A MODEL FOR ESTIMATING UNDERSTORY VEGETATION RESPONSE TO FERTILIZATION AND PRECIPITATION IN LOBLOLLY PINE PLANTATIONS

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Abstract—A model form is presented, where the model contains regressors selected for inclusion based on biological rationale, to predict how fertilization, precipitation amounts, and overstory stand density affect understory vegetation biomass. Due to time, economic, and logistic constraints, datasets of large sample sizes generally do not exist for understory vegetation. Thus, we wanted to see if the model form would provide reasonable estimates of understory biomass using a limited range of values for the regressors when estimating parameters.

Data from three loblolly pine (*Pinus taeda* L.) plantations located in the Western Gulf of the Southeastern United States were used to obtain parameter estimates for the biologically derived model form. Stand density index was used as the measure of stand density. Our model predicts that additional amounts of fertilizer and precipitation can increase understory vegetation biomass. However, at some point, depending on precipitation amounts and stand density, increases in fertilization and precipitation will produce decreases in understory vegetation biomass because of simultaneous increases in loblolly pine production. Based on validation results using data from independent studies in the Western Gulf, the model form provides reasonable estimates of understory biomass for regressor values beyond the range used in parameter estimation. Future research needs to concentrate on estimating parameters for the presented model form using a more complete dataset.

INTRODUCTION

Herbaceous vegetation, vines, and shrubs are a major component of nutrient cycles in young pine plantations in Western Gulf Coastal Plain stands of the Southeastern United States (Switzer and Nelson, 1972), add to the biodiversity of these plantations (Miller and Miller 1999, Wolters and Schmidtling 1975), provide wildlife habitat (Miller and Miller 1999, Wolters and Schmidtling 1975), and to some extent forage for domestic animals such as cattle. Understory vegetation also competes with trees for soil water and nutrients, and can detrimentally affect the growth of crop trees (Haywood and others 2003, South and others 2006). Thus, it is imperative to understand how overstory and understory vegetation interact with and affect one another in Western Gulf loblolly pine (*Pinus taeda* L.) plantations.

Studies have shown understory vegetation yield frequently increases in loblolly pine stands in the Western Gulf Coastal region after fertilization (e.g., Brockway and others 1998, Lauer 2003, Thill and Bellemore 1986, Wolters and Schmidtling 1975, Wolters and others 1995). However, increased growth of the overstory trees can eventually shade out the understory vegetation, particularly herbaceous vegetation. Many models have been developed to estimate the relationship between pine overstory density and understory vegetation using basal area per unit area in the Southeastern United States (Gaines and others 1954, Grelen and others 1972, Grelen and Lohrey 1978, Halls and Schuster 1965, Wolters 1973, Wolters 1982, Wolters and Schmidtling 1975, Wolters and others 1982). Mengak and others (1989) developed models to estimate understory yield in natural and planted loblolly pine stands using age as the independent variable in the Piedmont of SC. Despite all of these models, none were developed to estimate understory biomass in pure loblolly pine plantations in relation to stand density, let alone, response to fertilization in pure loblolly pine plantations. Additionally, other than Mengak and others (1989), all of these models predict herbaceous (grass and grass-like and forb) production and estimates do not include shrub production or biomass. Thus, there is a need to develop a more complete model to reasonably predict understory vegetation response to fertilization in Western Gulf loblolly pine plantations. All future reference to biomass refers to living, aboveground standing biomass.

Density Management Diagrams (DMDs) are available for loblolly pine in the Southeastern United States (e.g., Williams 1994, Dean and Chang 2002); however, no DMDs have graphically related understory biomass to overstory stand density. Vales and Bunnell (1988) found that Stand Density Index has a strong relationship with the transmission of light through canopy. Moore and Deiter (1992) is the only publication that we are aware of that relates understory vegetation to Stand Density Index; however, the study was conducted in the Pacific Southwest. By using Stand Density Index (Reineke 1933) to predict understory vegetation biomass, DMDs can be used to determine how an overstory objective may potentially affect understory biomass and hence affect wildlife and domestic animals (VanderSchaaf 2006), carbon budgets, etc.

The first objective of this paper was to develop a biologically meaningful model form sensitive to fertilization rates and precipitation amounts to predict understory vegetation biomass in pure loblolly pine plantations using Stand Density Index as the measure of overstory density. Due to time, economic, and logistic constraints, large sample size sets of understory vegetation data are usually not available. Thus, a second objective is to determine whether the model form will provide reasonable estimates of understory biomass when extrapolating beyond the range of regressor values used in parameter estimation.

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METHODS

The relationship between overstory loblolly pine density and understory vegetation was studied in response to fertilization at three cutover sites in the Western Gulf Coastal Plain two years after treatment (table 1). This study was part of a larger study looking at the effects of fertilization on loblolly pine growth (Forest Nutrition Cooperative 2003). Results from this understory vegetation study have been previously reported (McKnight and Heitzman 2004, McKnight 2005). Sites were located near Hermitage, AR, north of Leesville, LA, and near DeKalb, MS. All plantations were owned by forest industries; the AR site was owned by Potlatch Corporation, the LA site was owned by Forest Capital Partners, the MS site was owned by Plum Creek Timber Company. No thinning treatments were conducted at any site. The Hermitage, AR site soil was classified in the Stough series and is a coarse, loamy, siliceous, thermic Fragiaquic Paleudults. Site preparation consisted of a chemical treatment in September 1995 using 12 ounces of Arsenal (53.1 percent imazapyr) and 2 quarts of Accord (53.8 percent glyphosate) followed by a broadcast burn. Planting occurred in the 1995-1996 season. A first year herbaceous weed control treatment occurred in April of 1996 using 4 ounces of Arsenal and 2 ounces of Oust (75 percent sulfometuron methyl). The Leesville, LA site was classified in the Sacul series and has a fine, smectitic, thermic Chromic Dystraquerts soil and site preparation consisted of a broadcast burn followed by a Savannah plow in October of 1993. Planting occurred in the 1993-1994 season. A first year herbaceous weed control treatment was conducted using 4 ounces of Arsenal and 2 ounces of Oust. The DeKalb, MS site soil was classified in the Smithdale series and is a fine, loamy, siliceous, subactive, thermic Typic Hapludults. Site preparation consisted of a chemical site preparation in August of 1995 using 16 ounces of Arsenal and 1.5 quarts of Accord. Planting occurred in the 1995-1996 season.

Precipitation data for 2001 were obtained for all sites from AWIS (2001). See McKnight (2005) for the dominant understory species, based on percent cover values and visual observation, by lifeform and by site.

Loblolly Pine Measurements

All overstory measurements used in the model were performed during the winter months of 2000-2001. Loblolly pine measurement plots ranged in size from 0.03 to 0.08 ha, were surrounded by a 14 m buffer on all sides, and each contained a minimum of 60 trees at time of establishment. Nitrogen was applied by hand at rates of 0, 67, 134, 202, and 269 kg/hectare. Additionally, P was applied at a constant proportional rate of 10 percent to the N rate. At the DeKalb, MS site only, boron (B) was applied at a constant proportional rate of 0.005 percent to the N rate. A randomized block design was used, where each site had two blocks of the complete set of the 5 fertilizer rates. Measurements included diameter-breast height and total height.

Stand Density Index (SDI) was calculated using equation [1]:

$$\mathrm{SDI} = \mathrm{TPH}\left(\frac{\mathrm{QMD}}{25.4}\right)^{1.6} \qquad [1]$$

Where:
TPH – trees/ha
QMD – quadratic mean diameter (cm)

Values of SDI used in the understory model ranged from 279 to 402 at the Hermitage, AR site, from 338 to 461 at the DeKalb, MS site, and from 370 to 558 at the Leesville, LA site.

Understory Vegetation Biomass Measurements

During the last two weeks of August 2001, two 1-m^2 biomass plots were systematically established in both replications (blocks) of the four fertilization treatments and the control at each site to sample understory biomass. All living understory vegetation rooted within the 1-m^2 plot was hand clipped at ground level. These samples were taken to the laboratory at the University of Arkansas-Monticello and oven dried at 60 °C for 48 hours. After the samples were dry, they were weighed to determine oven-dry biomass. The average of the two samples per fertilizer rate, replication (block), and study site combination was calculated and used to fit the model. Therefore, a total of 30 observations were used (3 locations x 2 blocks per location x 5 rates = 30 plots). Other models to predict understory vegetation yield in relation to overstory density have used comparable sample sizes (e.g., Gaines and others 1954, Grelen and others 1972, McConnell and Smith 1970, Mengak and others 1989, Uresk and Severson 1989, VanderSchaaf 1999).

Statistical Analysis

The dependent variable in our study is the total amount of living, above-ground, understory vegetation biomass (grasses and grass-likes, forbs, woody vines, and shrubs) in mid- to late August. Least squares regression analysis was conducted to estimate parameters using PROC MODEL of SAS Institute Inc. (1988); the Gauss-Newton algorithm was used for non-linear model forms. Several different models were tested which included non-transformed, and natural logarithmic, square root, and exponential transformations of dependent and independent variables. For the linear model forms tested, transformations of the dependent variable and Stand Density Index were conducted since a negative curvilinear relationship between these two variables has been strongly and widely established (Jameson 1967, Uresk and Severson, 1989, VanderSchaaf 1999, Wolters and Schmidtling 1975).

SDI, rates of fertilizer, and precipitation during the period of March until the sampling date in August (in cm), were selected to be included in the model. The total amount of precipitation during these months was selected because this is often considered to be the growing season for most herbaceous, vine, and shrub species, and loblolly pine in this region. Regressors and regressor forms were selected based on biological rationale which is explained more fully in the Discussion below. The mean of the untransformed absolute value of the residuals (MR) was used to contrast and compare candidate model forms fitted using the data described above. Residual errors were examined for trends in the data and the coefficients of the regressors were examined to make sure they had biological meaning and were significantly different from zero at the alpha = 0.05 level.

Table 1—Understory vegetation biomass study establishment age, minimum, mean, and maximum understory vegetation biomass, Precip--amount of precipitation during the period from March until the sampling date in August (AWIS, 2001), Average--average amount of annual precipitation (NOAA, 2004) during the period from March until August from 1960 to 2001, Std. Dev--standard deviation of the amount of annual precipitation (NOAA, 2004) during the period from March until August from 1960 to 2001, and soil drainage where SPD -- somewhat poorly-drained, WD -- well-drained, and MWD -- mostly well-drained

		Understory vegetation biomass (kg/hectare)						
Site	Age	Min	Mean	Max	Precip (cm)	Average (cm)	Std. Dev (cm)	Drainage
Hermitage, AR	5	618	1186	1947	78.66	67.32	15.74	SPD
DeKalb, MS	5	1535	2428	3627	92.18	72.70	21.82	WD
Leesville, LA	7	262	519	1005	78.33	68.51	19.77	MWD

Site	Age	YST	QMD (cm)	TPH	SDI	BA (m^2)	Average HT (m)
Hermitage, AR	3	0	5.6	1254	112	3.1	3.7
	5	2	11.2	1236	331	12.1	5.7
DeKalb, MS	3	0	5.4	1621	135	3.7	4.0
	5	2	10.5	1616	394	14.0	6.8
Leesville, LA	5	0	7.7	1774	263	8.3	5.9
	7	2	10.8	1764	450	16.2	8.2

Overstory loblolly pine average plot-level characteristics by site are also given. Where: YST--years since treatment (0 -- at time of fertilization), QMD--quadratic mean diameter, TPH--trees per hectare, SDI--stand density index (metric), BA--basal area/ha, Average Ht--average total tree height of all trees.

Model Validation

As a means of determining the predictive ability of our model form (eq. 2) for independent populations vastly different than those used in model fitting, we compared estimated understory vegetation biomass (table 2) from equation 2 to published understory vegetation biomass values (Blair and Enghardt 1976, Lauer 2003). Precipitation data from March to August for the Blair and Enghardt (1976) study were obtained from the Woodworth 2 SE weather station (NOAA 1957, NOAA 1962, NOAA 1967, NOAA 1969). Precipitation data during the months of March to August for the years of 1987 and 1988 were obtained from NOAA (NOAA 1987, NOAA, 1988) using the Merrill and Atmore weather stations for the MS and AL sites, respectively (Lauer 2003). For the Blair and Enghardt (1976) study, understory vegetation was measured at ages 30, 35, 40, and 42. Although we can compare our estimates to their understory vegetation values, there are some complications that need to be addressed. First, basal area/ha and trees/ha were obtained from graphs, and quadratic mean diameter was calculated using the values of basal area/ha and trees/ha. Second, they measured “current season’s growth” rather than measuring standing biomass as in our study. For herbaceous vegetation this is not a major concern, but shrub annual production and shrub total standing biomass can differ greatly. Third, they merely state that samples were taken in late summer and do not give specific dates. Thus, we assume measurements were taken in mid- to late August. Fourth, a substantial midstory of hardwoods existed on the site which probably affected understory vegetation yield. The study by Lauer (2003) examined the impacts of first year fertilization, first year herbaceous vegetation control, and combinations of these factors on understory biomass in pine plantations. Understory biomass was determined one and two years after loblolly pine plantation establishment on a site in the MS county of George and a site in Escambia County, AL.

RESULTS

Equation 2 was the model form selected which we believe best predicts understory biomass in relation to fertilization rate, precipitation amounts, and overstory stand density based on both biological and statistical considerations:

$$\begin{aligned}\text{LnTotal} = &-20.0312 - 0.02987\text{LnPrecip}*\text{SDI}^{1/2} + 0.000177\text{Fert}*\text{Precip} \\ &+6.656713\text{LnPrecip} - 0.00015(\text{SDI}^{1/2} * \text{Fert}*\text{LnPrecip})\end{aligned} \quad [2]$$

Where:
Total = total understory biomass (grasses and grass-likes, forbs, woody vines, and shrubs) in mid to late August (kg/ha)
Ln = natural logarithm
Precip = total amount of precipitation from the beginning of March until the site-specific sampling date in August (cm).
SDI = stand density index (metric)
Fert = rates of fertilization (kg/ha) – since P rates are proportional to N rates, N rates are the regressor variable.
Adj. R^2 = 0.8324, MR = 285.1, n = 30

The model explained a large amount of variation in understory vegetation biomass. Standard errors of the parameter estimates are: (Intercept) -- 4.4174, (LnPrecip*$SDI^{1/2}$) -- 0.0148, (Fert*Precip) -- 0.000075, LnPrecip -- 1.1790, ($SDI^{1/2}$*Fert*LnPrecip) -- 0.000072. Model forms (e.g., square root transformations of the dependent and independent variables rather than natural logarithm transformations) other than equation 2 had inferior statistical or biological properties compared to equation 2 such as

Table 2—Comparison of predicted values using eqn. (2) and observed data from a thinning study conducted in a loblolly pine plantation in central LA (Blair and Enghardt, 1976) and from a first year herbaceous vegetation control and fertilization study conducted in loblolly pine plantations (it is assumed the plantations had 0 Stand Density Index) in MS and AL (Lauer, 2003)

Site	Year	Treatment	Age	SDI	Precip (cm)	Observed (kg/ha)	Predicted (kg/ha)	Error (kg/ha)
Thinning Study	1957	.	30	592	88.19	241	687	-446
	1957	.	30	536	88.19	310	804	-494
	1957	.	30	446	88.19	335	1056	-721
	1962	.	35	575	63.73	370	104	266
	1962	.	35	493	63.73	338	130	208
	1962	.	35	403	63.73	299	170	129
	1967	.	40	497	81.92	777	579	198
	1967	.	40	432	81.92	759	706	53
	1967	.	40	368	81.92	720	872	-151
	1969	.	42	464	82.98	756	692	64
	1969	.	42	403	82.98	742	840	-98
	1969	.	42	339	82.98	690	1045	-355
George, MS	1987	Control	1	0	71.04	3188	4222	-1034
		NP	1	0	71.04	6855	7434	-579
		HC	1	0	71.04	1584	4222	-2638
		NP+HC	1	0	71.04	1830	7434	-5604
		NPK	1	0	71.04	7393	7434	-41
		NPK+HC	1	0	71.04	798	7434	-6636
	1988	Control	2	0	90.86	2788	21721	-18933
		NP	2	0	90.86	2570	44790	-42220
		NPK	2	0	90.86	2770	44790	-42020
Escambia, AL	1987	Control	1	0	64.31	2565	2176	389
		NP	1	0	64.31	3638	3633	5
		HC	1	0	64.31	835	2176	-1341
		NP+HC	1	0	64.31	1303	3633	-2330
	1988	Control	2	0	63.98	2506	2103	403
		NP	2	0	63.98	3036	3501	-465
		HC	2	0	63.98	1643	2103	-460
		NP+HC	2	0	63.98	2296	3501	-1205

Where: Year--year of sampling, Treatment--[Control -- no fertilization or herbaceous vegetation control, NP -- N and P fertilization at a rate of 45 kg/ha and 56 kg/ha; respectively, NPK--in addition to NP, a K fertilization at a rate of 112 kg/ha, HC--first year herbaceous weed control treatment. For the NP and NPK treatments, a rate of 45 was used for the fertilizer rate in the model], SDI--stand density index (metric), Precip--amount of precipitation from March to August, Observed--understory vegetation data from Blair and Enghardt (1976) or Lauer (2003), Predicted--estimated understory vegetation using eqn. (2)

non-significant variables or poorer estimates of understory biomass across the range of SDI.

Based on the validation analyses and a general examination of model estimates (table 2 and fig. 1), a more complete dataset composed of more sites, sampling across several years thus allowing precipitation to vary at one site, a greater range of stand densities, etc., is needed to better estimate understory biomass across a range of site conditions. For example, when greatly extrapolating beyond the values of the regressors used in fitting equation 2, particularly extreme value combinations of the regressors used in the model, predictions are very poor. In many cases though, equation 2, fitted using a limited dataset, is robust enough to account for extreme limits of one and in some cases even two regressors [extreme overstory densities (SDI less than 200/ha), high rates of N (greater than 330 kg/ha), and high rates of March to August precipitation (greater than 92 cm)], but using extreme limits for three regressors will result in large overpredictions. Additionally, low rates of March to August precipitation (less than 55 cm) can potentially result in large underpredictions of understory biomass. Predictions using low values of SDI (less than 200) are reasonable for low fertilization rates, but low SDI in combination with higher rates of fertilizer and March to August precipitation produce large errors in understory biomass prediction. Herbaceous weed and site preparation treatments can greatly limit the applicability of our model, especially at lower stand densities. A reasonable maximum amount of understory production in these stands probably ranges from 6000 to 7000 kg/ha (Lauer 2003).

DISCUSSION

Biological Rationale behind Regressors in the Model

Our current model predicts that increases in precipitation (Grelen and Lohrey 1978, Wolters 1982) and fertilizer rate (Basile 1970, Bowns 1972) positively affect understory biomass -- Fert*Precip and LnPrecip regressors. Studies have showed the positive interaction between fertilization and moisture for understory yield (Bowns 1972, Riegel and others 1991, Thill and Bellemore 1986). The model form provides for additional amounts of understory production with increasing rates of fertilizer as precipitation becomes greater.

However, positive effects on understory vegetation following increases in fertilization and precipitation, and the synergistic interaction between fertilization and precipitation, are offset by increased growth rates of the overstory (Allen 1987), particularly crown production (King and others 1999, Vose and Allen 1988, Yu and others 1999), following additional amounts of precipitation and following fertilization treatments (Brockway and others 1998, Haywood and others 2003, Wolters and Schmidtling 1975, Wolters and others 1995). Increases in overstory production will reduce light to the understory and induce more competition for nutrients and moisture between overstory trees and understory vegetation. Plus, as stand density increases, greater amounts of nutrients become tied up in the overstory tree biomass (Borders and others 2004) that includes tree stems, crown branches and twigs, and roots that can further reduce nutrient availability to the understory vegetation. In addition to the negative aspects of the overstory on understory vegetation in terms of competition for resources, increases in needle cast associated with greater crown production following continually greater rates of fertilization may smother understory production (Haywood and others 2003). These overstory-understory vegetation biological interactions are represented by the negative coefficients for the LnPrecip*SDI regressor, and the three-way interaction regressor between SDI, fertilizer rate, and precipitation amount. Estimates from equation 2 show that overstory density produces the greatest change in understory vegetation production. Predictions show

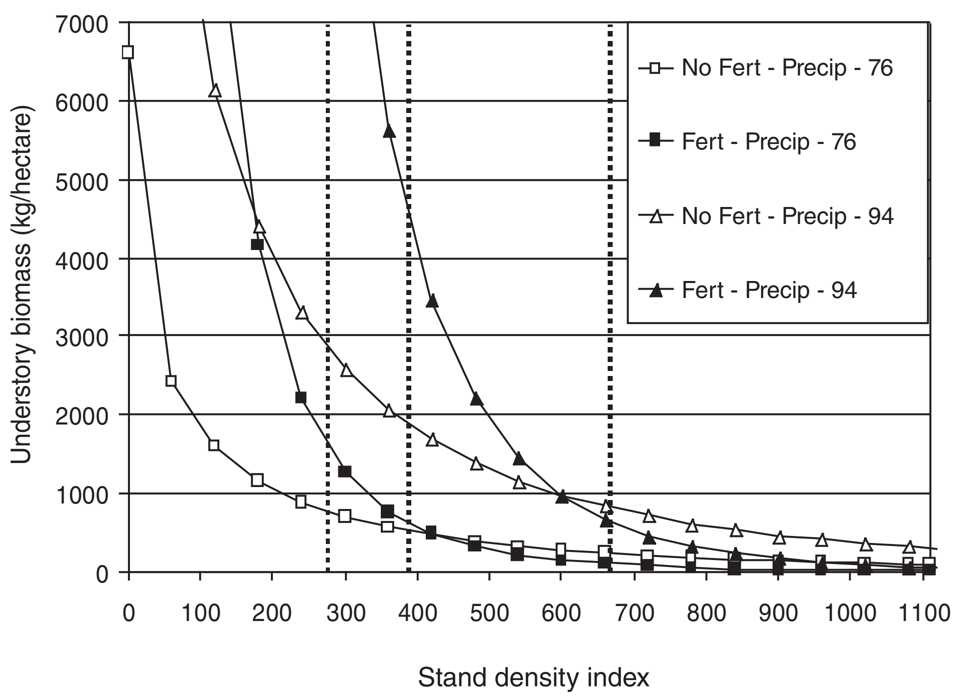

Figure 1—Estimated total understory biomass (kg/ha) for a control and a fertilization treatment of 269-27 kg/ha N, and P; respectively, over Stand Density Index. Where: solid symbols – fertilization treatments, open symbols -- no fertilization, Precip. is the amount of precipitation (in cm) during the month of March until the sampling date in August. The dashed lines are management zones of a DMD developed by Dean and Chang (2002). The lines are at SDI values of 278 (Canopy closure -- 25 percent of Maximum size-density relationship of 1110), 388 (Full-site occupancy -- 35 percent of 1110), and 666 (Threshold of self-thinning -- 60 percent of 1110).

that relatively greater overstory densities, regardless of the rate of fertilization or large amounts of precipitation, produce low understory vegetation biomass consistent with Haywood and others (2003).

Extrapolation of the Model beyond the Range of Stand Densities Used in Parameter Estimation

A negative curvilinear relationship between understory vegetation production and overstory stand density has been strongly and widely established (Jameson 1967, Uresk and Severson 1989, VanderSchaaf 1999, Wolters and Schmidtling 1975). Although our current model is based on data from plantations ranging in age from 5 to 7, we believe our model form can be used to reasonably predict understory vegetation biomass and response to fertilization treatments for ages greater than seven due to the negative curvilinear relationship. Certainly, as with most models, predicted values using equation 2 will never, beyond chance, coincide exactly with observed values. Obviously, silvicultural practices such as mid-rotation herbaceous or brush control, severe thinning, repeated fertilization treatments, etc. will limit the applicability of the model. However, when no other tool is available, model extrapolation can be useful. Based on the validation results from the study by Lauer (2003), our current model in certain instances can provide reasonable estimates of understory biomass following fertilization treatments conducted at ages younger than five.

Parameters in our current model were estimated using a SDI range from 279 to 558. At SDI values greater than these, the negative curvilinear relationship continues to decrease understory biomass (fig. 1). As stand density increases, although the percent error [(Predicted-Observed)/Observed] may continue to be large or even increase, the practical magnitude of the error decreases. For example, a 100 percent error in biomass prediction at high stand densities has little impact practically since the magnitude of the error will be small and will therefore have little effect on estimated stocking rates.

CONCLUSIONS

A model form developed based on biological rationale was presented to predict understory vegetation biomass in relation to fertilization rates, precipitation amounts, and overstory stand density. A limited dataset from loblolly pine plantations was used to estimate parameters of the presented model form. Based on validation results, and when using constraints on the regressors as discussed in the paper, our model form appears to provide reasonable estimates of understory biomass and response to N and P fertilization for regressor values outside the range used in parameter estimation. Partially based on this current analysis, we believe overstory density, fertilizer rates, and precipitation amounts are more important factors in determining understory biomass and response to fertilization in loblolly pine stands than plantation age (Bowns 1972, Riegel and others 1991, Thill and Bellemore 1986, VanderSchaaf and others 2002, Haywood and others 2003). Future research should concentrate on fitting equation 2 using a more complete dataset in terms of overstory stand density, precipitation amounts, stand ages, fertilization rates, and repeated measures. Additionally, future research should concentrate on obtaining understory data from studies using non-proportional rates of N and P and perhaps from studies quantifying multi-nutrient fertilization effects on understory biomass.

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