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A Density Management Diagram for Pitch Pine to Illustrate Tradeoffs between Carbon and Wildfire Risk

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Abstract

Pitch pine (*Pinus rigida* Mill.) can be found across a broad range in eastern North America but assumes local dominance only on poor soils in the northeastern United States. Contemporary management goals in the Northeast for areas dominated by pitch pine are focused on noncommercial benefits of forests, such as carbon density, reduced wildfire risk, habitat for rare species, and water provisioning. We present a density management diagram that empirically articulates the size-density limits of even-aged pitch pine stands. Included in the diagram are wildfire risk and carbon density, which are inversely related for most stand sizes. Maximum possible aboveground live tree carbon begins to decline at a quadratic mean diameter greater than 9 in., while crown fire risk remains high along the size-density limit until a quadratic mean diameter above 12 in. is achieved.

Study Implications: Modern silvicultural tools that illustrate forest stand conditions have not been developed for pitch pine, but this species occurs in a region with much public attention on forests. We develop and present a density management diagram to show the interplay of different social goals for the forest and how they relate to the maximum size-density relationship. Pitch pine stands with high levels of aboveground live carbon are at high risk of crown fire, particularly in the smaller size classes.

Keywords: stocking diagram, silviculture, thinning, mature stand boundary, *Pinus rigida*

Overstory occupancy by trees exerts a top-down control on the light environment within a forest, so that the survival and growth of different organisms are bounded by the available resources not used by overstory trees. Purposeful management for a variety of ecosystem attributes requires an understanding of how growing space is allocated in a forest. Foresters have long sought to define the bounds of available growing space to assess competition and stocking. Reineke's stand density index (SDI) (Reineke 1933) defined the maximum relationship between the number and size of trees in a stand, representing one early but robust index of competition used in North American forestry. Renewed interest in SDI stoked debate within forestry and ecology about the proper theoretical constructs to define the slope and location of the maximum size-density relationship for plant species (Jack and Long 1996; Osawa and Sugita 1989; Pretzsch and Biber 2005, Weller 1987, 1990). However, empirical approaches that use generally consistent methods have also been used to describe the limits of forest growth (Cao et al. 2000; Long and Shaw 2005; Vacchiano et al. 2008, 2013; Wilson et al. 1999).

Forest biometricians have developed different tools to take advantage of this empirical work to describe growing space utilization, such as "Gingrich" stocking diagrams and density management diagrams (DMDs) for even-aged stands (Drew and Flewelling 1979; Gingrich 1967; Jack and Long 1996). Although these tools are often used to understand tradeoffs in a wood production context, they are by no means limited to parameters of economic interest. DMDs have been used to visualize conditions and plan management trajectories for elk (Smith and Long 1987), red-cockaded woodpecker (Shaw and Long 2007), and northern goshawk (Lilieholm et al. 1994).

Biometric tools help to translate descriptive goals of conditions into prescriptive approaches to management, which greatly increases the ability of the manager to achieve specific goals (Lilieholm et al. 1994; Vacchiano et al. 2008, 2013). In the New Jersey Coastal Plain region dominated by pitch pine (*Pinus rigida*) forests, known more widely as the "Pine Barrens" and legally as the "Pinelands," the governing land management agencies have articulated goals of water provisioning, protection of life and property from wildfire, protection of forest health, habitat for rare plants

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and wildlife, net carbon sequestration, and attention to the emotions of urbanized public that is unfamiliar with forest management (New Jersey Forest Service 2020).

Pitch pine forests currently occur as the dominant tree species in northeastern US pine barrens ecotypes, mainly located in New Jersey, New York, and Massachusetts (USDA Forest Service, Forest Inventory and Analysis Program 2023). Pitch pine is most closely related to loblolly pine (*P. taeda*), table mountain pine (*P. pungens*), and pond pine (*P. serotina*), and shares the Australes subsection of the genus with other more commercially studied southern yellow pines, like slash (*P. elliottii*), longleaf (*P. palustris*), and shortleaf (*P. echinata*) (Gernandt et al. 2005). The tree is a component of xeric sites throughout the Appalachians into southeastern Canada (Illick and Aughanbaugh 1930). Pitch pine competes well both on excessively drained acidic soils and poorly drained sands (Little et al. 1967). Several competitive traits enable it to withstand fires that cause mortality for other species. Foliage may be burned off on a site, but if the terminal buds are uninjured following fire, shoot growth resumes anew (Little 1959). In addition, under its thick bark are abundant dormant buds that produce vigorous growth when stimulated by fire; scorched and leafless canopy trees can also continue shoot growth from these, usually along the trunk or large branches where the bark is thicker (Little 1953). Further, immature trees have a crook at the ground level so that basal buds can reinitiate stem growth if the tree is top-killed (Little 1959). Despite pitch pine's adaptations to fire, the trees themselves are not fireproof—sufficiently hot fires will kill the aboveground stems, although these also create favorable conditions for pitch pine to assert greater dominance over a site (Little and Moore 1953). Although most individuals produce cones that open soon after maturity, some trees produce cones that open only after substantial heat (Krugman and Jenkinson 2008; Ledig and Fryer 1972), allowing the species to germinate on the bare soil of a burned site faster than competitors.

Management in relation to using or preventing forest fires has been a driving factor in the governance of this landscape both in recent times and throughout history. Available cultural records and landscape conditions at the time of European settlement demonstrate a historical fire regime largely dominated by human-set very frequent (annual or near-annual) dormant-season low-intensity fire below a woodland canopy (Hanberry et al. 2020; Little 1979; Muntz 1959; Stewart 2002). European settlement began centuries of wholesale indiscriminate industrial forest use in the Pinelands that were accompanied and followed by widespread higher-intensity fire that repeatedly swept over younger growth (Muntz 1959; Wacker 1979), especially favoring pitch pine due to its extreme fire adaptations (Little 1959). However, patterns of forest use and fire suppression since the early twentieth century have shifted the fire regime towards smaller, less frequent burns (Forman and Boerner 1981). The reduction in disturbance for the pine forests of this region has been matched by an increased abundance of high-density pine stands (Crocker et al. 2017). High density and/or a lack of disturbance in pitch pine forests has been linked to increased risk of high-intensity crown fire (Bried et al. 2015), increased risk of southern pine beetle (SPB) outbreak (Asaro et al. 2017; Nowak et al. 2015), loss of habitat for rare plants and wildlife dependent on open pine forests (Albanese et al. 2007; Golden et al. 2009; King et al. 2011; Peters 1995), and possibly reduced water yield (Isaacson et al. 2023; Sun et al. 2015). Thus, quantitatively understanding pine forest density is essential for addressing the articulated goals for this landscape.

Despite these interests, biometric forestry tools have largely not yet been developed for the Pinelands landscape, nor have the limits of site occupancy been characterized for pitch pine, presenting an opportunity to do both. This study sought to create a DMD for pitch pine that characterizes some local management objectives. We show how forest density is related to crown fire risk, illustrate stand carbon density, and define a maximum size-density relationship for even-aged stands. These attributes provide a framework on which to place ecosystem attributes so that management tradeoffs can be easily visualized for silvicultural evaluation and planning.

Methods

Inventory Datasets

State Forest Inventory Data

Forest inventory data were collected by state agencies in Wharton State Forest and Penn State Forest between 2017 and 2019 to support the development of forest management plans. Located in Burlington, Camden, and Atlantic Counties (New Jersey, USA), these parcels are dominated by pitch pine and underlain by sandy, acidic soils. The contracting public agency used aerial imagery to delineate forest type boundaries for stratifying the spatial distribution of inventory plots. Plots were arranged randomly within types to reduce type-level variance in basal area per acre. LandVest, Inc. of Ridgway, Pennsylvania, completed the contract to place the plots and collect the data; random re-measurement was used to check for accuracy.

Plots used a nested sampling design. Overstory stems (>4 in. diameter at breast height [DBH]) were assessed using variable radius point sampling of either basal area factor (BAF) 10 or 30 (ft^2/ac, 2.3 and 6.9 m^2/ha); advanced regeneration (tree species ≥ 4.5 ft tall and < 4 in. DBH) was measured using a 1/50th ac (1/123.5th ha) circular plot, and ground cover was measured using a 1/500th ac (1/1325th ha) circular plot. All three levels of sampling used the same plot center point. For all plots except those placed in the Atlantic white cedar (*Chamaecyparis thyoides* (L.) B.S.P.) forest type, the contractor used a BAF of 10; for cedar plots, the contractor used BAF 30. This was done to roughly maintain sample variance, as Atlantic white cedar stands in the Pinelands typically achieve basal areas more than three times the level of adjacent forests.

Grouping and Filtering State Inventory Data

We summarized state forest inventory data at two scales: the cluster (stand-like), and the point. For most of the analysis, we used cluster-level data. Only for the maximum size-density relationship portion did we use the ungrouped point data. Although we sought to perform analysis at the stand scale, the state forest inventory data were collected at the point scale without respect to stand boundaries. Hence, we needed a method to group points into stands, which we refer to as "clusters" throughout this document, in contrast to their original collection scale, which we call "points."

To group the points, we used stratified spatial clustering based on a supervised classification of the landscape. For our strata, we collected Sentinel 2A L1C images (top-of-atmosphere reflectance) for five dates (March 11, 2016, July 17, 2016, September 28, 2016, November 09, 2016, and January 1, 2018). Images were close in time to each other and concurrent with ground-based inventory; data consisted of the sensor's 10 m spatial-resolution bands, supplemented by normalized difference vegetation index images for each date. We selected thirty-three supervised classification training areas of the dominant local forest types and land covers, comprising 11,275 pixels. Notably, we excluded the pine plains as a separate forest type from other pine cover; this unique dwarf pitch pine–dominated community has different genetics from the rest of the pitch pine–dominated forest in the area (Ledig et al. 2013). We then used this classified map (figure 1) to stratify the point data for grouping. Using only BAF-10 points falling in the pine forest type, we grouped the points into clusters of two to six neighboring points via k-means clustering, where our predictor variables were latitude and longitude. From these clusters we calculated stand-level attributes.

We used two filters on both the point and the stand-scale cluster data from the state inventory. First, we removed datapoints (clusters or points) where the relative basal area of pitch pine was less than 90%. Next, to restrict ourselves to even-aged data, we calculated SDI following both the summation method (SDI*) and the quadratic mean diameter method (SDI), then only considered clusters and points where SDI*/SDI was greater than 0.95 (Shaw 2000, 2006). These criteria left us with 455 stand-scale clusters and 2,256 points from the state inventory data with which to conduct analysis (Table 1).

USFS FIA Data

To expand both the size of our dataset and the geographic range of the analysis, we also used USDA Forest Service (Forest Service) Forest Inventory Analysis (FIA) data. Using the "rFIA" package (Stanke et al. 2020), we downloaded the FIA databases for states with populations of pitch pine from New Hampshire to Georgia and west to Kentucky. From these data we selected a population of unique "conditions" that could be treated as stands and subplots that could be treated as points. The FIA conditions are somewhat like inventory plots in other systems, but because FIA collects continuous forest inventory data, two conditions may occur in the same location from different points in time.

We used the FIA "PLOT" table to subset those FIA plots that were of the current plot design (Burrill et al. 2021). Of these, we made a table of unique locations, recording the plot sequence number (PLT_CN) and year of each plot measurement, then subset the "COND" table ("condition") to these PLT_CNs. Each plot sequence number is the unique identifier for a single location's record at a single point in time. We then removed nonforest conditions and those with incompletely sampled subplots.

For these FIA data, we calculated the same attributes as for the State Forest Inventory data, again at two scales, condition (stand-scale) and subplot (point-scale). At the FIA condition level, we summarized tree observations using the unique PLT_CNs. For FIA subplots, we selected distinct combinations of PLT_CN and subplot in the TREE table; these became the unique identifiers with which we calculated the same attributes. As with the state inventory data, we removed subplots and conditions with less than 90% relative basal area of pitch pine. To remove uneven-aged data, we also filtered out those FIA subplots where SDI*/SDI was less than 0.95 and those FIA conditions where this ratio was less than 0.90. A final filter on the conditions removed those conditions with only a single subplot. This left us with 91 pure, even-aged FIA stand-scale conditions and 455 pure, even-aged FIA point-scale subplots (Table 1).

A geographic review of the FIA data show that most of the pure pine FIA data occurred in New Jersey (figure 2). There

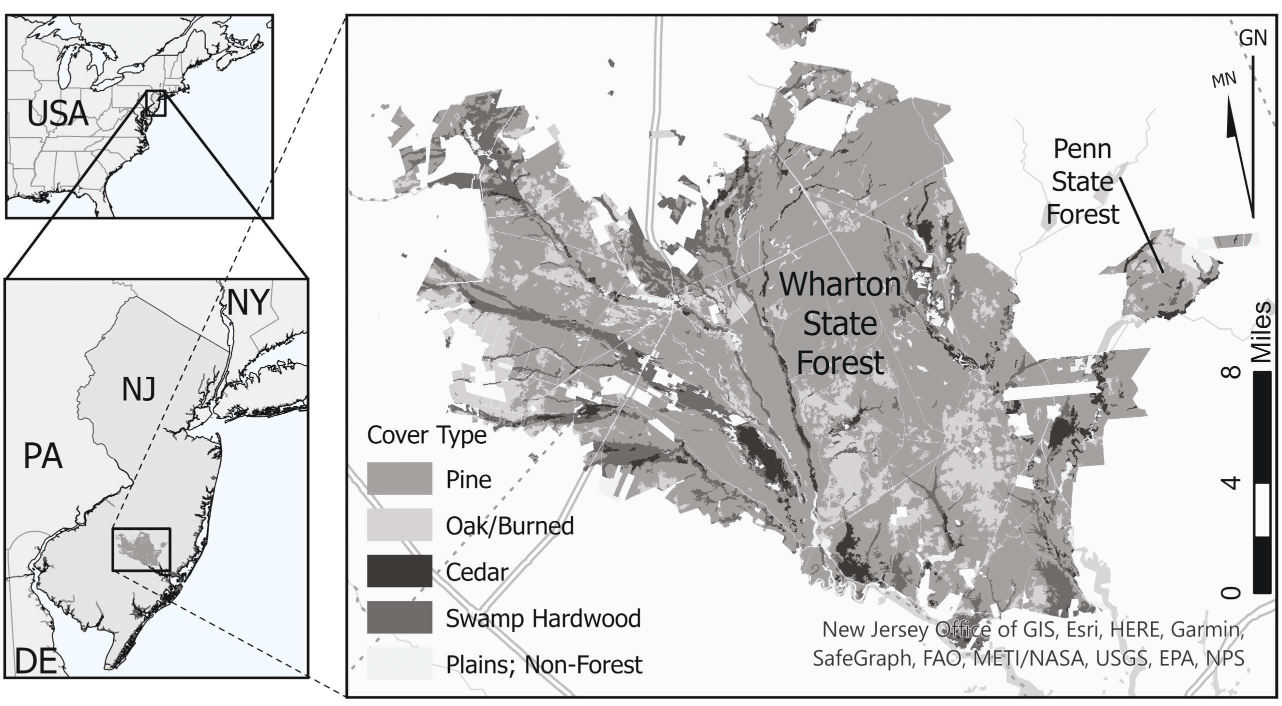

Figure 1. Data location for state forest inventory dataset and forest type classification for Wharton State Forest and Penn State Forest.

Table 1. Inventory characteristics for stand- and point-scale datasets. Sample means shown with data ranges in parenthesis.

Dataset	Scale	*n*	Stand Age (Years)	Quadratic mean diameter (in.)	Trees per acre	Basal area (ft²/ac)	Stand height (ft)
State inventory	Point	2,256	67 (11–154)	8.2 (4–17.7)	316 (6.3–1529)	94 (10–230)	48.7 (5–77.3)
State inventory	Stand (cluster)	455	67 (21–146)	7.6 (4–15)	320 (8.1–1103)	92 (3–195)	50 (15–71.3)
FIA	Stand (condition)	91	NA	6.3 (2.8–11.3)	467 (12–1491)	81 (2.1–155)	42.7 (14.6–63.8)
FIA	Point (subplot)	455	NA	8.2 (1.3–20.3)	297 (18–2699)	75 (3.6–211)	43.7 (10–91)

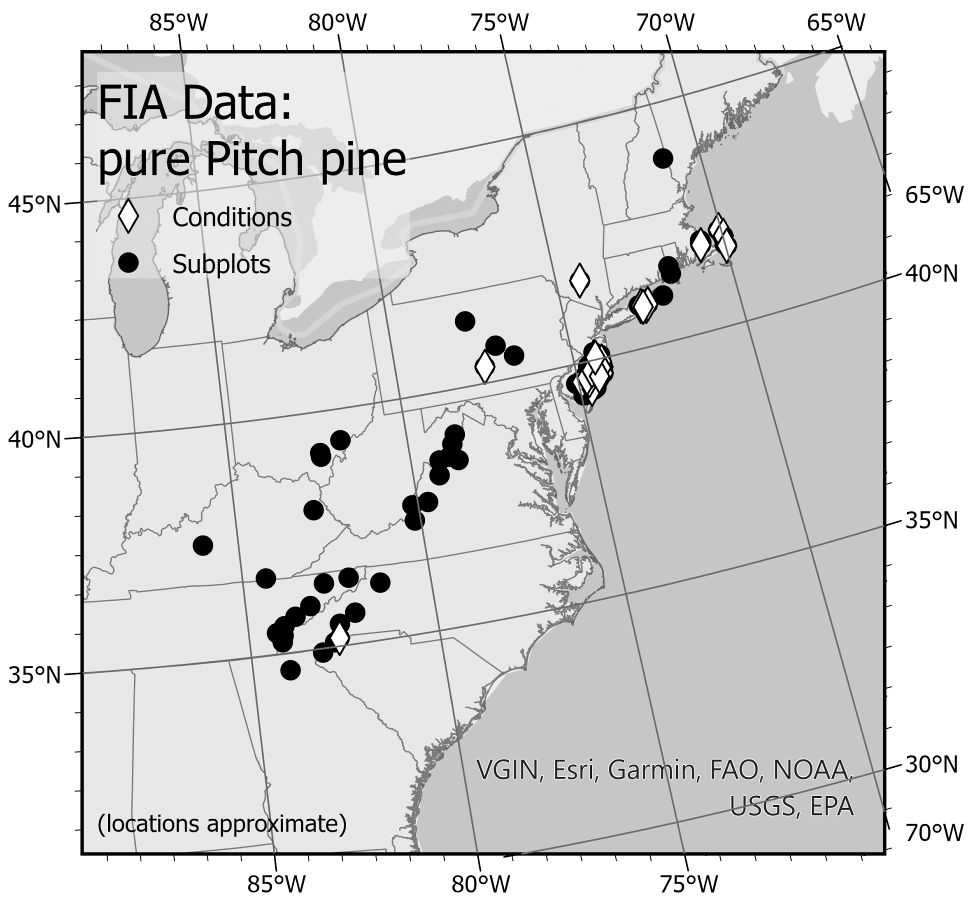

Figure 2. Approximate locations of FIA subplots and conditions used in the analysis. All locations are at least 90% *Pinus rigida* by relative basal area of live trees. Only even-aged locations were considered.

are also clusters on the southeastern coast of Massachusetts, the eastern portion of Long Island, New York, and scattered plots in the Appalachian Mountains, Cumberland Plateau, and Allegheny Plateau. Notably, many of the plots are not independent: some of them are remeasurements of the same location separated only by time. Due to the paucity of data on pure pitch pine outside of New Jersey, we included remeasured plots in this dataset. Unfortunately, we were unable to include any meaningful analysis of the trajectory of these individual locations through time, as there were relatively few remeasurement cycles per location, with disturbances such as intense wildfire and SPB outbreaks paring down further this small amount.

Analysis

Modeling Stand Height

Stand height was determined by averaging the height of the forty tallest trees per acre in the stand, with consideration of the expansion factor for each sampled tree. We compared the performance of four different models to predict stand height across the combined stand-scale dataset, using the nlsLM function in the "minpack.lm" package in R (Elzhov et al. 2022). A rearrangement of model (1) was used by Long and Shaw (2005); model (2) was used by Long and Shaw (2012); a rearranged version of model (3) was used by Barrio Anta and Álvarez González (2005), Minoche et al. (2017), and Patrício and Nunes (2017); and a rearranged version of model (4) was used by Vacchiano et al. (2008).

$$Height = \left(\frac{QMD - b_1}{b_2 - b_3 \times TPA^{b_4}}\right)^{\frac{1}{b_5}} \quad (1)$$

$$Height = \left(\frac{b_1 + QMD}{b_2 \times TPA^{b_3}}\right)^{b_4} \quad (2)$$

$$Height = \left(\frac{QMD}{b_1 \times TPA^{b_2}}\right)^{\frac{1}{b_3}} \tag{3}$$

$$Height = \frac{QMD}{b_1 - b_2 \times \log_{10} TPA} \tag{4}$$

where height is in feet, quadratic mean diameter (QMD) is in inches, and TPA is trees per acre.

Aboveground Tree Carbon

We included aboveground tree carbon on our diagram using the component ratio method (Heath et al. 2009; Woodall et al. 2011), which is the sum of sub-estimates for the tree bole, the stump, and the tops/limbs. For the northeastern region of the United States, gross volume calculations are based on bole height (height where trunk diameter is 4 in.) (Scott 1981), which we determined using the taper equations of Westfall and Scott (2010). For the diagram, the tree heights used for taper calculations were the product of our derived relationship between TPA and QMD, above. Stand-level biomass values were converted to carbon by multiplying by 0.5 (Burrill et al. 2021).

Crowning Index

We sought to include in our analysis a metric that would separate ecosystem conditions that would lead to differences of fire behavior. For this, we used the crowning index (CI), which is the windspeed at 20 ft height that supports an active crown fire. Crowning index is inversely related to forest density: higher density results in a lower CI, and a lower CI indicates a heightened risk of active crown fire. Determined from canopy bulk density, crown spacing, forest type, and slope, CI is calculated as part of the model outputs of the Forest Service's Forest Vegetation Simulator's (FVS) (Dixon 2002; FVS Staff 2008) Fire and Fuels Extension (Rebain 2010). Rather than duplicate the calculation of CI, we formatted the state inventory data for input into FVS (Crookston et al. 2003) for use in other projects. We ran all state inventory clusters through FVS, with the only model adjustment being to modify the fuels behavior. We selected the "new" fuels model logic for fire behavior calculations, which uses the forty Scott and Burgan fuel models (Scott and Burgan 2005).

From the FVS output database, we queried the "potential_fire" table to obtain CI for all clusters. We used only the initial CI for each cluster at the inventory year. As there were multiple plots in each cluster and those plots may have been collected in different years (data were collected 2017–2019), we assigned the most recent inventory year for any of the plots for the cluster. We then linked inventory variables that would exist on the density management diagram to crowning index using model (5):

$$\log_{10}(CI) = \beta_1 + \beta_2 \times \log_{10}(SDI) + \beta_3 \times HT + \beta_4 \times RP \tag{5}$$

where CI is crowning index, SDI is stand density index$_{(summation\ method)}$, HT is stand height (ft), and RP is relative basal area of pine (0–1).

Mature Stand Boundary

We sought to place the mature stand boundary (Shaw 2006; Shaw and Long 2007) on our density management diagram to define the upper limit of site occupancy possible for pure pitch pine stands. To cover a wider range of site occupancy conditions, we attempted to the fit the boundary using both stand-scale datasets together (state clusters and FIA conditions), and with the combined point-scale data (state points and FIA subplots). We selected the upper boundary of the point cloud by sorting all observations by decreasing numbers of trees per acre. The first three observations are the points with the top three most TPA; working down the dataset, each observation is compared with the QMD of the third-highest QMD yet seen. If an observation has a QMD equal to or greater than the third-highest QMD yet seen, it is included in the "upper envelope" of points.

We used a model from Shaw and Long (2007) of the following form to fit a line to the stand-level data:

$$QMD = \beta_1 + \beta_2 \times e^{\beta_3 \times TPA^{\beta_4}} \tag{6}$$

We fit this model using the stand-scale data, then shifted the predicted values upward to circumscribe the upper envelope data. First, we found the proportion of the predicted values divided by the observed values for each of the upper envelope points used to fit the model. The smallest of these became the adjustment value: to shift the full curve, we divided all of the fitted y values by this adjustment value.

Determining the appropriate adjustment value is by its nature highly sensitive to data already on the edge of observed values, making it somewhat imprecise; for this reason, we sought additional approaches. Because we wanted to determine the boundaries of stand occupancy at larger diameters, we looked to the larger dataset underlying the stand-scale data: the point-scale data. Combining the FIA subplot-level data and the state forest inventory point data, we found the upper envelope of the observations using the same approach described above but only used the two highest TPA points (instead of three as for the stand-level curve), as there were many more point-scale datapoints. We fit the following models:

$$QMD = \beta_1 + \beta_2 (\log_{10} TPA) \tag{7}$$

$$QMD = \beta_1 \times \left(TPA^{-0.623}\right) \times \left(1 - e^{\left(\beta_2 * TPA^{\beta_3}\right)}\right) \tag{8}$$

Model (8) follows Cao et al. (2000). We did not apply any adjustment factor to these to ensure the fit was above all of the point-scale observations. Instead, we superimposed these point scale–derived curves on the stand data to evaluate its performance at that scale. We compared (7) and (8) using the same goodness-of-fit characteristics as in the height models (1 through 4).

Results

Stand Height

The FIA data had a slightly wider dispersion of stand heights, whereas the state data were heavily clustered across a narrower range. State inventory data had a median height of 52.5 ft, with the middle 95% occurring between 25 and 66 ft. FIA conditions had a median height of 43.8 ft, with the 2.5% and 97.5% quantiles occurring at 17.8 and 59 ft, respectively.

Model parameter estimates and standard errors can be found in Table 2. Goodness-of-fit evaluations of the four models (Table 3) showed uniform better performance for (1),

Table 2. Model parameter means and standard errors (in parenthesis).

Model	Trait	β_1	β_2	β_3	β_4	β_5
1	Height	2.27 (-0.262)	15.4 (-183)	15.3 (-183)	$8.00 \cdot 10^{-4}$ ($-9.64 \cdot 10^{-3}$)	1.28 (-0.0827)
2	Height	-1.73 (-0.37)	0.269 (-0.0937)	-0.301 (-0.0221)	0.823 (-0.0668)	-
3	Height	0.805 (-0.0822)	-0.231 ($-6.82 \cdot 10^{-3}$)	0.903 (-0.0233)	-	-
4	Height	0.35 ($-6.79 \cdot 10^{-3}$)	0.0814 ($-2.67 \cdot 10^{-3}$)	-	-	-
5	Crowning index	3.24 (0.0739)	-0.678 ($9.04 \cdot 10^{-3}$)	$1.944 \cdot 10^{-3}$ ($2.28 \cdot 10^{-4}$)	-0.302 (0.0701)	-
6	Mature stand boundary	0.554 (-2.25)	14.4 (-2.73)	$-9.28 \cdot 10^{-3}$ ($-5.44 \cdot 10^{-3}$)	0.702 (-0.119)	-
7	Mature stand boundary	29.6 (-0.284)	-7.83 (-0.111)	-	-	-
8	Mature stand boundary	487 (-15.6)	-0.0537 ($-2.37 \cdot 10^{-3}$)	0.562 (-0.0166)	-	-

with the lowest Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), lowest standard error of the residuals, and the smallest residual deviance. The models showed divergence in predictions mainly at high and low TPA levels. Based on the model statistics we chose to use model (1) in the density management diagram.

Crowning Index

The mass of the stands measured from 2017 to 2019 had a crowning index between 20 and 40; the median crowning index was 32. There was a strong linear relationship between the logarithm of crowning index and the logarithm of SDI. Including other terms in the model improved fit meaningfully, although $\log_{10}$(SDI) alone explained 92% of the variation in $\log_{10}$(crowning index) (figure 3). After we added other terms to test different models, we found that crowning index was slightly better predicted by including height and the proportion of pine. Model parameters can be found in Table 2; R^2 for the selected model was 0.94. The isolines displayed in the density management diagram show modeled crowning index for pure pine stands, with the height component of the crowning index model filled using model (1).

Mature Stand Boundary

All the stand-level datapoints from both the state inventory data and the FIA condition data fell within the area bounded by the best fit of models (7) and (8) (figure 4). Although model (6) did a good job characterizing the upper envelope of our combined dataset at the stand scale, the tails of our observed stands-scale data distribution were highly leveraged. This was apparent from the mature stand boundary curving so far away from parallel with SDI as to suggest that it was not possible to have mature pitch pine stands with QMD greater than 17 in. We felt that rather than this being a physical upper limit to the species, that instead it was a limitation of the data—out of 545 stand-level datapoints, only one had a QMD greater than 12.5 in. Model coefficients for (6), (7), and (8) can be found in Table 2.

This absence of large-diameter observations in the stand scale data spurred our fitting models (7) and (8) on the point-scale data. Although models (7) and (8) aligned closely, model (7) generated a lower AIC, lower BIC, lower residual standard deviation, and lower residual deviance (Table 3). When the stand-scale adjusted curve (model [6]) was plotted together with the unadjusted point-scale curve (model [7]), both tracked each other below about 15 in. QMD. Above this value, the point-scale curve continued to modestly increase in QMD where the adjusted stand-level curve did not.

Table 3. Goodness-of-fit evaluations for selected models.

Model	Trait	*N*	Akaike Inormation Criterion	Bayesian Information Criterion	Sigma	Deviance
1	Height	545	3,287	3,312	4.9	12,982
2	Height	545	3,316	3,337	5.04	13,750
3	Height	545	3,324	3,341	5.08	14,008
4	Height	545	3,336	3,349	5.15	14,384
7	Mature stand boundary	84	125	132	0.496	20.2
8	Mature stand boundary	84	146	155	0.559	25.3

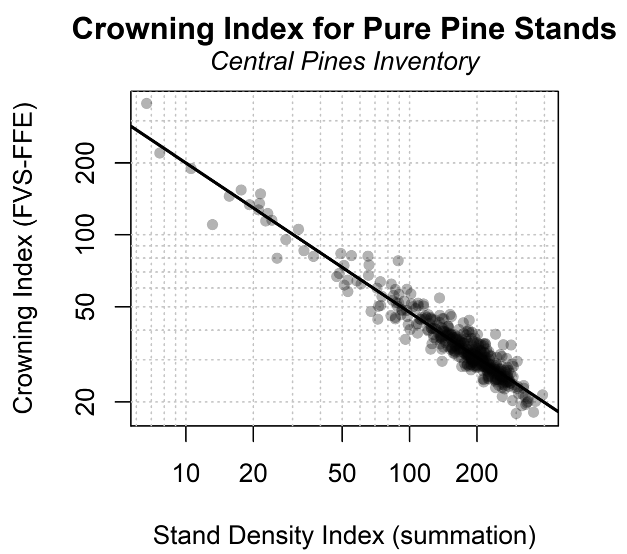

Figure 3. Relationship between the crowning index (FVS-derived) and stand density index on logarithmic axes.

Density Management Diagram

Figure 5 is our DMD. It incorporates the isolines for aboveground tree carbon, our stand height model (model [1]), our model for crowning index (model [5]), and our mature stand boundary using the point scale-derived boundary (model [7]).

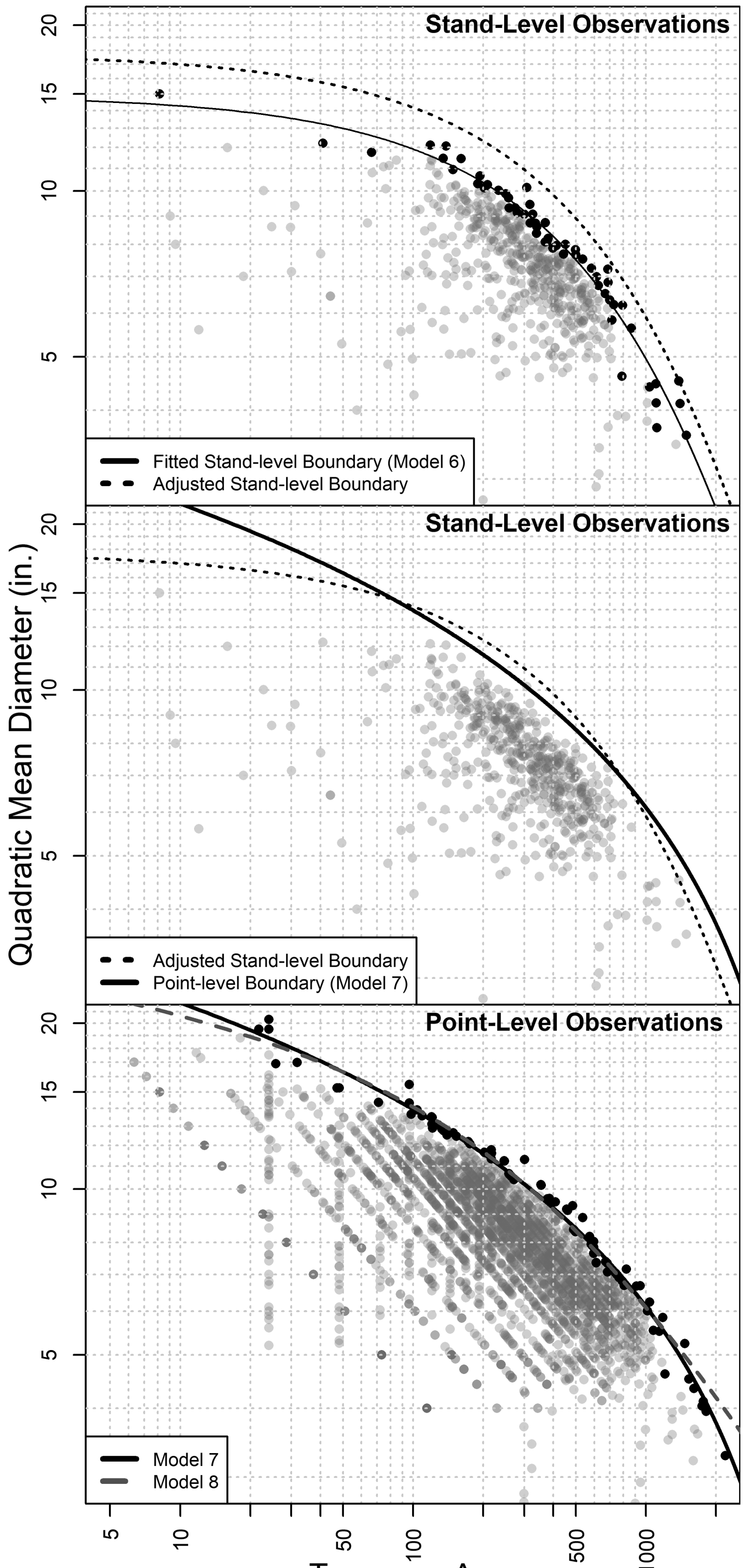

Figure 4. Method for determining the mature stand boundary. Top and middle panel datapoints show the stand-level observations; bottom panel shows New Jersey Forest Service point-level and FIA subplot-level datapoints. Black dots represent upper-envelope points used for model fitting. In the top panel the solid black line is model 6 fit to the stand-level upper envelope; the dotted line represents the same curve shifted up using the adjustment factor to circumscribe all observations in the top panel. The dotted line from the top panel and model 7 fit to point/subplot level data from bottom panel are not shifted in the middle panel.

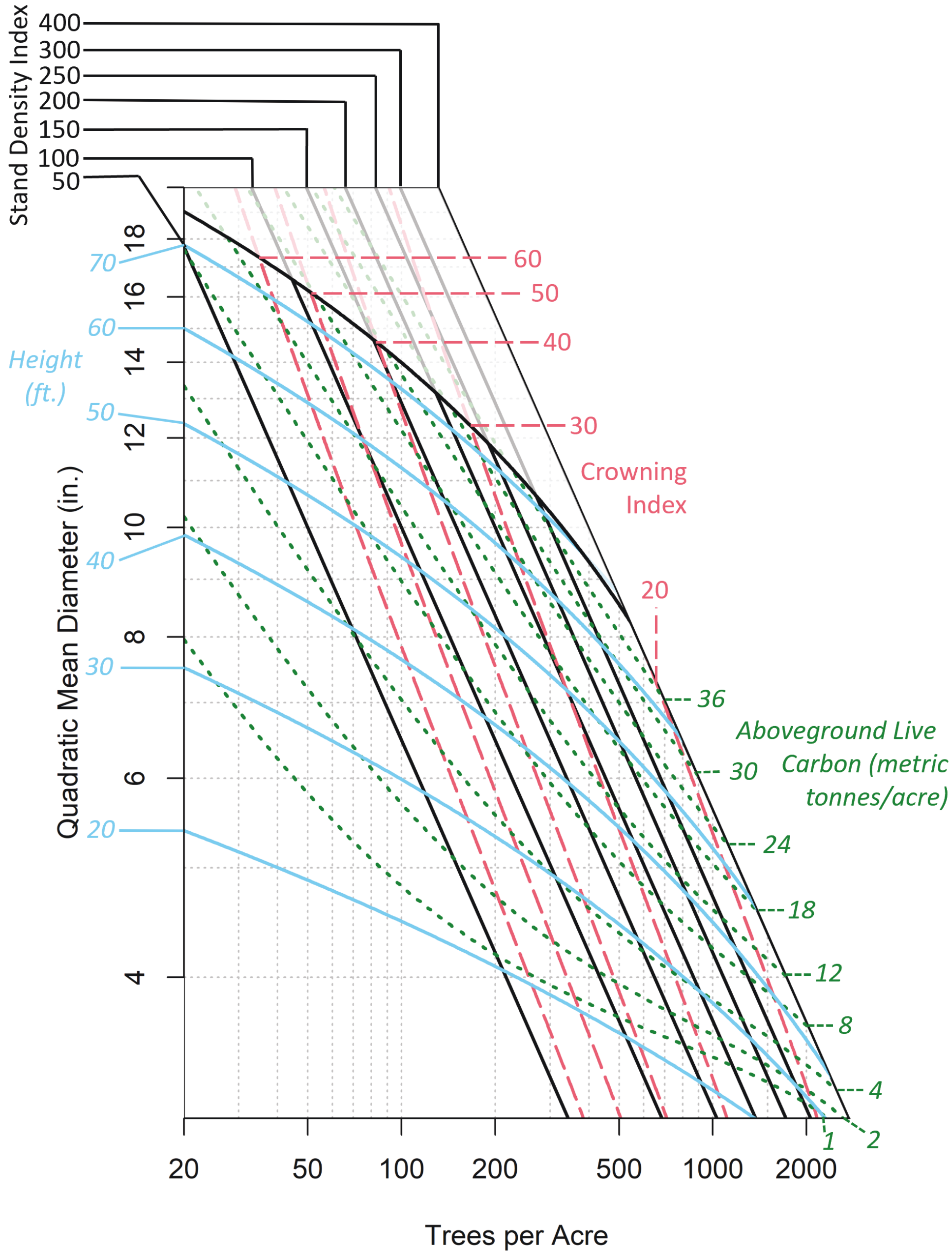

Figure 5. Density management diagram for pitch pine.

The diagram shows that stands have the greatest wildfire risk (lowest CI) below a QMD of 7 in. At QMD values between 5.5 and 14 ft., stands at the highest possible density achieve greater than 24 metric tonnes of aboveground live tree carbon per acre, and the maximum appears to be possible at 7 to 11 in. QMD. Outside of the maximum, there are different stable points for large masses of carbon: the same mass of carbon can be stored at QMD of 15 in. at the mature stand boundary as at 5 in. at the boundary but CI at the higher QMD is around 45 instead of less than 20.

Discussion

Limitations

We approached the creation of this diagram with a different set of constraints than have been present for other diagrams, for example, a dearth of biometric datasets for this broad but sparsely distributed species. This introduces several possible sources of error, both from the underlying data as well as from our methods.

Two attributes of the height data reduced precision for the height models. Heights in the state inventory dataset were collected to the nearest 5 ft. increment, rather than to the nearest foot. Whether or not the models capture the variability in heights for the species, the standard error of the residuals for the height models (1 to 4) was close to the measurement tolerances. This suggests that improvements in modeling pitch pine height from QMD and TPA will need more measurement precision. As well, there were very few young stands in the dataset; less than 7% of the stand-scale observations had a canopy height shorter than 30 ft. This limited model precision along the bottom and left edges of the diagram, whereas in the more populated portions of our DMD, all of the models produced similar height estimates. Improving precision for young stands would require a change in inventory design so that trees smaller than 4 in. DBH are measured as part of the overstory plot.

Our method for grouping the state points into clusters using forest type and proximity may have introduced error by inappropriately lumping together point samples that were dissected by actual stand boundaries. The practical effect of our cluster assignment method on the mature stand boundary relationship would be to smooth out the extremes in the dataset, so the clusters we used might not have come as close to the maximum boundary. However, because we used the point-scale data to fit the boundary line, and point data is capable of achieving higher densities than stand-level data (Long and Shaw 2010), we felt that our point clustering was successful in characterizing the boundary.

Our choice of using the subplot-based curve instead of the shifted stand-based curve was also based on the arbitrariness of the amount by which to shift the stand-based curve to delineate the maximum size-density boundary. The magnitude of the shift was dependent on which portions of the data range we included in locating the upper envelope of the data. In contrast to the shifted stand-based curve, using the subplot-scale data placed the boundary in a similar location yet additionally belted all the stand-scale datapoints without adjustment. This point-based curve seemed to be as good of a placement of the mature stand boundary as the adjusted stand-based approach.

Applications

To our knowledge, this is the first DMD constructed for pitch pine, as the species has not received the level of attention paid to its more commercially used cousins. We included in our diagram two of the attributes of the ecosystem of stated importance to the local decision-making process for setting forest policy: risk of damaging wildfire and the size of the carbon pool (New Jersey Forest Service 2020). The utility of this diagram is that it adds provides a multidimensional illustration of an assessment of the resource.

Pitch pine sites are capable of burgeoning regeneration following stand-replacing wildfire, increasing the risk of repeated high-intensity wildfire. In the year following severe fire, Little and Moore (1953) observed nine hundred seedlings per acre in uplands, >6,700 seedlings per acre in the wettest sites, but excess of twenty-two thousand seedlings per acre in transitional sites. In portions of Wharton State Forest with complete overstory mortality from summer fires in 2007 and 2008, state inventory data collected 11 years later (this dataset) had a range of 0 to 16,750 small pitch pine stems per acre (<4 in. DBH but taller than 4.5 ft) with a mean of 2,685. This condition placed these naturally regenerating even-aged stands at extreme risk of wildfire, well below a crowning index of 20. In an event that underscored the risk of major wildfire to unmanaged high-density stands, this area burned again as the starting location of a growing-season wildfire in June 2022, becoming the largest fire (by area) in the state in 15 years. Managing density in this context is particularly important for mitigating the risk of and damage from wildfire.

In a no-management scenario with thousands of regeneration stems per acre, the stand will grow up (vertically) along the TPA line until it approaches the SDI limit and begins experiencing density-related mortality. Stands that follow this trajectory achieve the highest aboveground live carbon per acre at the smallest diameter and at the shortest height. However, they simultaneously maintain the lowest CI, which represents the highest risk of high-intensity wildfire. Not all fires have the same effect on standing carbon stocks. In this same ecosystem, Clark et al. (2015) observed dormant-season prescribed fire to consume only two to three years of sequestered carbon, but noted that this is because fire is applied only within tightly prescribed environmental conditions. In contrast, high-severity wildfire in similarly fire-adapted ecosystems that are currently outside of their historical normative conditions can consume enormous proportions of the aboveground live carbon and shift what remains to other pools, such as the aboveground dead pool (Dore et al. 2010; North and Hurteau 2011).

Many authors have examined forest restoration treatments to reduce density and wildfire risk in fire-adapted ecosystems currently experiencing high fuel loads, usually including some combination of thinning and burning with attention to the broader set of social objectives (Bried et al. 2014; Foster et al. 2020; Hurteau et al. 2016; James et al. 2018; Kalies and Yocom Kent 2016). An application of the pitch pine DMD along these lines can be found in figure 6, showing three potential trajectories of stand development. All lines start from the average stand condition of pitch pine's most prolific age cohort (60 to 80 years) on state/local government-owned forestland in New Jersey based on inventory data from 2016 to 2020 (USDA Forest Service, Forest Inventory and Analysis Program 2023); this corresponds with 553 TPA and a QMD of 6.1 in. Track "A" shows an unmanaged stand trajectory, where stand density decreases immediately as a result of competition-induced mortality, and eventually follows along the mature stand boundary. Track "B" shows a pathway where a low thinning is applied immediately, with the largest roughly 200 TPA left as residual. This corresponds to a reduction of BA from 113 to 68 ft^2/ac. Track C follows B but applies a second low thinning shortly after the stand exceeds 80 ft^2/ac, the threshold recommended to reduce the frequency and severity of SPB outbreaks. The second thinning reduces the overstory to the largest trees and a cumulative BA of 60 ft^2/ac.

Track A achieves the highest possible aboveground live carbon and continues to maintain the highest level of carbon until significant mortality has accrued. However, it does so with a lower CI, making it more susceptible to wildfire. Track B immediately sacrifices roughly one-third of aboveground live carbon (6 of 18 tonnes C/acre) but decreases the risk of crown fire, changing CI from 26 to 38. Track B will eventually grow above the carbon density of the starting point but does not drop below a CI of 30, reducing fire risk. Track C involves two treatments that sacrifice carbon to keep stand conditions unsuitable for the spread of high-intensity fire or SPB outbreaks. Thus, maximizing stand carbon increases vulnerability of that carbon to disturbance, illustrating tradeoffs between maximizing carbon and disturbance vulnerability in management options (D'Amato et al. 2011).

Southern pine beetle is currently undergoing a northward range expansion (Dodds et al. 2018) likely due to warmer winter minimums (Ungerer et al. 1999). Lesk et al. (2017) demonstrated that forests closer to the coast are forecast to experience SPB-suitable climate decades before interior areas, putting more immediate risk on coastal plain pitch pine forests like those of the Pinelands. Although the southeastern

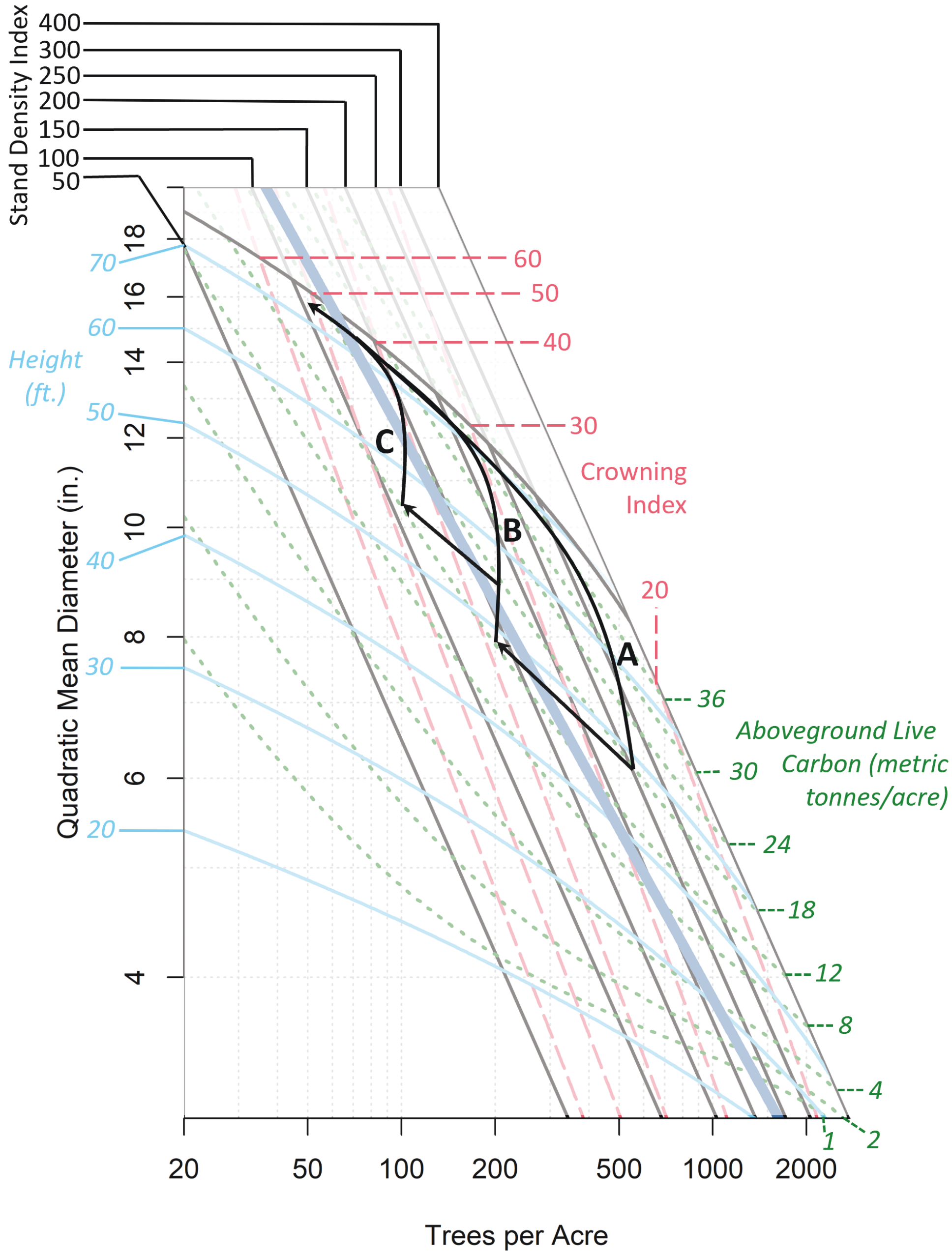

Figure 6 Example of use of density management diagram for pitch pine. Thick diagonal line corresponds to a basal area of 80 ft^2/ac. Starting point of lines A, B, and C is current average stand condition of pitch pine's most prolific age cohort (60 to 80 years) on state/local government-owned forestland in New Jersey based on 2016–2020 inventory data from USDA Forest Service FIA.

region of the United States has extensive experience with SPB outbreaks and damage prevention (Asaro et al. 2017; Coulson and Klepzig 2011; Nowak et al. 2015), the previous widespread absence of SPB from pitch pine forests means that the social landscape of the region is unfamiliar with methods of SPB prevention. As management of forest stress through control of growing space is a key component of options for the silviculturist, this diagram should help to illustrate SPB risks and mitigation in even-aged stands.

Conclusion

This study characterized the maximum size-density relationship for pitch pine, the dominant tree species of the New Jersey Coastal Plain and pine barrens in the northeastern United States. Local management considerations like fire risk, aboveground live carbon storage, and site occupancy are included in our management diagram, and it is possible to include other traits once they have been described. Although the tradeoffs inherent in management decisions may already be clear to land managers, visual tools that depict the tradeoffs involved in management can enable more productive engagement of the great diversity of stakeholders interested in forest policy. This density management diagram illustrates how different objectives are balanced in making choices for forest stands and can be used to determine different trajectories for pitch pine stand development.

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Conflict of Interest

The authors have no conflicts of interest to declare.

Data Availability

The raw data for this project can be obtained from the USDA Forest Service Forest Inventory and Analysis (FIA) Program and the New Jersey Forest Service. FIA data can be downloaded from the DataMart App at https://apps.fs.usda.gov/fia/datamart.datamart.html. New Jersey Forest Service data can be obtained by contacting the Trenton headquarters at (609) 292-2532 or mail stop code 501-04, NJ Forest Service, PO Box 420, Trenton, NJ 08625-0420, USA.

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