Global Agroforestry Systems: Spatial Analysis of Allometric Equations

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Introduction

There is limited understanding of how much carbon can be stored in agroforestry systems, and how that varies depending on the geographic location and type of agroforestry practice. Understanding carbon sequestration through agroforestry is essential to curbing climate change. Work led by The Nature Conservancy (TNC), in collaboration with scientists and practitioners across the globe, intends to robustly characterize the climate mitigation potential of agroforestry. However, practitioners across the globe are struggling to apply correct allometric equations for agroforestry systems as oftentimes the “best available” equations are not a good fit for specific agroforestry systems.

Here, we conducted a meta-analysis of existing literature and identified the various allometric equations used to estimate carbon stored within woody species. This information will provide TNC a database of allometric equations used and referenced in agroforestry papers. The database will provide a standardized allometry resource for scientists, farmers, and carbon project developers across the globe facilitating more accurate assessments of the carbon capacity of trees grown in agroforestry systems. The University of Maryland Environmental Science & Policy students provided a diverse array of strengths, backgrounds, and interests within the environmental fields to effectively serve the interests of TNC.

Background

Anthropogenic climate change is altering our world, posing serious threats to the ecological functions and services on which we depend. Agriculture, in particular, has become a major contributor to climate change as it requires vast amounts of land and energy resources to feed a rapidly growing world population (“Climate-Smart Agriculture” 2021). The global food system alone contributes to approximately 30 percent of total global greenhouse gas (GHG) emissions, with land clearing and deforestation being the major sources of emissions (Clark et al. 2020). Land clearing and deforestation typically require significant fossil fuel usage and strip the environment of its biological diversity. Agroforestry represents a compromise between agricultural land use and environmental sustainability, making it a critical nature-based climate solution (Figure 1) ("Agroforestry" 2019).

According to the U.S. Department of Agriculture, agroforestry is the "intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits" ("Agroforestry" 2019). By integrating trees and shrubs, farmers have the capability to increase yields and diversify crops grown, as well as create a carbon sink (Schroeder 1994). Trees and other vegetation in agricultural settings help store and remove carbon dioxide that would otherwise be emitted into the atmosphere – in a process called carbon sequestration. Carbon capture provides an opportunity for farmers to participate in carbon pricing programs. As of 2022, 71 carbon pricing programs were operating or scheduled for implementation worldwide, including those for carbon taxes and emissions trading systems ("State and Trends" 2022).

Figure 1. *Image depicting an agroforestry system outside Managua, Nicaragua including pineapple, pitaya, mango and native woody plants. Photo taken by Virginia Borda, January 2023.*

Allometry provides farmers with the opportunity to quantify the amount of carbon their agroforestry systems capture so that they can participate in these programs. Allometric equations relate a dependent variable, such as above ground biomass, to measurable metrics, such as height or diameter at breast height. Without allometric equations, destructive sampling methods are used to determine the biomass for woody plants. Destructive sampling involves cutting into the plant in order to physically determine this biomass which kills the plant and is an expensive, time consuming, and labor-intensive process ("*Destructive sampling and specimen preparation*" n.d.). Unlike destructive sampling, allometric equations allow farmers to estimate the amount of carbon sequestration occurring in their agroforestry system without harming trees. Allometric equations can be used on large or local scales for estimating biomass. For this reason, allometric equations represent a good way for farmers to quantify the benefits of their agroforestry systems, specifically when it comes to carbon sequestration benefits.

Using allometric equations, policymakers can implement policies that compensate farmers for the carbon sequestration that results from their agroforestry system, incentivizing the continued expansion of agroforestry systems. For this reason, agroforestry represents one of the largest potential nature-based climate solutions. In addition to climate mitigation benefits, there are several other significant benefits associated with agroforestry systems. These benefits include protecting crops from extreme weather, slowing runoff, capturing water and nutrients from below ground, building soil health and productivity, and creating habitats for pollinators such as bees and birds (Jose 2009). Thus, agroforestry systems allow farmers to boost their agricultural productivity by increasing crop yields and participate in a carbon credit system to obtain additional revenue for creating an agroforestry system.

Objectives

The goal of this project was to conduct an in-depth qualitative literature review, synthesize the allometric equations used in agroforestry systems around the world, and compile the meta-data associated with equations into a single database. Currently, there is no resource containing easily accessible allometric equation information that is informative enough for widespread use. While other databases exist, such as GlobAllomeTree, they are not comprehensive. Therefore, TNC is working to compile a hub of reliable and suitable allometric equations available for future contributors to agroforestry. This way, these allometric equations can be easily found on a computer or even while in the field on a mobile device. This will allow for suitable allometric equations developed in similar climates and environments to be quickly accessed in order to obtain the desired data.

To accomplish this task, we conducted a literature review of 424 scientific papers to identify the allometric equations these papers used to estimate carbon stored within woody species. We tracked down the original publications that developed the allometric equations, to determine what types of systems they apply to (i.e., forest versus agroforest, specific species, etc.). Next, we analyzed the suitability of the allometric equations currently being used by identifying climate zones and countries of origin. For this our team used ArcGIS to create maps to illustrate the trends of equations in different countries and climates.

Methods

TNC provided our group with 424 scientific papers related to agroforestry, excluding papers that were not in English or were over 60 pages. We scanned each paper for allometric equations by searching the ‘Methods’ section and using the ‘Find’ tool (Ctrl+F) and searching relevant terms such as “allometric”, “biomass”, or “estimation”. The equation(s) used in each paper were either original to the paper or referenced from another study. If the equation was from another study, we located the original source by following the citations (Figure 2). We recorded information on the background of the paper, including its country of origin and the number of allometric equations it uses in Google forms. In a second Google form, we recorded detailed information about the equation's parameters, including the measured variables, location, whether the equation was created for agroforestry systems, and the species of tree. The two forms fed this information directly into an Excel spreadsheet where the data was stored.

Table 1. Allometric equations used to assess the biomass of each type of tree or shrub vegetation.

Forest Type	Allometric Equation	
AB of *Juglans* spp.	$\text{Log}_{10}\text{Y} = -0.834 + 2.223 \times \text{Log}_{10}\,(\text{dbh})$	[24]
AB of *Inga* spp.	$\text{Log}_{10}\text{Y} = -0.889 + 2.317 \times \text{Log}_{10}\,(\text{d}_{15})$	[24]
AB of *Grevillea robusta*	$\text{LnY} = -2.0082 + 2.3293 \times \text{Ln(dbh)}$	[25]
AB of coffee plants	$\text{Log}_{10}\text{Y} = -1.113 + 1.578 \times \text{Log}_{10}(\text{d}_{15}) + 0.581 \times \text{Log}_{10}(\text{h})$	[24]
AB of avocado plants	$\text{Y} = 10^{\,(1.12+2.62\times\text{Log}_{10}(\text{dap})+0.03\times\text{Log}_{10}(\text{h}))}$	[26]

AB: aboveground biomass, Y = Biomass (kg), Log_{10} = logarithm base 10, ln = natural logarithm, dbh = diameter at breast height or 1.30 m height (cm), d_{15} = diameter over 15 cm height (cm), h = total tree height (m).

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↓

Model specie/s	Biomass component (kg)	Estimated coefficients a	b	R^2	MSE	RMSE	PRESS	FI
For all		Equation 1: $\text{Log}_{10}Y = \text{a} + \text{b} * \text{Log}_{10}\text{dbh}$ (cm)						
1	Foliage	−1.557	2.098	0.78	0.04	0.20	1.11	1.73
2	Branch	−1.452	2.286	0.74	0.08	0.29	2.92	2.93
3	Branch + foliage	−1.008	2.029	0.71	0.07	0.27	2.63	3.02
4	Stem	−1.196	2.294	0.87	0.04	0.19	1.32	2.28
5	Total	−0.834	2.223	0.93	0.02	0.13	0.61	1.89
Inga punctata								
6	Branch + foliage	−1.825	2.704	0.73	0.05	0.22	0.61	2.82
7	Stem	−1.830	2.847	0.86	0.03	0.16	0.25	2.18
8	Total	−0.559	2.067	0.97	0.00	0.05	0.02	1.35
Inga tonduzzi								
9	Foliage	−1.471	1.964	0.81	0.04	0.21	0.63	1.64
10	Branch	−1.541	2.527	0.85	0.06	0.24	0.63	2.51
11	Branch + foliage	−1.252	2.362	0.85	0.05	0.22	0.58	2.45
12	Stem	−1.146	2.208	0.80	0.06	0.24	0.74	2.62
13	Total	−0.936	2.348	0.95	0.01	0.12	0.23	1.78
I. punctata + I. tonduzzi								
14	Foliage	−1.464	2.003	0.80	0.04	0.19	0.77	1.70
15	Branch	−1.287	2.275	0.79	0.05	0.23	1.00	2.56
16	Branch + foliage	−1.030	2.157	0.83	0.04	0.20	0.78	2.35
17	Stem	−1.347	2.419	0.84	0.05	0.21	0.85	2.52
18	Total	−0.889	2.317	0.96	0.01	0.10	0.24	1.64

Figure 2. *Example of tracing allometric equations (top) from Ayala-Montejo, 2022. Using the citation (middle), we can track down the original source (bottom), which in this case was Segura, 2006.*

To better understand the global implications for agroforestry equation development, we analyzed spatial trends in the climate and country of origin of the equations. We ran our analysis on the top five countries which had the most total equations and comprehensive data. These included Ethiopia, Brazil, India, Ethiopia, and the United States. Next, we searched the Form 1 and Form 2 data spreadsheets for equations from our selected countries and identified the form number, ecosystem, region, city, and climate zone for each equation.

Using ArcPro, we created four different maps, including a Form 1 country map, Form 2 country map, Form 1 climate zone map, and Form 2 climate zone map. To do this, we imported a pre-existing world country border shapefile and world climate zone shapefile from the ArcGIS Hub created by Esri. We created a new ‘Equations’ field to enter our data into each of the attribute tables.

For the country maps, we compiled a count of the number of equations used and developed in each country. We then entered it as a count into the Equations field, in the row corresponding to the country. For the climate maps, we used the ArcGIS ‘Locate’ tool to find the precise location where each equation was developed or used to determine which regional climate zone in which the equation was developed (based on the city and region field from our form data). The ‘Locate’ tool pinpointed the precise location of each equation. For each location, we added a count to the corresponding climate zone, also recording the column number of the zone. To further explain, each climate zone occupied a different column number, as it was an entirely different polygon. Therefore, there could be several climate types across the world. Recording the column number allowed us to ensure that the data was being entered to correspond with the correct climate zone polygon.

Lastly, we conducted a series of statistical tests to analyze the results from Form 1 and Form 2 among the five most prominent countries: India, Indonesia, Ethiopia, Brazil, and the United States. For Form 1 entries, we ran two-sided two-proportion z-tests to determine if there was a statistical difference between Form 1 country counts within a specific climate type. This same type of test was run regarding Form 2, and as a result, statistical differences for Form 2 country counts within climate types were also established. All z-tests were conducted using RStudio. Regarding each of the z-tests, the null hypothesis was that the population proportion for one country and climate type would be equal to the population proportion for the other four countries in that same climate type. Statistical significance was indicated for results where this null hypothesis was rejected at a 5% level of significance, indicating that the country had a particularly high or low number of entries for the climate type.

Results

The use of these allometric equations in agroforestry investigations was most prominent in five countries: India, Indonesia, Ethiopia, Brazil, and the United States. In total, there were 106 equations developed in these countries, 13 from the United States, 20 from India, 14 from Indonesia, 35 from Brazil, and 24 from Ethiopia. Figures 3 and 4 display the distribution of the allometric equations that were both used and developed in countries around the world. Figure 3 represents the variety of allometric equations that were used in agroforestry studies derived from the original 424 scientific articles provided by TNC. Furthermore, Figure 4 depicts the locations where the equations were originally developed in their own primary scientific studies that may or may not have been related to agroforestry.

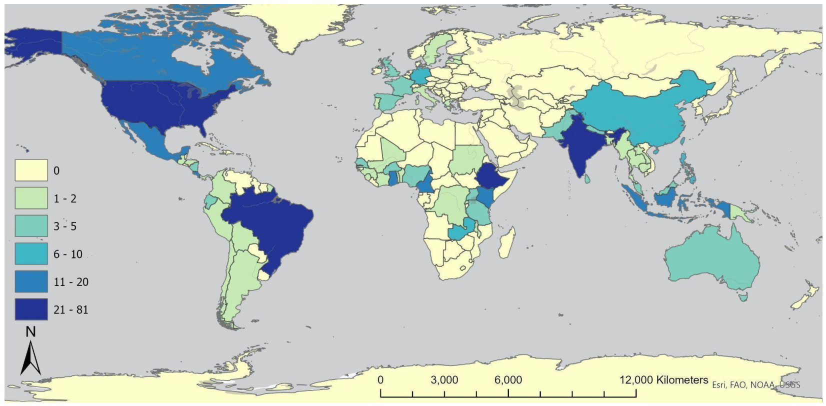

Figure 3. *Form 1 entries by country (i.e., shows where agroforestry studies were conducted).*

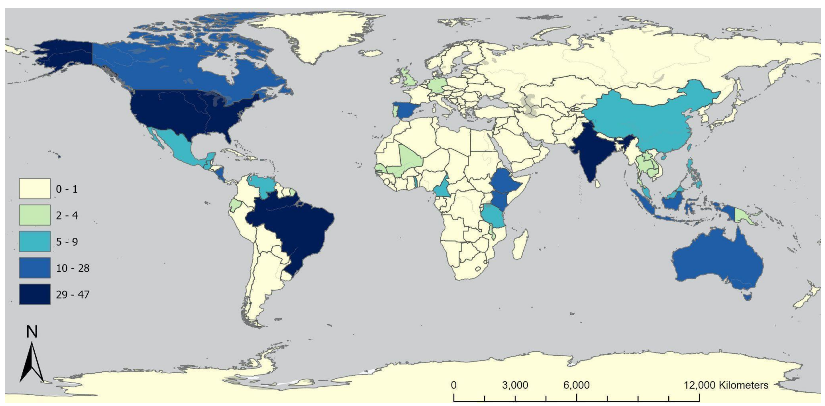

Figure 4. *Form 2 entries by country (i.e., shows where allometric equations were originally developed).*

The United States had 22 equations used in studies for Form 1. Nine of these equations were applied in humid continental climate, eight equations in humid subtropical, one equation in semi-arid, one equation in highlands, one in Mediterranean, and two equations in marine (Figure 5 – left). Of the 13 equations that were developed in the United States (Figure 5 – right), seven were developed in humid subtropical climate, two in humid continental, two in semi-arid, and two in highlands.

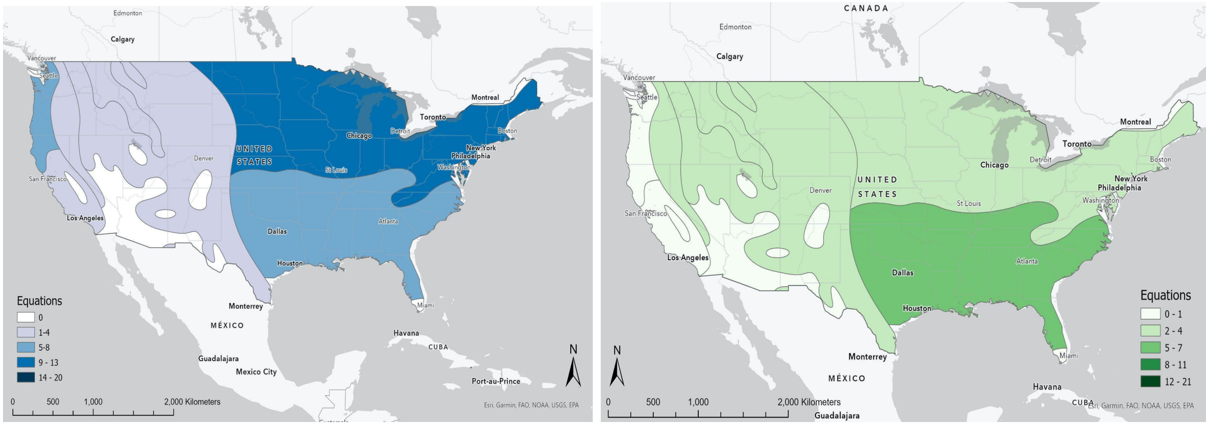

Figure 5. *Form 1 (left) and Form 2 (right) entries for the U.S. based on climate type. Observed climate types were humid subtropical, humid continental, semi-arid, highlands, Mediterranean, and marine.*

India had 54 equations used in studies. Nine were applied in tropical wet climate zones, seven in tropical dry, 20 in humid subtropical, 16 in semi-arid, one in arid, and one in highlands (Figure 6 – left). This shows that the most equations came out of humid subtropical (20) and semi-arid (16). On the other hand, the right map of Figure 6 shows that 20 equations were developed in India. 2 came from tropical wet, 2 in tropical dry, 11 in humid tropical, 3 in semi-arid, and 2 in arid. This shows that the most equations developed in India came from humid tropical conditions.

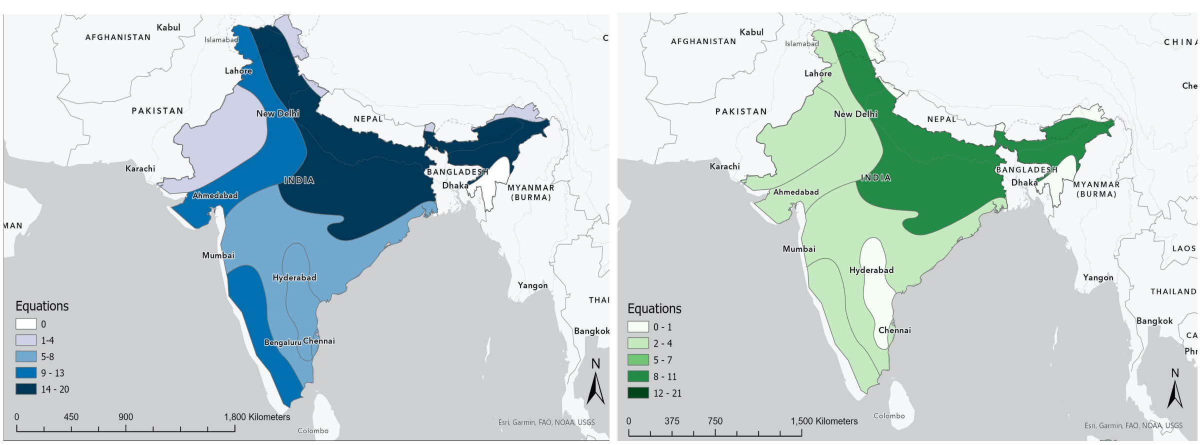

Figure 6. *Form 1 (left) and Form 2 (right) entries for India based on climate type. Observed climate types were tropical wet, tropical dry, humid subtropical, semi-arid, arid.*

There were 17 equations used in studies across Indonesia. Of the 17 equations, 16 were used in tropical wet and 1 in highland studies (Figure 7 – right). All 14 equations that were developed in Indonesia were developed in a tropical wet climate (Figure 7 – right).

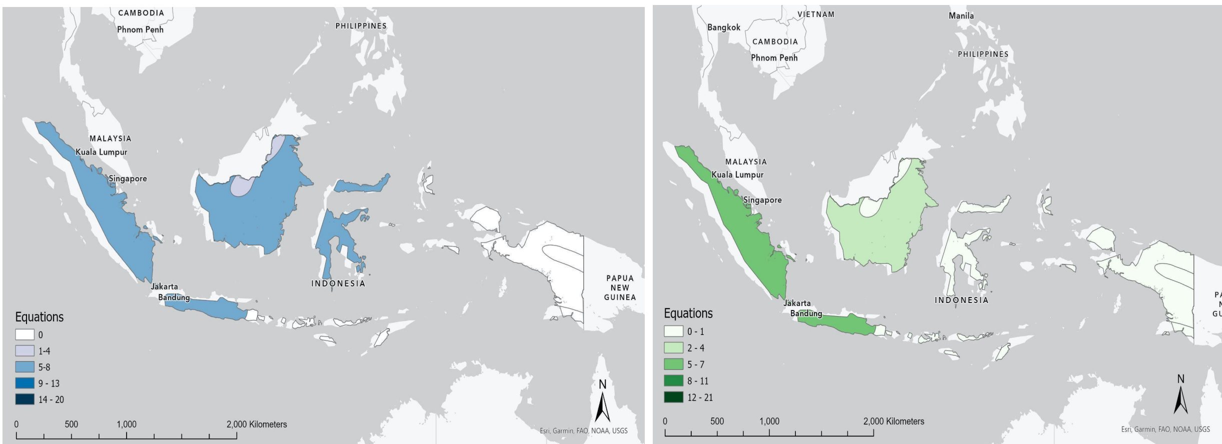

Figure 7. *Form 1 (left) and Form 2 (right) entries for Indonesia based on climate type. Observed climate types were tropical wet and highland.*

Twenty-five equations were used in studies across Brazil. Of those 25, 11 were applied in tropical wet climate zones, three in tropical dry, 10 in humid subtropical, and one in semi-arid (Figure 8 – left). A total of 35 equations were developed in Brazil (Figure 8- right). Of those 35, 27 were developed in tropical wet, 4 in tropical dry, and 4 in humid subtropical.

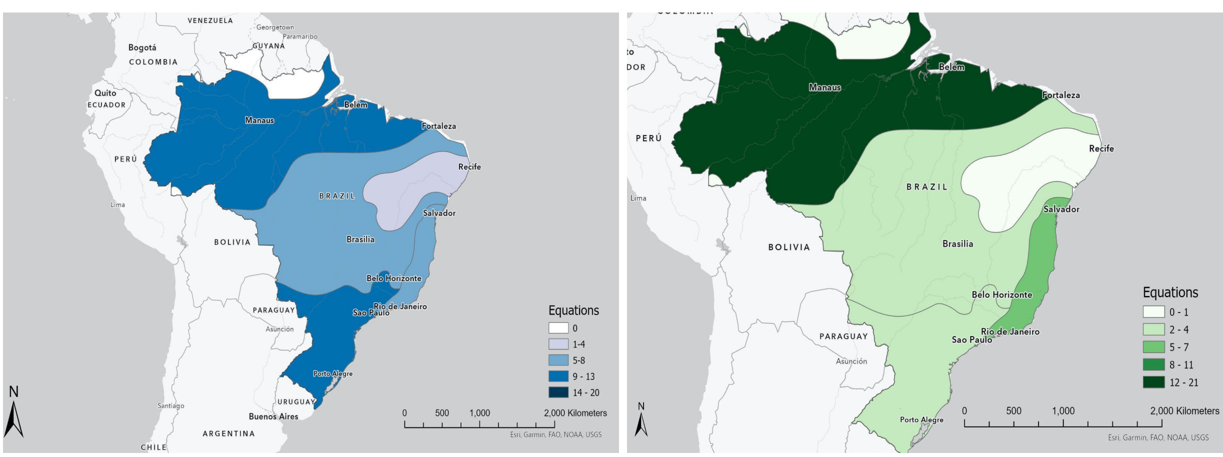

Figure 8. *Form 1 (left) and Form 2 (right) entries for Brazil based on climate type. Observed climate types were tropical wet, tropical dry, humid subtropical, semi-arid.*

There were 25 equations used across Ethiopia (Figure 9 – left). Of those 25, 19 were applied in the highlands and 6 in semi-arid regions. Of the 24 equations that were developed in Ethiopia, 17 were developed in the highlands and 7 were developed in the semi-arid region (Figure 9 – right).

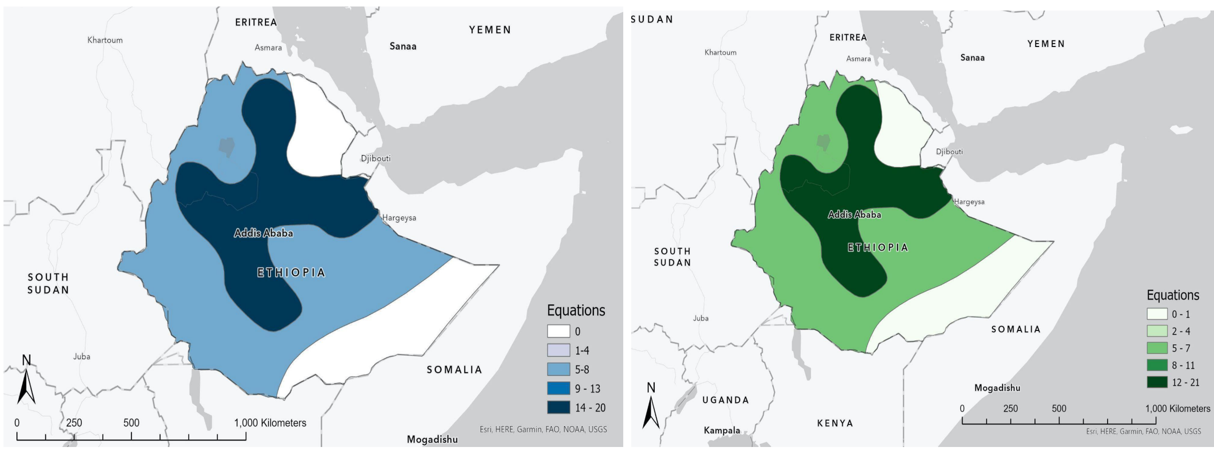

Figure 9. *Form 1 (left) and Form 2 (right) entries for Ethiopia based on climate type. Observed climate types were highlands and semi-arid.*

Table 1 shows the number of agroforestry studies by climate type for India, Indonesia, Ethiopia, Brazil, and the USA. For studies in tropical wet climates, there was a significantly high number of studies from Indonesia and a significantly low number from Ethiopia and the USA. Regarding humid subtropical climates, a significantly high number of studies were found in India, and a significantly low number of studies were found in Indonesia and Ethiopia. For semi-arid climates, a significantly high number of studies were from India and a significantly low number were from Indonesia. In humid continental climates, there was a significantly high number of studies in the USA and a significantly low number in India. For highland climates, a significantly high number of studies were found in Ethiopia, and a significantly low number of studies were found in India and Brazil. In addition, there was a significantly high number of marine climate studies found in the USA.

```
# Let p1 be the population proportion for Indonesia
# Let p2 be the population proportion for India, Brazil, Ethiopia, and the USA
# H0: p1 = p2
# Ha: p1 ≠ p2

prop.test(x = c(16, 36-16), n = c(17, 143-17) , alternative = "two.sided")
```

Country	Tropical wet	Tropical dry	Humid subtropical	Humid continental	Semi-arid	Arid	Highlands	Mediterranean	Marine	**Total**
India	9	7	20*	0*	16*	1	1*	0	0	54
Indonesia	16*	0	0*	0	0*	0	1	0	0	17
Ethiopia	0*	0	0*	0	6	0	19*	0	0	25
Brazil	11	3	10	0	1	0	0*	0	0	25
USA	0*	0	8	9*	1	0	1	1	2*	22
Total	36	10	38	9	24	1	22	1	2	143

Table 1. *Form 1 entries by climate type for India, Indonesia, Ethiopia, Brazil, and the USA. For each cell, a two-sided two-proportion z-test was conducted to determine if there was a statistical difference between Form 1 country counts within the climate type (*p<0.05). Red cells were significantly high, and orange cells were significantly low. Example hypothesis test in RStudio is shown for Indonesia tropical wet entries.*

Table 2 shows the number of allometric equations developed in each climate type for India, Indonesia, Ethiopia, Brazil, and the USA. For equations from tropical wet climates, there was a significantly high number developed in Indonesia and Brazil and a significantly low number from Ethiopia and the USA. Regarding humid subtropical climates, a significantly high number of equations were developed in India and the USA, and a significantly low number of equations were developed in Ethiopia. For equations developed in humid continental climates, there was a significantly high number of equations from the USA and a significantly low number from Brazil. For equations developed in highland climates, a significantly high number of equations were from Ethiopia, and a significantly low number of equations were from India and Brazil. Lastly, there was a significantly high number of tropical dry equations developed in Brazil and a significantly high number of arid equations from India.

Country	Tropical wet	Tropical dry	Humid subtropical	Humid continental	Semi-arid	Arid	Highlands	**Total**
India	2	2	11*	0	3	2*	0*	20
Indonesia	14*	0	0	0	0	0	0	14
Ethiopia	0*	0	0*	0	7*	0	17*	24
Brazil	27*	4*	4	0*	0*	0	0*	35
USA	0*	0	7*	2*	2	0	2	13
Total	43	6	22	2	12	2	19	106

Table 2. *Form 2 entries by climate type for India, Indonesia, Ethiopia, Brazil, and the USA. For each cell, a two-sided two-proportion z-test was conducted to determine if there was a statistical difference between Form 2 country counts within the climate type (*p<0.05). Red cells were significantly high, and orange cells were significantly low.*

Discussion

Our spatial analysis revealed gaps and trends in the global distribution of agroforestry systems and use of allometric equations. Our result revealed that five countries—USA, India, Indonesia, Brazil, and Ethiopia—were most commonly cited for having developed and used allometric equations. Upon further investigation of these five countries, we identified that in Brazil a significant number of equations are being developed in climate types tropical wet and tropical dry but not frequently used in those same climates. A similar trend was seen in the USA where many equations were developed in a humid subtropical climate but not used for that same climate. In India, it was identified that a semi-arid climate is where many of the allometric equations were used but developed in other climate types. These trends reveal that allometric equations are being developed in a specific climate and being applied to different climates, reducing the truth of the system's carbon sequestering ability. For example, in Ethiopia we observed that many equations were developed in semi-arid climates, but comparatively, not that many agroforestry studies were conducted in Ethiopia. Thus, for semi-arid climates, the data suggests that it is possible that semi-arid equations were being developed in Ethiopia but used for agroforestry studies located in India. Further research should be conducted to investigate the impact on the accuracy of carbon sequestration estimates that results from equations being developed in different countries or climate types than where they are used.

Limitations and Recommendations

This study had some potential limitations. The first is the pool of scientific papers we reviewed was constrained to those written in English and under a certain page count, which excluded sources such as dissertations or books. Therefore, the results are subject to biases that may have influenced our maps and statistical outcomes. The second limitation concerns the method of data collection and reporting due to time constraints. Our team received 424 papers to review and analyze in approximately two months, so in the interest of time, we divided them amongst the team so that each person reviewed about 29 unique papers. We developed forms to standardize responses, however, there was still room for potential differences in reporting. Lastly, there were some data limitations. As part of our analysis, we conducted source tracing to find the original study where the allometric equation was created. However, there were instances of "dead-end" papers, whether that be two sources citing each other as the source of the equation, an undiscoverable paper, or the paper not citing a source for the equation. These cases were flagged throughout the process, but still represent a loss of information and data which could impact the accuracy of our maps and analysis.

We recommend that additional research be done to review papers that are not in English to expand the reach of our data and create a stronger, more accurate depiction of where allometric equations are being developed and used. Moreover, we suggest that further investigation is done into tropical dry, arid, humid continental, and Mediterranean climate types, as our results demonstrate that relatively few allometric equations are being developed for these climate types. Similarly, our results also indicate that further research should focus on developing allometric equations in the global north. Lastly, we suggest that TNC assess allometric equations' sensitivity to a variety of factors including variables, climate type, and country of origin. Such an analysis would provide agroforestry professionals with a better understanding of which equations tend to be most useful within specific contexts.

Conclusion

Allometric equations estimate the amount of carbon and biomass within arboreal systems in a non-destructive manner. More specifically, when focusing on agroforestry systems, these equations will be used towards improving soil quality, protecting crops, minimizing runoff, and improving water capture. Our contributions towards the extensive literature review of scientific articles, as well as spatial analysis of the geographic locations and climate regions will hopefully aid The Nature Conservancy as well as farmers, scientists, and other non-governmental organizations towards a better understanding of carbon sequestration within these agroforestry systems across the globe. As one of the first of its kind, our research broke ground towards centralizing the information and equations within the plethora of disconnected and scattered scientific studies. After straightening the variety of allometric equations and organizing the different regions and climate zones, we expect our categorized spreadsheets and geographical layouts to be very useful in future projects for The Nature Conservancy.

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