Exploring the potential of a distance-based tree competition index to determine understory competition and offer a new competition covariate for forest ecosystem research

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Introduction

The species composition and structure of forest understories are largely dictated by the overstory trees (Spurr & Barnes 1980). Through their own consumption via their crown and root systems, incoming light quality is reduced, and soil nutrient and water availability become restricted for understory herbaceous and woody species (Keddy 1989). Both above and below ground consumption are integral for determining interspecific competition (Schnitzer *et al.* 2005, Toledo-Aceves & Swaine 2008). Both above and belowground competition are considered 'size-asymmetric', wherein larger individuals reduce the available light or nutrients available for smaller individuals (Cahill & Casper 2000). The importance of an individual's size is the essential baseline assumption that allows for the use of size-based competition indices in quantifying inter-individual competition in forest systems.

Competition indices (CIs) have typically been used to predict growth through analysis of individual trees experiencing competition from other nearby trees (Radtke *et al.* 2003). Several measurements can be utilized when performing CIs in stands, including selected tree and neighbor trees' diameter at breast height (DBH), height, and horizontal distances; the latter being integral for distance-based CI models as opposed to distance-independent models. Generally, incorporating the distance between trees offers more effective models of competition as increasing distance between individuals reduces competition (Rouvinen & Kuuluvanien 1997).

Aside from being used for growth rate surveying, CIs have also been used to achieve alternative goals within practical forest management and ecological research. These models have successfully been utilized to measure competition on tree plantations (Morris & MacDonald 1991) and measure components of and mechanisms affecting tree competition (Weldon & Slauson 1986, Brunner & Nigh 2000).

A CI model typically used to analyze tree-on-tree competition and predict tree growth rate has been repurposed in this study to specifically analyze the impact of spatial-located trees within long-term nutrient limitation experimental stands to determine the impacts of fertilization on forest community competition. Generally, short-term fertilization studies have found little significant impacts of fertilization on competition (Wilson & Tilman 1993), however it is hypothesized that long-term fertilization may impact competition across several successional stages. A completed CI model within the experimental plots also offers opportunities for explaining patterns in soil respiration, herb cover, and root density of previous and future studies as well as the potential for predicting likely locations of future successful herbaceous and woody species recruitment.

Methods

Site Description

The Multiple Element Limitation in Northern Hardwood Ecosystems (MELNHE) study is a long-term nitrogen (N) by phosphorus (P) full factorial fertilization? experiment in temperate forest ecosystems. The study takes place in three experimental forest sites in the White Mountain National Forest, New Hampshire, U.S.A that share similar topoedaphic and climatic characteristics (**Figure 1**). The study region is mountainous with Spodosol soils developed in glacial till while the climate is characterized as humid continental receiving on average 1400 mm of rain annually with a temperature range of -5°C to 32°C (Bailey *et al.* 2003, Vadeboncoeur *et* *al.* 2014). The Bartlett Experimental Forest (BEF) (44° 02–04'N, 71° 16–19'W, 330-570 m elevation) has nine MELNHE stands (C1,C2,....C9) (**Figure 2**), the Hubbard Brook Experimental Forest (HBEF) (43° 56'N, 71° 44'W, 500 m elevation) has two MELNHE stands (HBM and HBO) (**Figure 3**), and Jeffers Brook (JB) (44° 02'N, 71° 53'W, 730 m elevation) has two stands (JBM and JBO) (**Figure 4**).

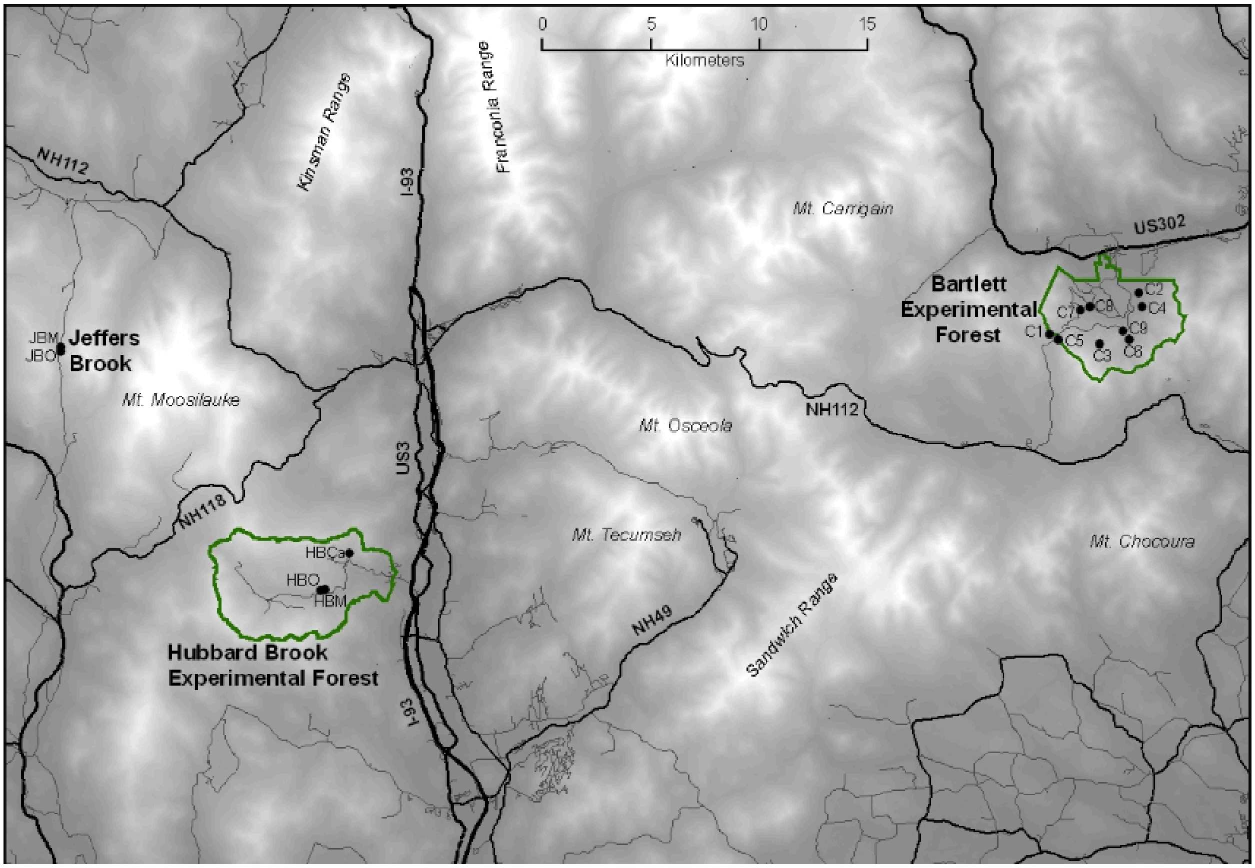

Figure 1 Three MELNHE sites across the White Mountains National Forest, New Hampshire, U.S.A.

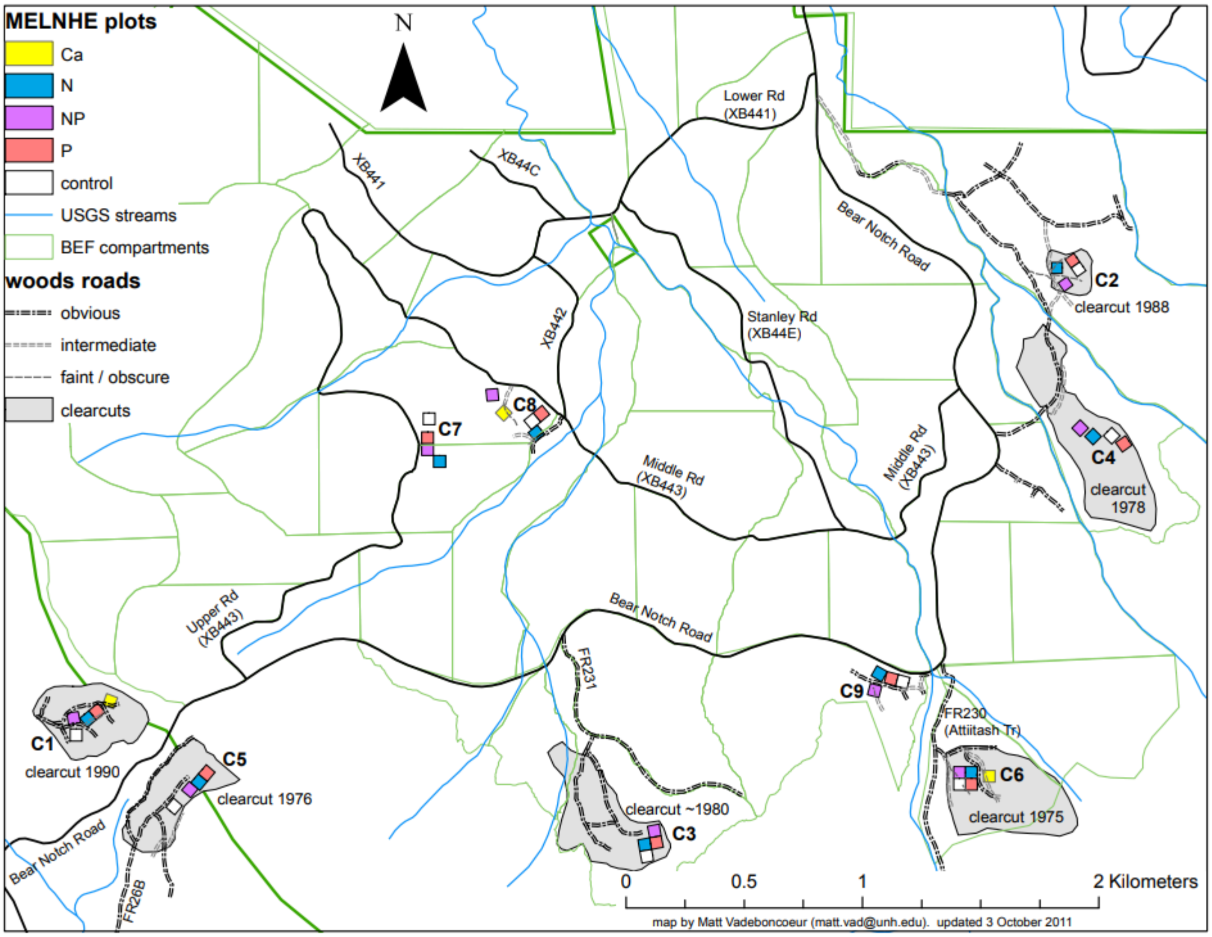

Figure 2 Nine of the MELNHE stands in the Bartlett Experimental Forest. Only stands C4, C6, C7 and C8 have been stem mapped with buffer trees. Mid-aged stand age is represented by stands C4 and C6. Mature is represented by stands C7 and C8.

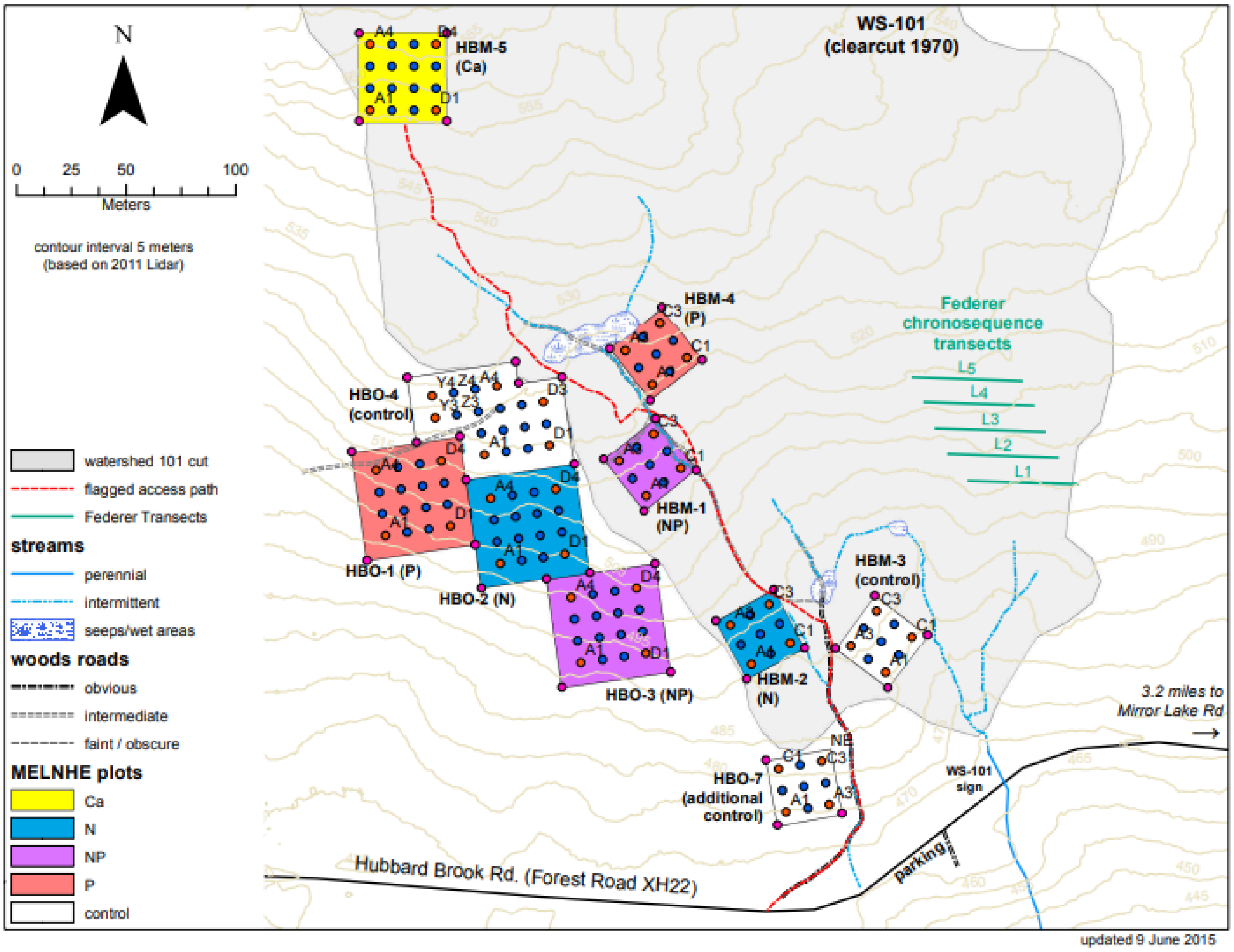

Figure 3 Stands HBO (mature) and HBM (mid-aged) at Hubbard Brook Experimental Forest.

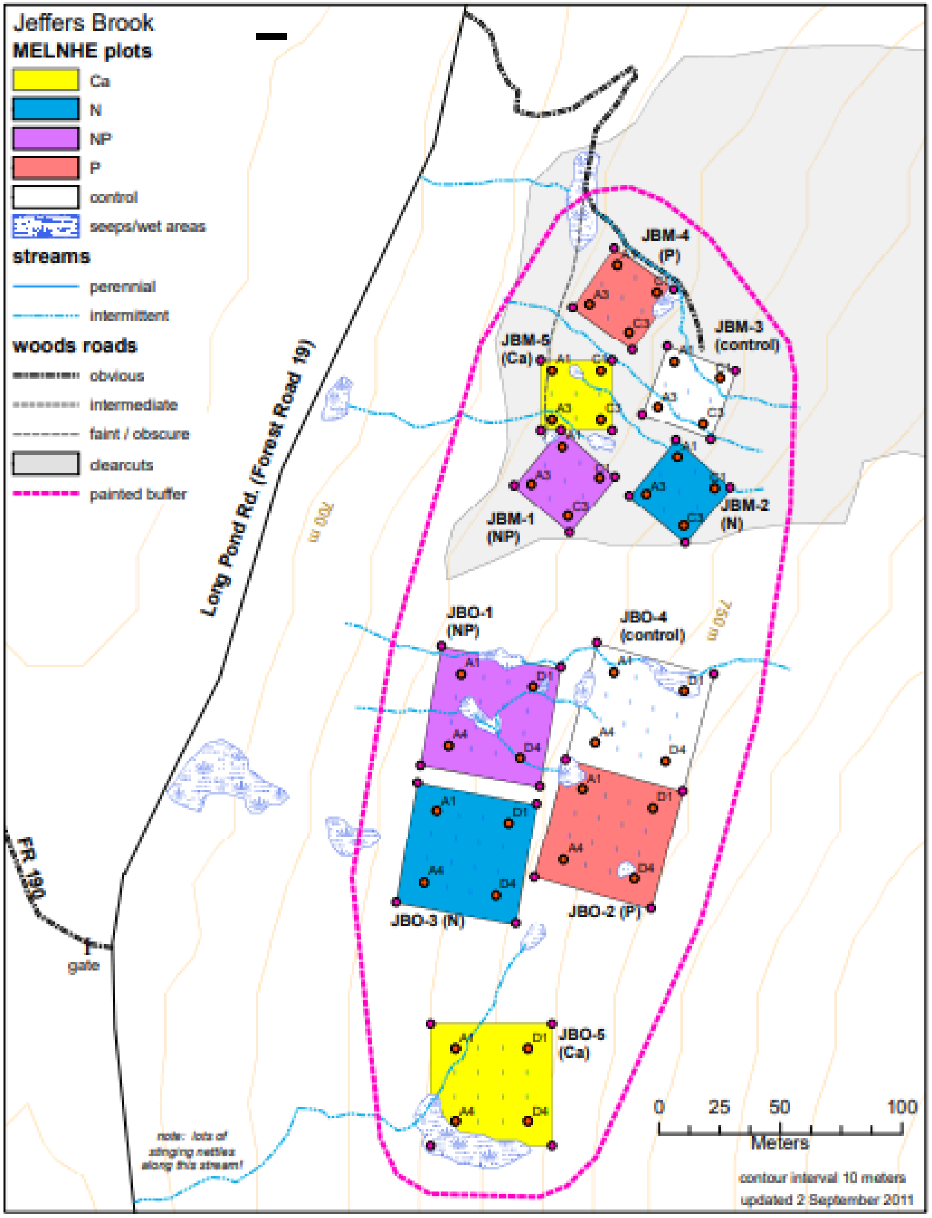

Figure 4 Stands JBO (mature) and JBM (mid-aged) at Jeffers Brook.

Across all three sites, stands were selected according to the time of last harvest to offer different successional conditions for the nutrient limitation experiment. Young stands were last harvested between 1982-1990 and include stands C1, C2, and C3. Mid-aged stands were harvested between 1970-1978 and include stands C4, C5, C6, HBM, and JBM. Mature stands are the oldest aged being last harvested between 1883-1915 which include stands C7, C8, C9, HBO, and JBO. Tree species composition is variable across sites but typically includes the following species in some abundance: American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), red maple (*A. rubrum*), white ash (*Fraxinus americana*), yellow birch (*Betula alleghaniensis*), paper birch (*B. papyrifera*), and pin cherry (*Prunus pensylvanica*) (**Figure 5**).

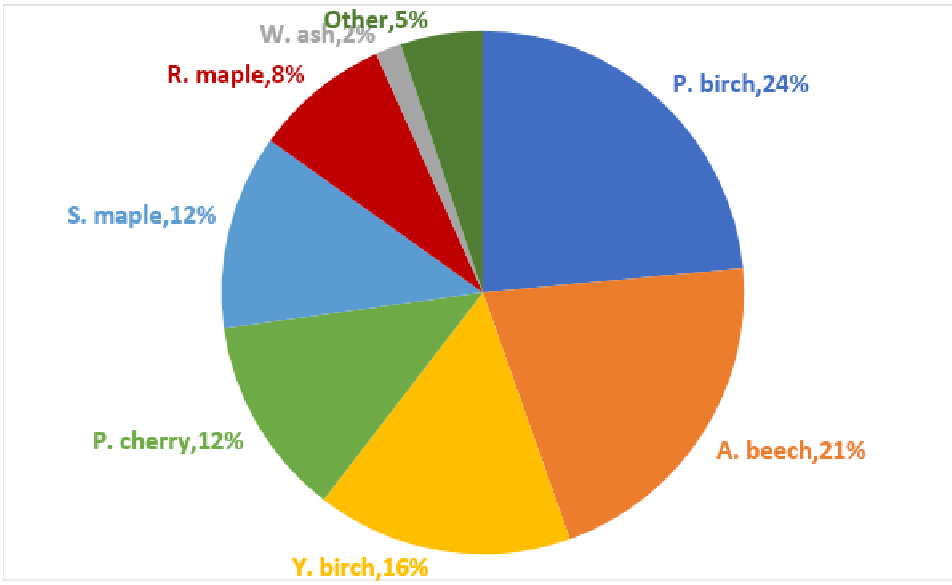

Figure 5 Species composition across the 13 MELNHE stands of tree individuals with >10 cm DBH from 2014 tree inventory (Goswani *et al.* 2018).

In each stand, four–in some cases five–experimental plots were set up and classified as N, P, NP, and control treatments. Each plot was created with a 30x30-m interior surrounded by a 10 m buffer around on the exterior (**Figure 6**). Nutrient additions began in 2011 with 30 kg/ha/year of N as NH_4NO_3 to N plots, 10 kg/ha/year of P as NH_4NO_3 to P plots, both together in NP plots, and neither to control plots. A few select stands had an additional plot fertilized with 1,150 kg/ha of calcium (Ca) as $CaSiO_2$ as a one-time fertilization event, but these stands were not included in this study due to lack of data of buffer trees.

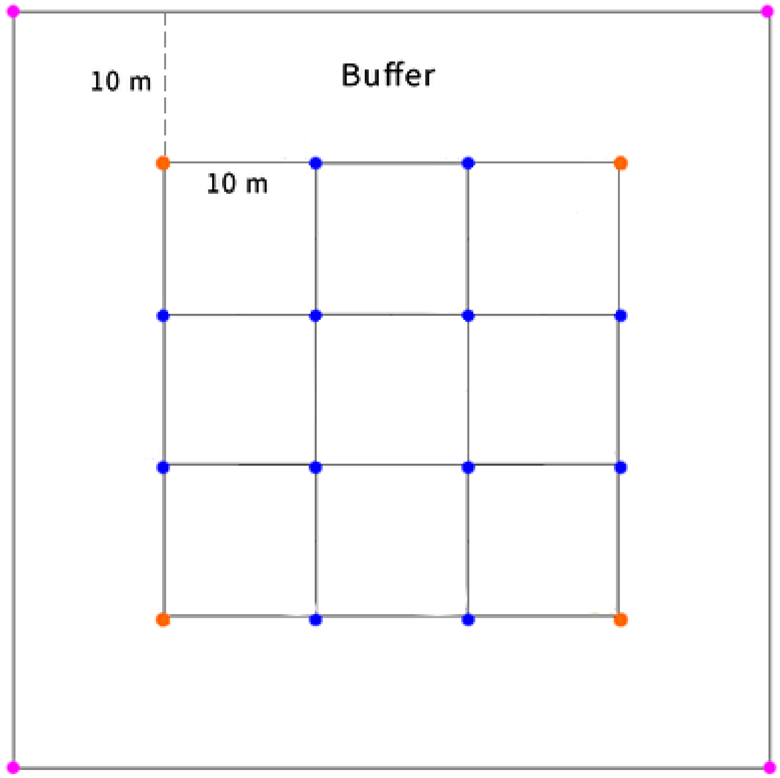

Figure 6 Layout of the experimental plots within each typical 50x50-m stands. Stands HBM and JBM have only 4 interior sub-plot. Pink stakes mark the edges of each buffer region. Lines between blue and orange interior stakes are 10 m in length.

Tree Inventory and Geolocations

A long-term tree inventory for all MELNHE plots began prior to the initial fertilization in 2011. Subsequent updates to the inventory occurred in 2015 and 2019. The inventories recorded species and diameter of every tree with DBH >10 cm being affixed with numeric tree tags for long-term monitoring purposes. In 2015-2016, an effort began to incorporate spatial location to all tagged trees across the MELNHE stands—young stands (C1, C2, and C3) were excluded from this effort). In 2019-2020, this effort was expanded upon to include untagged buffer trees wherein their species, DBH, and spatial locations were recorded and added to the stem location dataset.

Not all stands could be assessed for competition index due to one of two constraints: 1) no current stem location dataset, and 2) a lack of mapped buffer trees (**Table 1**).

Table 1 Full list of MELNHE stands and reasons for rejection of omitted stands for this study.

Stand Name	*Analyzed / Not analyzed*	*Reason for Rejection*
C1	Not analyzed	No stem location dataset available
C2	Not analyzed	No stem location dataset available
C3	Not analyzed	No stem location dataset available
C4	Analyzed	
C5	Not analyzed	No mapped buffer trees
C6	Analyzed	
C7	Analyzed	
C8	Analyzed	
C9	Not analyzed	Inconsistent mapping of buffer trees

HBM	Analyzed
HBO	Analyzed
JBM	Analyzed
JBO	Analyzed

Competition Index Equation and Mapping

The following equation from Rouvinen and Kuuluvanien (1997) was used with the stem location dataset to establish CI values at every 1x1-m square across the interior of applicable MELNHE treatment plots:

$$CI = \sum_{i=1}^{n} \text{arctan } arctan\left(d_i / dist_i\right)$$

where

d_i= tree DBH (cm)

$dist_i$=distance (m) from point of interest to tree

This equation used untagged buffer tree data as well as the tagged trees within the measurement area. The search radius for each competition point was set to 10 m—the same length as the buffer around all treatment plots. This followed a similar protocol to Contreras *et al.* (2011) wherein all trees were assessed in a search radius of 11 m–a radius 3.5 times the average radius of tree crowns and roughly the span of an average mature tree's root system

(Lorimer 1983). The reduction from 11 m to 10 m was unlikely to reduce the efficacy of the competition index for the MELNHE plots.

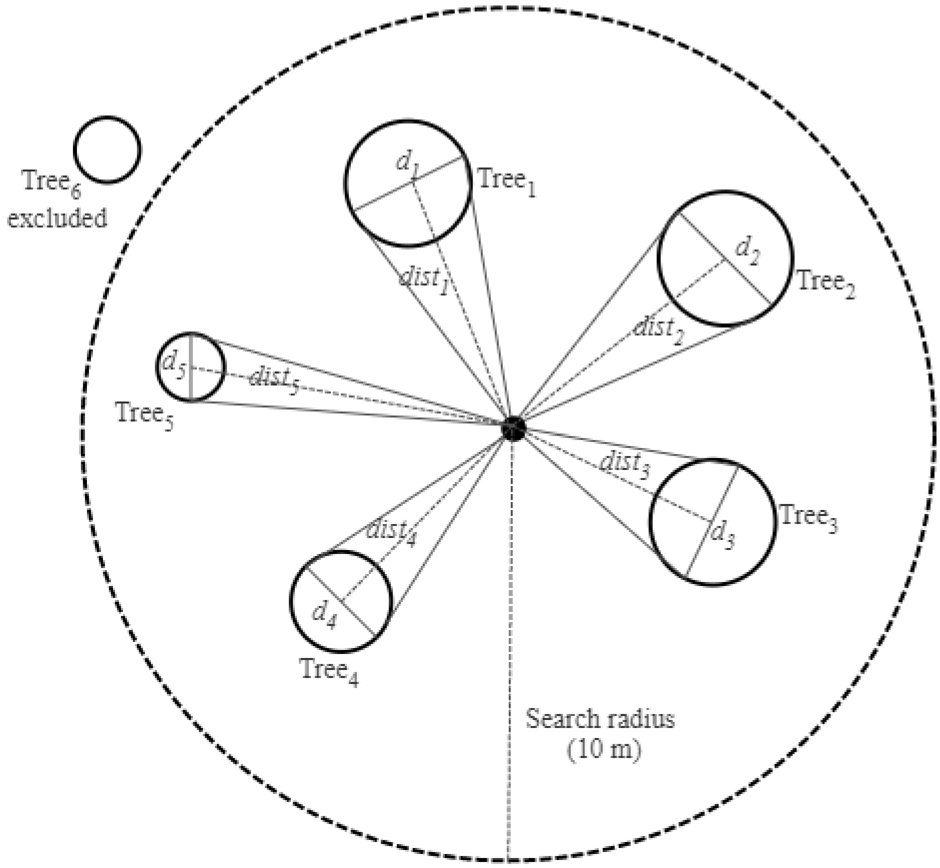

Figure 7 Model based on Contreras *et al.* (2011) of the CI model computation. Horizontal angles from the focal point (center) to all surrounding trees within 10 m were created using the arctangent of the distance and DBH. Focal points were based for calculation at the center of each 1x1-m across the experimental plots.

A map layer consisting of a grid of 1x1-m squares was added as a feature class layer in ArcGIS Pro overlapping all MELNHE stands where CI was applicable. Following calculation, these points were color-coded based on their calculated CI values from green (low competition) to red (high competition) to display tree-dictated competition within that 1x1-m area at that location within the plots. Each experimental plot contained 900 1x1-m CI squares. Plot features including boulders and seeps/periodic wet areas were added to the maps to offer possible explanation to some CI patterns.

Statistical Analysis

With 3600 CI values in every typical stand (1600 in HBM and JBM), there were a total of 24800 CI values for statistical analysis. A full factorial analysis of variance test with interactions (df=1) was performed in R to analyze the significance of stand age (mid-aged vs mature) and fertilization addition (N added yes vs no, P added yes vs no). Subsequent interaction plots were created to analyze the interactions themselves.

Results

The CI equation from Rouvinen and Kuuluvanien (1997) was successfully computed using the MELNHE stem location dataset and ArcGIS to create CI maps for 8 of the 13 MELNHE stands. These visually show on a heat-scale from green (low) to red (high) how surrounding trees influence competition in several 1x1-m quadrats across the experimental plots (**Figure 7**, **Figure 8**). The CI values in these map layers were extracted for statistical analysis.

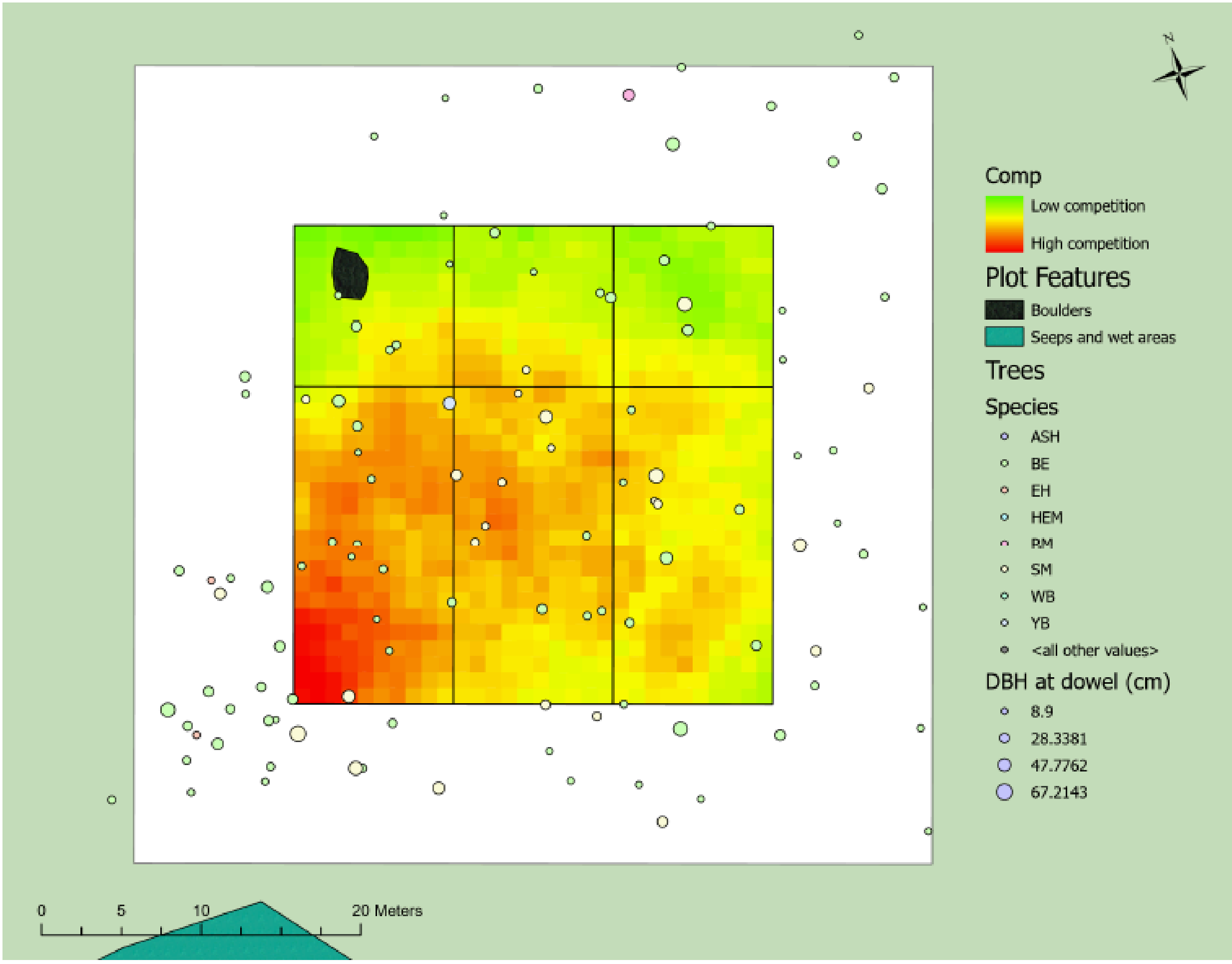

Figure 7 Competition index map of the control plot in MELNHE stand C7 in Bartlett Experimental Forest, New Hampshire, U.S.A. Resolution of CI is 1x1 m. Tree symbols are not spatially to scale and are scaled by DBH as indicated in the legend.

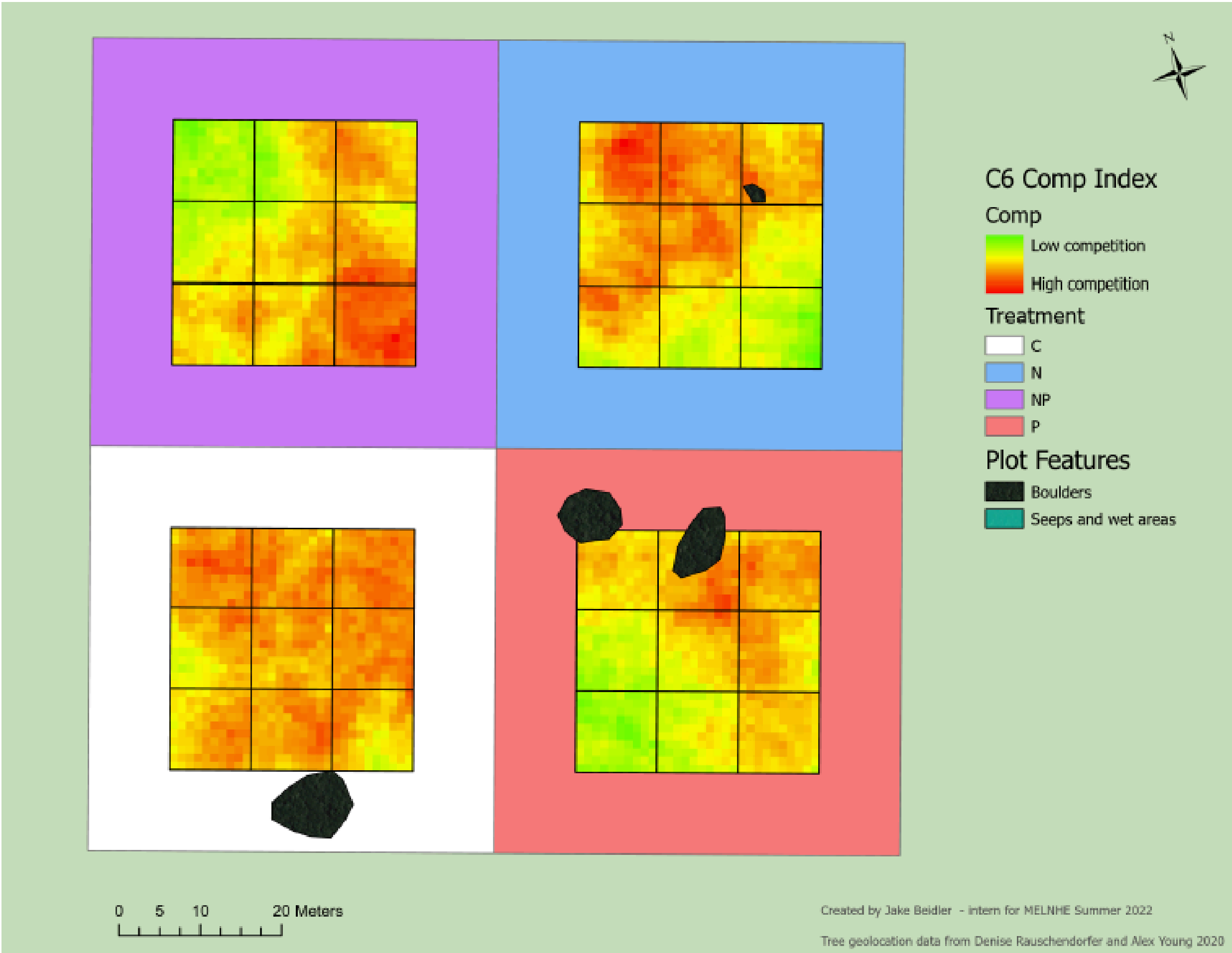

Figure 8 Competition index map of MELNHE stand C6 in Bartlett Experimental Forest, New Hampshire, U.S.A. Resolution of CI is 1x1 m. The tree layer is hidden in this instance.

The results from the statistical analysis of CI values under differing stand age and fertilization treatment show that both factors significantly impacted tree-dictated competition via the full-factorial analysis of variance test. In general, mid-aged stands had significantly higher average CI values compared to mature stands. In both age classes, the average CI values in control treatments was higher than that of other fertilization treatments. In mid-aged stands, the NP (additions of both N and P) plots had a higher average CI value than both N and P individual treatments, however, this pattern was reversed in the mature stands wherein the NP treatment averaged lower CI values compared to N and P individual treatments (**Figure 9**). Interaction plots of both the mid-aged and mature-aged stands show that interaction is present between the addition or non-addition of N with the addition or non-addition of P (**Figure 10**).

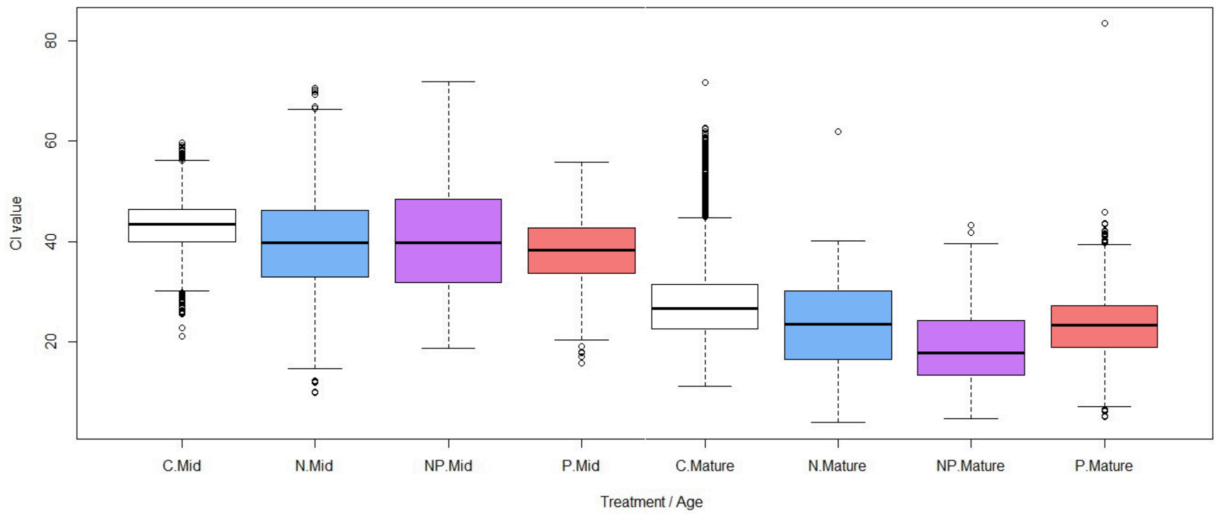

Figure 9 Boxplot of all calculated CI values categorized by stand treatment (C=control, N=nitrogen, NP=nitrogen and phosphorus, P=phosphorus) and stand age (Mid=mid-aged, Mat=mature). CI values were significantly impacted by both stand age and fertilization via a full-factorial ANOVA with interactions ($p<0.05$, df=1).

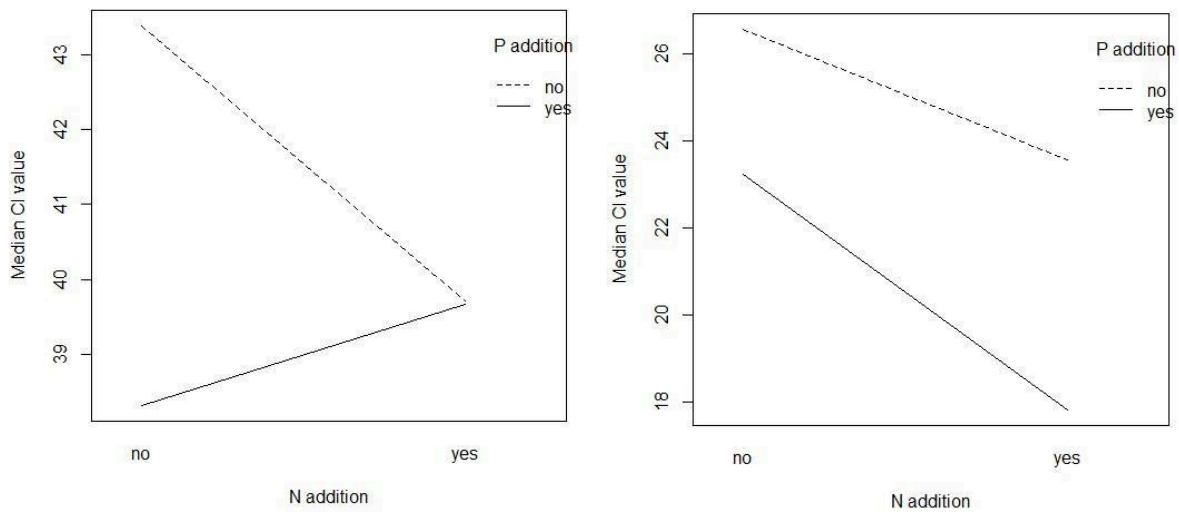

Figure 10 Interaction plots of fertilization addition on median CI value in mid-aged (**left**) and mature-aged (**right**) stands.

Discussion

According to modern understanding of disturbance and steady-state dynamics of forests, total biomass increases to a state of maximum accumulation before declining to the steady-state (Bormann & Likens 1979). The amount and density of trees generally declines as a stand progresses from mid-aged to mature, freeing up light and soil resource availability above- and below-ground, respectively. This explains the general trend that can be seen when examining the impact that stand age has on CI values. With a larger density of tree stems in the mid-aged stands compared to mature stand, the resulting CI values are significantly higher in the mid-aged stands.

Previous experimental studies exploring the impacts of fertilization on general plant competition, like that performed by Wilson & Tilman (1993), show that plant competition does not significantly vary with nutrient fertilization—specifically N fertilization to induce P limitation. However, Wilson & Tilman (1993) also admitted in this study that almost all of these fertilization studies were short-term wherein the MELNHE study is a long-term fertilization experiment which offers a new perspective of fertilization and plant competition. Soil microbial communities, for example, are strongly affected by long-term fertilization as opposed to short-term in terms of changes in community composition and structure (Li *et al.* 2014). Results from the CI computation and analysis show that tree-dictated competition was in fact significantly impacted by additions of N, P, and both N and P as an interaction in the MELNHE stands. This in itself is evident of how long-term fertilization impacts plant communities in forest systems. From the results of this analysis, fertilization generally reduced competition in the plots, signifying that there may be potential avenues for reducing tree-on-tree competition in managed stands to increase lumber yields or offer more opportunities for theoretically increased understory community structure.

The CI maps created for several of the MELNHE stands offer several potential uses for the project as a whole. On these maps, patches of high competition—in the maps showing as warmer, redder colors—visually describe areas within a plot with denser tree stems, densely rooted soils, and, likely, closed canopies. This information is invaluable for not only future projects for developing experimental methods to incorporate and statistically analyze an additional competition covariate, but also in providing possible explanation for results in previous MELNHE projects. Because forest understory (Spurr & Barnes 1980) and, to an extent, soil structure (Binkley 1995) is heavily tied to trees in the overstory, the competition between these trees provides context on what may be occurring on the forest floor with soil respiration, herb cover, root density, and tree recruitment.

It should be noted that there are several “holes" on the created MELNHE tree maps where green (low competition) appears due to a notable absence of trees within subplots or within the buffer region. While most of the stands suffer this to an extent, a large offender of this is HBO wherein several subplots are devoid of trees. In reality, there were trees present here and this was an issue with the stem location dataset. With a tree re-inventory of all MELNHE stands slated for summer 2023, these stem maps will dated and will not include any new trees, tree deaths, or DBH increases. Eventually, a new geolocation dataset will need to be produced for future CI studies in the MELNHE stands if the competition covariate should remain as accurate and up to date as possible.

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Competition Mapping for Dummies: MELNHE Edition

What you need to begin:

- ArcGIS Pro
- Microsoft Excel or Google Sheets
- Tree locations (found on the MELNHE website under Maps)

Step 1:

Combine both inner trees and buffer trees into one continuous sheet on Excel. Be sure to include the locations of the trees with other parameters (DBH, species, tag number, etc.) depending on on what kind of equation you are using. Do this for all the stands you intend to map. Be aware that Ca trees may be included but will not have buffer trees.

Step 2:

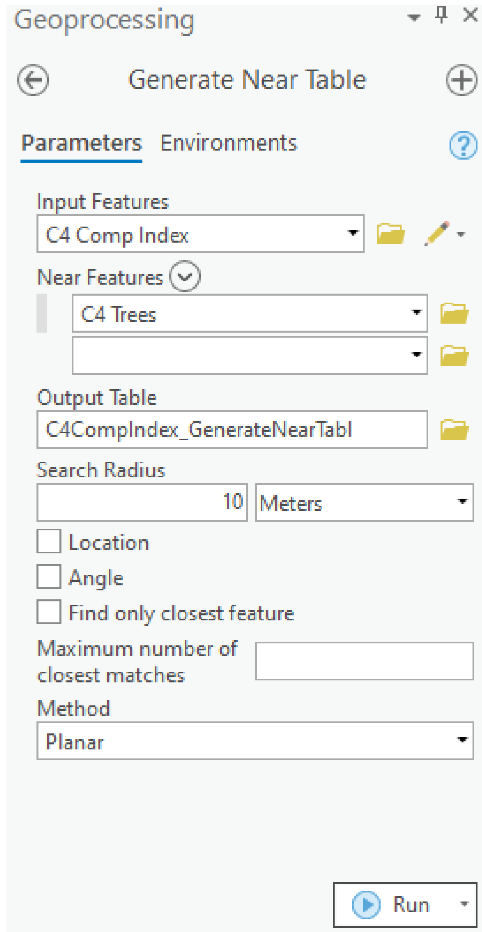
Open ArcGIS and import treatment plots you need using available the shapefiles from the MELNHE website. Also import trees from the Excel made in Step 1 using the Add Data dropdown on the Main pane in ArcGIS. A table will appear at the bottom of the Contents pane in ArcGIS after importing. Right click the table and select Display XY Data. A dialogue box will appear where you need to match the longitude and latitude to the longitude and latitude from the Excel file. To finish, select the appropriate projection system (probably NAD 1983 (2011) UTM Zone 19N) to display the trees on the map.

Step 3:

On ArcGIS, create a new polygon layer to serve as your competition index polygon. Make sure to add an additional field in the attribute table to copy in your competition index values later and make sure this field uses the double number data type. Once this is created, draw the new polygons over top of the interior of the stand. You will divide the polygon using the Divide tool to any area you intend to analyze. This process is tedious and takes the most time as there is not really a good way to divide polygons into equal areas with same length and widths with the base ArcGIS license.

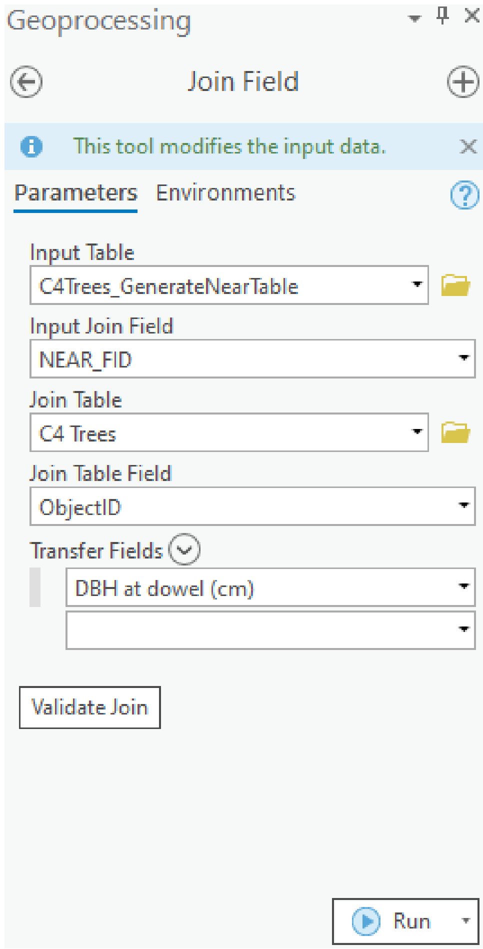
Step 4:

Use the Generate Near Table geoprocessing tool in ArcGIS Pro with the following settings applied. If you are performing the competition index under differing parameters, feel free to change the settings to fit your intended purposes. A table should now appear at the bottom of the Contents pane in ArcGIS.



Step 5:

Use the Join Field geoprocessing tool to Join any parameters from the trees to the Near Table created in the last step. This will use the Feature ID (which are automatically created when you add the tree into ArcGIS) of the trees and NOT the tree tags.



Step 6:

The DBH (or whatever information you selected) should now be included within the Near Table from Step 4. Select and copy this whole table to a new sheet in Excel. In Excel, create an equation that uses the distance calculated in the near table (for example, my equation for each row was =atan(dbh/distance)). Double-click to apply this equation to all rows. If you have any distances that =0, use the Find and Replace tool in Excel to change 0 to 0.01.

Step 7:

Still in Excel, select all the data and create a Pivot Table. Use the "In_ID" as the Rows and the equation (in my case "Sum of atan") as the Values. Copy all of the sums as your competition index values and paste them into your competition index feature class in ArcGIS.

Step 8:

The last step is to make your symbology to show the differences in the competition values. For me, I used Unclassed Colors from green to red to show competition from low to high. I also removed borders from the 1x1-m squares for aesthetical reasons. You could also use Classed Colors to find areas of a more quantifiable competition value.