relies on approximate years and time frames, and rounded estimates of percentages and affected acres of forest. More in depth forest cover data, such as NLCD forest canopy data sets, could help provide more precise forest cover figures, particularly in more recent years as this type of data has become easier to access.

With all of this in mind, this project should be viewed as a proof of concept for evaluation of this novel spin up approach. While these results require several assumptions and generalizations, they do indicate that, in this case, the steady state assumption appears to represent an oversimplification, which could in turn have a significant impact on environmental models which are sensitive to those spin up results. Further study is required to make a definitive claim regarding the validity of this assumption in the case of soil carbon modeling of Vermont farmland, however these results show that this type of deeper study could be worthwhile.

FUTURE WORK

As mentioned above in discussing the limitations of this project, a future direction that could be taken with this would be to look at this data locationally, in order to get a finer history of the land use over time. This would allow for a more precise timeline and therefore a more precise understanding of carbon sequestration for the various land types. Along these same lines, being able to dive deeper into various land uses beyond just forestation, such as pasture and crop land, would also provide a much more accurate history and timeline of carbon content in the soil over time. The main obstacle for this particular path, however, is simply the lack of available data of this type. The afforestation and deforestation of Vermont over time has been relatively well documented, even if only anecdotally, over the course of its recent history. However, this same type of data for land uses like pastures and crops is not as widely available, so would require much more time, and likely reaching out to certain organizations in order to obtain any data on this that may exist.

Going further with obtaining more locationally precise data, it would be very interesting, as well as very beneficial to the accuracy of the results, to incorporate any kind of GIS data for these land uses, and to be able to evaluate the changes in land uses over time using this type of software. This would not only allow for locationally accurate data, but also the ability to make locationally based visualizations to help show the changes in land use over time for various areas, as well as visually what kind of effect that ultimately had on carbon sequestration.

ACKNOWLEDGEMENTS

I would like to thank the members of my committee, Dr. Brian Beckage and Dr. Jeffrey Buzas, for their feedback and support. I would also like to thank Dr. Serge Wiltshire for his guidance and expertise throughout this project.

REFERENCES

1. Benbi, D. K., & Brar, J. S. (2008). A 25-year record of carbon sequestration and soil properties in intensive agriculture. *Agronomy for Sustainable Development*, *29*(2), 257–265. https://doi.org/10.1051/agro/2008070

2. Blanco-Canqui, H., & Lal, R. (2004). Mechanisms of carbon sequestration in soil aggregates. *Critical Reviews in Plant Sciences*, *23*(6), 481–504. https://doi.org/10.1080/07352680490886842

3. Bushnell, M. (2018, July 15). *Then again: When the green mountains were not so green*. VTDigger. Retrieved 202AD, from https://vtdigger.org/2018/07/15/green-mountains-not-green/

4. Coleman, K., & Jenkinson, D. S. (2004). RothC - A model for the turnover of carbon in soil. Rothamsted Research.

5. Dabritz, C. (n.d.). *Where have all the forests gone? A History of Deforestation in Vermont*. Lecture, Burlington, VT; University of Vermont.

6. Dewar, R. C., & Cannell, M. G. R. (1992). Carbon sequestration in the trees, products and soils of forest plantations: An analysis using UK examples. *Tree Physiology*, *11*(1), 49–71. https://doi.org/10.1093/treephys/11.1.49

7. Dhanwantri, K., Sharma, P., Mehta, S., & Prakash, P. (2014). Carbon Sequestration, Its Methods and Significance. In *Environmental Sustainability: Concepts, Principles, Evidences and Innovations* (pp. 151–157). essay, Excellent Publishing House.

8. Hanan, E. J., Tague, C., Choate, J., Liu, M., Kolden, C., & Adam, J. (2018). Accounting for disturbance history in models: Using remote sensing to constrain carbon and nitrogen pool spin-up. *Ecological Applications*, *28*(5), 1197–1214. https://doi.org/10.1002/eap.1718

9. *History of Forestry in Vermont*. Department of Forests - Parks and Recreation. (n.d.). Retrieved from https://fpr.vermont.gov/forest/vermonts-forests/history-forestry-vermont

10. Klyza, C. M. G., & Trombulak, S. C. (2015). A Landscape Transformed. In *The Story of Vermont: A Natural and Cultural History* (pp. 66–67). essay, University Press of New England.

11. Lal, R. (2003). Global potential of soil carbon sequestration to mitigate the greenhouse effect. *Critical Reviews in Plant Sciences*, *22*(2), 151–184. https://doi.org/10.1080/713610854

12. Merck. (2019, October 25). *History of Vermont Forests & Farmland*. Merck Forest & Farmland Center. Retrieved from https://www.merckforest.org/history-of-vermont-forests-farmland/

13. Morin, R.S.; Domke, G.M.; Walters, B.F.; Wilmot, S. (2017). Forests of Vermont, 2016. Resource Update FS-119. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 4 p.

14. Morin, R. S. (2018). Forests of Vermont, 2017. Resource Update FS-164. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 3 p.

15. Nemo, Klumpp, K., Coleman, K., Dondini, M., Goulding, K., Hastings, A., Jones, M. B., Leifeld, J., Osborne, B., Saunders, M., Scott, T., Teh, Y. A., & Smith, P. (2016). Soil Organic Carbon (SOC) equilibrium and model initialisation methods: An application to the Rothamsted Carbon (rothc) model. *Environmental Modeling & Assessment*, *22*(3), 215–229. https://doi.org/10.1007/s10666-016-9536-0

16. Ontl, T. A. & Schulte, L. A. (2012) Soil Carbon Storage. *Nature Education Knowledge* 3(10):35

17. Wiltshire, S., & Beckage, B. (2022). Soil carbon sequestration through regenerative agriculture in the U.S. state of Vermont. *PLOS Climate*, *1*(4). https://doi.org/10.1371/journal.pclm.0000021