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A 50-Year Retrospective of the Forest Productivity Cooperative in the Southeastern United States: Regionwide Trials

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Abstract

In 2019, the Forest Productivity Cooperative (FPC) celebrated its 50th anniversary. The mission of the FPC is and has been creating innovative solutions to enhance forest productivity and value through the sustainable management of site resources. This industry-government-university partnership has generated seminal research with sweeping implications for increasing productivity throughout the southeastern United States and Latin America. To commemorate this semicentennial, we highlighted some of the pivotal findings in the southeastern United States from the past 50 years derived from our large, regional experiments: regionwide trials.

Study Implications: Fifty years of research have yielded substantial management implications for intensively managed loblolly pine in the southeastern United States. Some of our most impactful findings are the following: our generalized fertilization rate of 200 lb ac^{-1} elemental N and 25 lb ac^{-1} elemental P has been found to increase growth on most plantations in the region when applied at or before midrotation, whereas the addition of K and micronutrients was found to be important on the Pleistocene Terraces. Stands with a leaf area index (LAI) less than 3.5 will respond to fertilization, increasingly, so the lower the initial LAI. Our long-term site preparation studies demonstrated the importance of pairing optimal site preparation with fertilization and that subsoiling and tillage typically yielded lesser gains than fertilization and vegetation control at establishment. Fertilization tends to be more important to growth responses at midrotation than onetime vegetation control treatments, but an additive response when the two treatments are applied together is generally experienced. When fertilization is paired with thinning, the rate of postthinning diameter growth is accelerated.

Keywords: loblolly pine, fertilization, thinning, vegetation control, site preparation

Prior to the incorporation of intensive silvicultural practices, loblolly pine (*Pinus taeda* L.) had a reputation of needing no silvicultural intervention to be productive. This reputation was garnered through observations of loblolly pine quickly establishing on land deemed too infertile and eroded for agricultural use (Carter et al. 2015). Of course, today, this view of loblolly pine is antithetical to what we have learned about pine plantation management in the southeastern United States. The extensive gains in our understanding of factors affecting the growth of loblolly pine made by intensive silvicultural researchers in the southeastern United States have resulted in a tripling or quadrupling of per-acre productivity while halving the average rotation length in pine plantations from 50 to 25 years (Fox et al. 2007).

Dubbed "The Great Alliance" (Carter et al. 2015), the industry-university cooperative model—pioneered by Bruce Zobel, the founder of the Forest Tree Improvement Program at Texas A&M University—has been producing impactful research since the 1950s. In the aftermath of the corporate divestment and restructuring that occurred among timber companies in the United States, starting in the 1980s, the importance of these research cooperatives only grew. Without internal research and development programs of their own, companies increasingly relied on universities to supplement or serve as their research arms. Today, this relationship is still thriving and is continuing to provide impactful research to one of the most important timber producing regions in the world: the southeastern United States.

A foremost contributor to these advancements over the last half century has been the Forest Productivity Cooperative (FPC). The research generated by the FPC has been used in numerous extension and outreach articles and put into widespread practice throughout the southeastern United States and South America. Many of the contributions made by the FPC to this enhanced understanding of pine plantation management were garnered through regionwide trials (RWs). RWs are studies conducted throughout the southeastern United States and Latin America on operational forest plantations owned or managed by FPC members. This industry-government-university partnership has resulted in 28 RW series, numbered sequentially as they were initiated.

The broad geographic expanse of the FPC's membership has enabled researchers to answer questions regarding the effects of silvicultural inputs on the growth of loblolly pine throughout its planted range from establishment to midrotation age. Individual studies typically ranged from six to 18 years in duration but could extend into the subsequent rotation (Table 1). We highlight major findings over the last 50 years of FPC research garnered from these RW series in the southeastern US (Figure 1). We will cover the history and evolution of the FPC and the key findings from our RWs in a silvicultural procedural order: site preparation, fertilization, vegetation control, and thinning and fertilization. This order also loosely follows the chronological order of the establishment dates of these trials. We finish the review with a brief overview of the FPC's presence in South America; our often unmentioned, or "lost," RW trials; and products produced by this Cooperative over the span of its life, thus far.

FPC History

The FPC is an international industry-government-university silvicultural research cooperative. The membership consists of variously sized private companies, state and federal agencies (Table 2), and four universities. Led by forestry faculty at North Carolina State University (NCSU), Virginia Polytechnic Institute and State University (Virginia Tech), the Universidad de Concepción (UdeC) in Chile, and the Universidade Federal de Lavras in Brazil, the FPC is one of the oldest and largest cooperatives of its kind.

Since its inception in 1969, the FPC has undergone a series of name and personnel changes. Under the leadership of Wayne Haines (1969–1977), the first director, the Cooperative was named the North Carolina State Forest Fertilization Cooperative. Bob Kellison (1977–1978) and Russ Ballard (1978–1980) oversaw the Cooperative until Lee Allen (1980–2008) became director in 1980. Allen changed the name of the Cooperative to the North Carolina State Forest Nutrition Cooperative in 1986 to reflect the broadening of the Cooperative's research agenda beyond regionally based loblolly pine fertilization regimes. At the end of Dan Kelting's (2000–2003) tenure as codirector in 2003, the Cooperative's name was shortened to the Forest Nutrition Cooperative in response to Tom Fox (2003–2017) at Virginia Tech partnering with Allen and NCSU. Rafael Rubilar (2007–present) at UdeC was the first codirector from South America when he joined in 2007. Shortly thereafter, Allen became director emeritus of the Cooperative after 28 years of service and was replaced by José Stape from 2008 to 2015. In 2010, the Cooperative changed its name to its current moniker, the Forest Productivity Cooperative, to better define the Cooperative as a

Table 1. Summary table of regionwide series conducted in the southeastern United States discussed in this review. Regionwide trials (RW) not listed are either found exclusively in South America or did not yield published results (i.e., the "lost" regionwide trials). The order of the RW are presented in the order in which they are discussed in this article, which is in a silvicultural procedural order, with the exception of regionwide 1.

RW	Establishment Year	Duration (Years)	No. of Sites	Primary Question(s)
1	1970	8	101	Does loblolly pine productivity increase in response to fertilization?
7	1979	14 to 18	6	Do soil/site preparation, weed control, and fertilization have additive or synergistic effects on stand productivity?
16	1994	6	15	Do subsoiling and tillage modify soil physical properties and increase forest productivity?
13	1984	10	42	Is there a synergistic effect of N and P fertilization dose levels on stand growth at midrotation? How much N and P are required to generate a growth response?
14 & 15	1989	8	23	Are other nutrients besides N and P limiting productivity at midrotation?
17	1996	10	13	What is the effect of competing vegetation removal at midrotation on stand productivity with and without fertilization?
18	1998	12	22	Do stands respond to repeated juvenile fertilization? If so, what is the optimal rate and frequency of application?
19	2006	Ongoing	9	How do midrotation stockings after thinning and fertilization affect individual tree and stand growth and value?
20	2007	Ongoing	3	How does intensive silviculture at establishment and initial stocking interact with clonal forests within the planted range of loblolly pine? Why do trees grow faster in South America than in the United States?
28	2019	Ongoing	15	Can phosphorus applied in a previous rotation affect productivity in the subsequent rotation?

research body that studies all silvicultural inputs. Rachel Cook (2016–present) replaced José Stape as codirector at NCSU, followed shortly thereafter by the addition of Otávio Campoe (2016–present) at the Universidade Federal de Santa Catarina in Brazil. In 2019, Campoe moved to the Universidade Federal de Lavras in Brazil. Jay Raymond (2017–2018) at Virginia Tech served as interim codirector of the FPC before Dave Carter (2018–present) joined.

The program has also had a number of key support personnel who were critical for program success including Mike Kane (1977–1982), Steve Anderson (1982–1987), Stephen Colbert (1989–1998), Leandra Blevins (2004–2012), Colleen Carlson (2005–2013), and Tim Albaugh (1983–present). This group, and others not mentioned here, worked together with co-/directors to ensure that trials answered critical questions, study sites were managed appropriately, data were collected properly, analyses were completed in a timely manner, and, ultimately, that member reports and scientific publications were written to keep the program relevant to the industrial and scientific communities.

The corporate restructuring from vertically integrated companies to investment-oriented ownerships and the consolidation of companies influenced the membership structure of the FPC over the years. To, in part, adapt to these industry changes, FPC leadership decided to create a new membership category for members without landholdings and broaden the geographic reach of the FPC to South America. These changes were important to ensuring the continued existence of the FPC.

The First Regionwide Trial

Initially, the directive of the Cooperative was to determine the economic feasibility of fertilizing loblolly

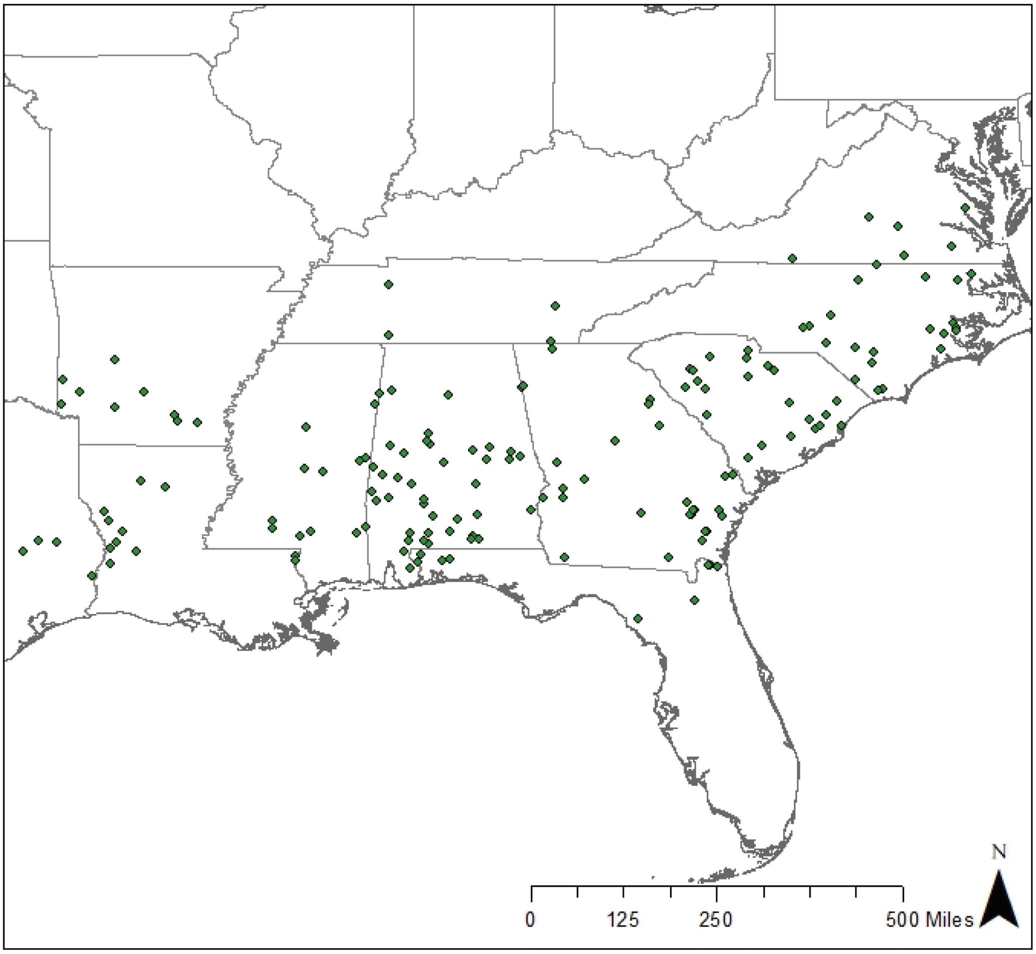

Figure 1. Study site locations for regionwides 7, 13, 14, 15, 16, 17, 18, 19, 20, and 28 in the southeastern United States.

Table 2. A complete list of current members of the Forest Productivity Cooperative.

American Forest Management	Greenwood Resources	OMYA
ArborGen	Hancock Forest Management	Rayonier
BASF	International Forest Company	Red River Specialties
Bayer	Jordan Lumber	Resource Management Services
BTG Pactual	Klabin	Smurfit Kappa Colombia
Campbell Global	Lesco Aviation	Smurfit Kappa Venezuela
Chem-Air	Masisa Chile & Argentina	Superior Pine Products
Deforsa	Miliken Forestry	Timberland Investment Resources
FitsNR, LLC	Molpus Woodlands Management	USDA Forest Service
CMPC (F. Mininco & Bosques del Plata)	North Carolina Forest Service	Virginia Department of Forestry
Forestry & Land Resource Consultants	Nutrien Ag Solutions	Volterra S.A.
FuturaGene		Weyerhaeuser

pine plantations in the Piedmont and Coastal Plain of the southeastern United States. It was anticipated this objective would be completed in five years. The impetus for this directive was driven, in part, by the success of the Cooperative Research in Forest Fertilization program at the University of Florida in finding strong fertilization responses with slash pine (*Pinus elliotti* Engelm.) in the Flatwoods of Florida.

The first RW (RW 1) was a fertilization trial of nitrogen (N), phosphorus (P), and potassium (K) established in 1970, across 101 sites, to answer the original question that inspired the creation of the FPC, "Does loblolly pine respond to fertilization?" The elemental rates of the four fertilization treatments were as follows: (1) 100 lb ac^{-1} elemental N, (2) 50 lb ac^{-1} elemental P, (3) 100 lb ac^{-1} + 50 lb ac^{-1} elemental N + P, and (4) 100 + 50 lb ac^{-1} + 50 lb ac^{-1} elemental N + P + K. The researchers applied these treatments to sites ranging in age (7–28), site index (42–90 ft), density (169–1,883 trees per acre), and initial basal area (26–271 ft^2 ac^{-1}) in the Coastal Plain and Piedmont. Under these treatments, loblolly pine did, in fact, prove responsive to fertilizer on the Upper and Lower Coastal Plain as well as in the Piedmont, which was a seminal finding for the time. However, the five-year growth responses of mature and semimature loblolly pine stands ranged dramatically: –486 ft^3 ac^{-1} to 872 ft^3 ac^{-1} (Allen and Duzan 1983). Early evidence suggested that growth responses to N and P applied together, rather than individually, were synergistic. An internal FPC report written in 1980 about this RW contains the following quote: "The impact of a P-deficiency on the effectiveness of an N-fertilizer treatment should be given special attention so as to maximize the yields from a given N treatment" (Lea 1980, p. 33). It would be another two decades before this early observation was crystallized into peer-reviewed publication (sensu Ducey and Allen 2001). Furthermore, the first RW results showed regionally specific responses to fertilization, with the growth of Upper and Lower Coastal Plain sites possessing relatively greater responses to P and K, when applied with N, than those measured in the Piedmont. Early on, it was clear that responses to silvicultural inputs were likely to be site specific. Thus, the groundwork was laid for decades of subsequent research focused on tailoring fertilization regimes and, later, silvicultural prescriptions, to site conditions in the southeastern United States and, eventually, South America.

Site Preparation

The RW 7, a site preparation and establishment treatments study, compared two mechanical site preparation treatments. When this study was initiated in 1979, fundamental questions regarding the impact of mechanical intervention on a site (i.e., whether these inputs enhanced or degraded productivity) remained to be answered.

Sites were either treated with optimal site preparation (e.g., shear, rake, pile, disk, bed, double-bed) or operational—usually current operational site preparation treatments (e.g., chop, burn, shear, pile) (Nilsson and Allen 2003). Within these main plots, subplots were assigned to a randomized 2 × 2 factorial of fertilization and herbicide at establishment. Diammonium phosphate (DAP) was either applied (250 lb ac^{-1} of DAP, equivalent to 40 lb ac^{-1} elemental N and 50 lb ac^{-1} elemental P) or not immediately following planting. Similarly, either an herbicide treatment (1.2 m banded application of hexazinone) was applied once during each of the first two growing seasons or no herbicide treatment was applied. The long-term view of this study—18 years, extending well into the rotation—allowed, for the first time, an investigation into the duration of the growth response caused by site preparation treatments.

In general, it was found that the optimal site preparation treatment yielded greater volume production than the operational site preparation treatment. Average values ranged from 160 ft^3 ac^{-1} yr^{-1} in the operational site preparation treatment to 220 ft^3 ac^{-1} yr^{-1} in the optimal site preparation treatment. Fertilization treatments resulted in greater volume growth in the optimal site preparation treatment, and herbicide resulted in greater volume growth in the operational site preparation treatment. The differences in volume growth between these treatments were presumed to reflect the increased vegetation control from more intense mechanical site preparation on competing hardwoods. However, most importantly, this study demonstrated that site preparation, if done properly, could result in a long-term, sustained 38% growth response.

During the 1990s, it was commonly thought subsoiling and tillage were necessary on upland soils to alleviate soil strength, promote root growth, and increase nutrient availability, based on agricultural experiences in the southeastern United States (Kamprath et al. 1979, Vepraskas and Miner 1986). The RW 16, established in 1994, studied the effects of surface and subsurface tillage on growth in 15 studies across three mineralogies: kaolinitic, siliceous, and mixed (Carlson et al. 2008). Surface tillage resulted in a long-term, increasing growth response relative to the control, but differentially among mineralogies (siliceous: 73 ft^3 ac^{-1}; kaolinitic: 57 ft^3 ac^{-1}; and mixed mineralogy: 44 ft^3 ac^{-1}). Conversely, although subsoiling improved survival on Piedmont sites by 8%, volume responses at these sites tended to dissipate by age 6. Overall, the effects of surface and subsurface tillage on stand uniformity were negligible. Volume and uniformity responses from vegetation control and fertilization tended to be greater and much less expensive.

Although these studies concluded nearly 20 years ago and have been published for more than a decade, site preparation-related questions continue to reoccur. These studies provide an immense utility as their long-term data provide robust insight into the effects these inputs have on productivity and continue to address remerging questions.

Midrotation N + P

The RW 13, established in 1984, was a seminal study in that it was the first to determine that there was often a synergistic effect of N and P at midrotation (i.e., the responses to the combined application of N and P were more than the sum of their individual contributions to productivity). When applied together at a rate of 200 lb ac^{-1} elemental N and 25 lb ac^{-1} elemental P, growth responses averaged 50 ft^3 ac^{-1} yr^{-1} and ranged from 27 to 134 ft^3 ac^{-1} yr^{-1} for eight years after the application. When N is applied alone at this same rate, the growth response may only be 12.5 ft^3 ac^{-1} yr^{-1} for eight years (Fox et al. 2006). Specifying these fertilization rates further, it was found that the magnitude and duration of responses to N and P additions varied by the amount added and by the drainage class of the soil (Amateis 2000).

Using RW 13 data, Ducey and Allen (2001) provided an ecophysiological justification of why we need to fertilize with N and P at these quantities, which is to keep up with the estimated system demand of approximately 45 to 90 lb ac^{-1} yr^{-1} of N and 4.5 to 9 lb ac^{-1} yr^{-1} of P. These estimates correlated with previous findings and agreed with later findings, which indicated the critical level for foliar N and P levels are 1.2% for N and 0.12% for P (Wells and Allen 1985, Allen 1987, Jokela 2004, Albaugh et al. 2010a). Logically, fertilization recommendations started to include projected LAI (units of foliage area per unit of ground area) as nutrient availability is an important driver of foliage production (Vose and Allen 1988, Albaugh et al. 1998). A projected LAI threshold for N and P fertilization for fully stocked stands (basal area = 100 ft^2 ac^{-1}) was set at ≤3.5 with the magnitude and duration of the fertilization response expected to be greater with lower LAI (Fox et al. 2011). Estimated thresholds for deciding when to fertilize derived from these studies and others are provided in Table 3.

Table 3. A summary of variables and their estimated thresholds that can be used to detect nutrient deficiencies in loblolly pine in the southeastern United States, indicating the need for fertilization. Site, soil profiles, stocking, and time of year (foliar samples should be collected December 1 through January 31 in the southeastern United States) should also be considered. Importantly, projected leaf area index (LAI) has been found to be a superior predictor of N- and P-deficiencies compared with foliar analyses, and the alleviation of N- and P-deficiencies may accelerate the expression of deficiency in some other limiting nutrient (Albaugh et al. 2010a). A range of values is provided for foliar boron as more empirical work is needed to improve the accuracy of this estimate (Albaugh et al. 2010a). Nutrient limitations are derived from Wells and Allen (1985), Allen (1987), Jokela (2004), and Albaugh et al. (2010a); however, none of the estimated nutrient thresholds for deficiency listed here have been confirmed experimentally, and these are guidelines based on the literature and experience among those with the Forest Productivity Cooperative. The projected LAI threshold is from Fox et al. (2011).

Indicator Variable	Critical Level
Projected LAI	≤3.5 ft^2 ft^{-2}
Crown length	≤25 ft
Foliar nitrogen	≤1.2%
Foliar phosphorus	≤0.12%
Foliar potassium	≤0.38%
Foliar calcium	≤0.15%
Foliar magnesium	≤0.08%
Foliar sulfur	≤0.11%
Foliar manganese	≤30 ppm
Foliar zinc	≤15 ppm
Foliar boron	≤5–8 ppm
Foliar copper	≤2.5 ppm

The strong relationship between LAI and productivity reported by Vose and Allen (1988) led to a simple but powerful concept: Leaves grow trees, resources grow leaves, and silviculture is the manipulation of site resources. This provides the ecophysiological basis for plantation production and has been adapted to a graphical representation (Figure 2).

Early hypotheses among FPC scientists of stand responses to fertilizer N and P additions anticipated a one-year age-shift or acceleration in standwide volume. Carlson et al. (2008) documented that a midrotation fertilization treatment of 200 lb ac^{-1} of N and 25 lb ac^{-1} of P in fact yielded a 2.4-year age shift in volume production, more than twice the expected result. Fox et al. (2006) noted further that 85% of stands in the

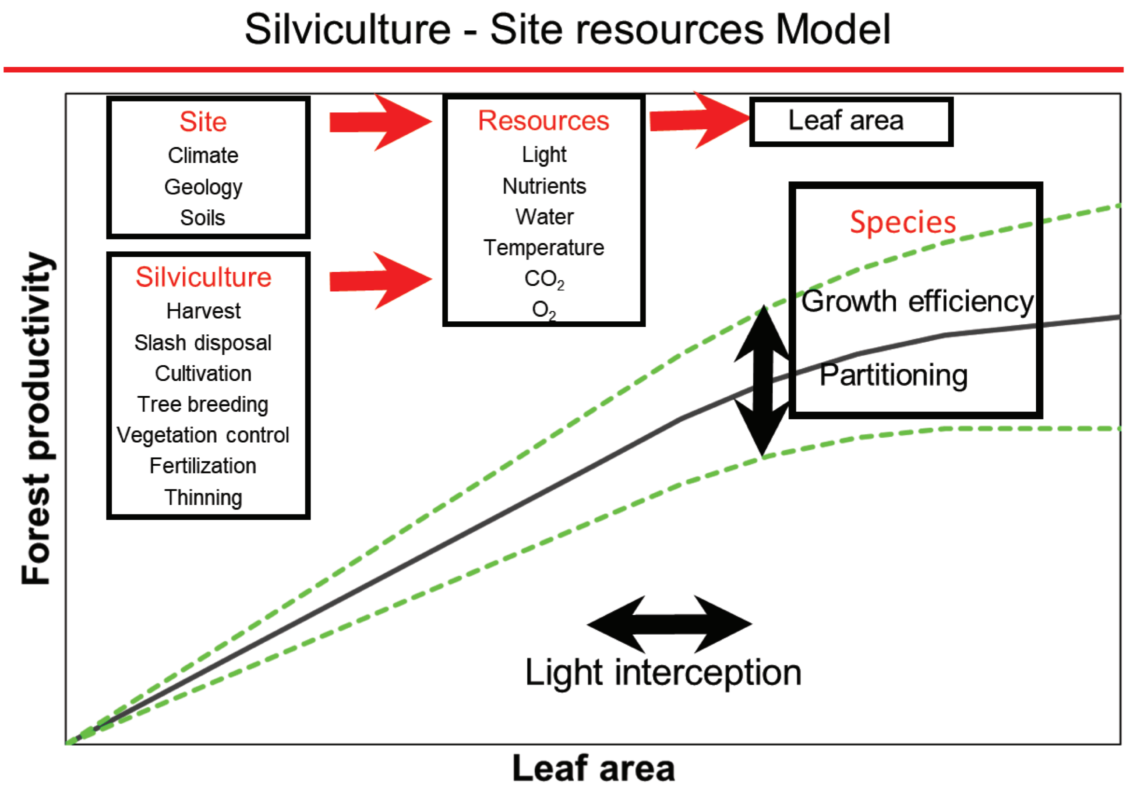

Figure 2. A graphical representation of the ecophysiological basis for plantation production.

southeastern United States respond to N and P at midrotation and sites average an additional 50 ft^3 ac^{-1} yr^{-1} over eight years from one application of 200 lb ac^{-1} of N and 25 lb ac^{-1} of P (Fox et al. 2007).

NPK + Micros

Data from the RWs 2, 9, and 13 indicated that 57% of the studies had K limitations after receiving fertilization treatments and that 20% of these plots were primarily limited by K, not N or P. The results from RWs 14 and 15 further specified where nutrient limitations occurred consistently, and what other limitations, besides just N and P, existed on the landscape. This work demonstrated that the Citronelle Formation (Figure 3; Horton et al. 2017) and associated formations along the Gulf Coastal Plain were consistently P-deficient (Allen 1987, Allen and Lein 1998). The RWs 14 and 15 showed that Pleistocene Terrace sites—the Talbot, Penholoway, Wicomico, Sunderland, and Coharie Terraces of Georgia and the Carolinas (Figure 4), between 30 and 215 ft in elevation—were often K and micronutrient limited (Carlson et al. 2014). Pleistocene Terrace sites, on average, responded 23 ft^3 ac^{-1} yr^{-1} less to N and P additions than other sites (Pleistocene Terrace sites: 38 ft^3 ac^{-1} yr^{-1}; rest of the southeastern United States: 61 ft^3 ac^{-1} yr^{-1}). When NPK (38 + 19 ft^3 ac^{-1} yr^{-1}) and NPK plus the full suite of micronutrients (38 + 37 ft^3 ac^{-1} yr^{-1}; Ca, S, Mg, Fe, Mn, Cu, Zn, B, and Mo) were applied; however, substantial gains in productivity were measured. Importantly, study sites outside of the Pleistocene Terraces did not respond to nutrient additions beyond N and P. These regional differences in nutrient deficiency can further aid in deciding whether to fertilize, in addition to using critical thresholds (Table 3).

Rate and Frequency of Fertilizer Applications

Results from the RW 13 indicated that fertilizer use efficiency was maximized when applied at 100 lb ac^{-1} elemental N and was twice what was measured at 300 lb ac^{-1} (0.4 versus 0.2 ft^3 ac^{-1} yr^{-1} lb^{-1} of applied N). Additionally, the RW 7 and RW 14 results suggested that substantial productivity gains would be forgone if fertilization did not occur before midrotation to maintain higher leaf area levels. Together, this indicated to FPC scientists at the time that the 200N + 25P recommendation for midrotation fertilization, while an acceptable generalized fertilization prescription, could be improved.

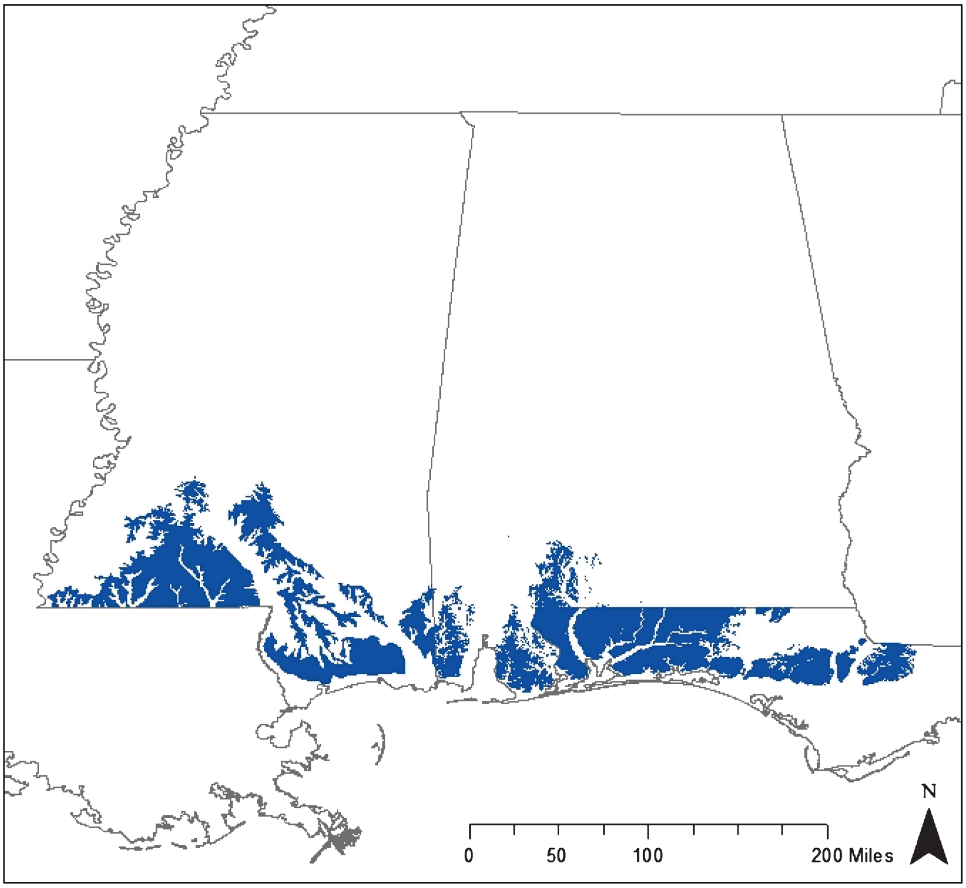

Figure 3. Stands located on the Citronelle Terrace, in blue, are where Forest Productivity Cooperative researchers have consistently found phosphorus deficiencies.

The RW 18 study was developed in 1998 to elucidate the proper rate and frequency of nutrient applications in juvenile pine stands (ages 2 to 6) to maintain rapid growth. This study was composed of 24 trials (23 loblolly pine, 1 slash pine) spread across a range of Coastal Plain and Piedmont sites in the southeastern United States. Researchers sought answers to the following questions: Which sites respond to juvenile fertilization? Does application frequency influence growth responses?

The RW 18 demonstrated that juvenile stands can respond to N and P fertilization (Albaugh et al. 2015). In this study, there were five levels of N and P application rates (0, 60, 120, 180, and 240 lb N ac^{-1}) with P applied at one-tenth the rate of N, and five levels of frequency (none, and every one, two, four, and six years). K, B, Mn, and Mg were added to sites, as needed, on subsequent fertilizations when foliar samples indicated insufficiencies. The magnitude of fertilizer rate response over an eight-year period was site specific depending on soil drainage and texture, where experimental sites on poorly to excessively drained spodic soils or soils without a clay subsoil responded positively up to a dose of 720 lb N ac^{-1} at 180 ft^3 ac^{-1} yr^{-1} while growth reached an asymptote with 267 to 357 lb ac^{-1} of N at 50 ft^3 ac^{-1} yr^{-1} on those soils with a clay subsoil, both poorly and well drained. The frequency of application was not influential in predicting growth, but the cumulative dose was. These juvenile applications did result in high basal area levels that would likely require early thinning treatments to prevent mortality, however.

The RW 18 laid the groundwork for a follow-up study on the carryover effect on P into subsequent rotations, the RW 28 (established in 2019). The hypothesis is the extent to which tree growth in a subsequent rotation responds to P fertilization from the previous rotation will be dependent on the application rates and properties of the soils found on these sites. This RW will further inform P fertilization guidelines at stand establishment.

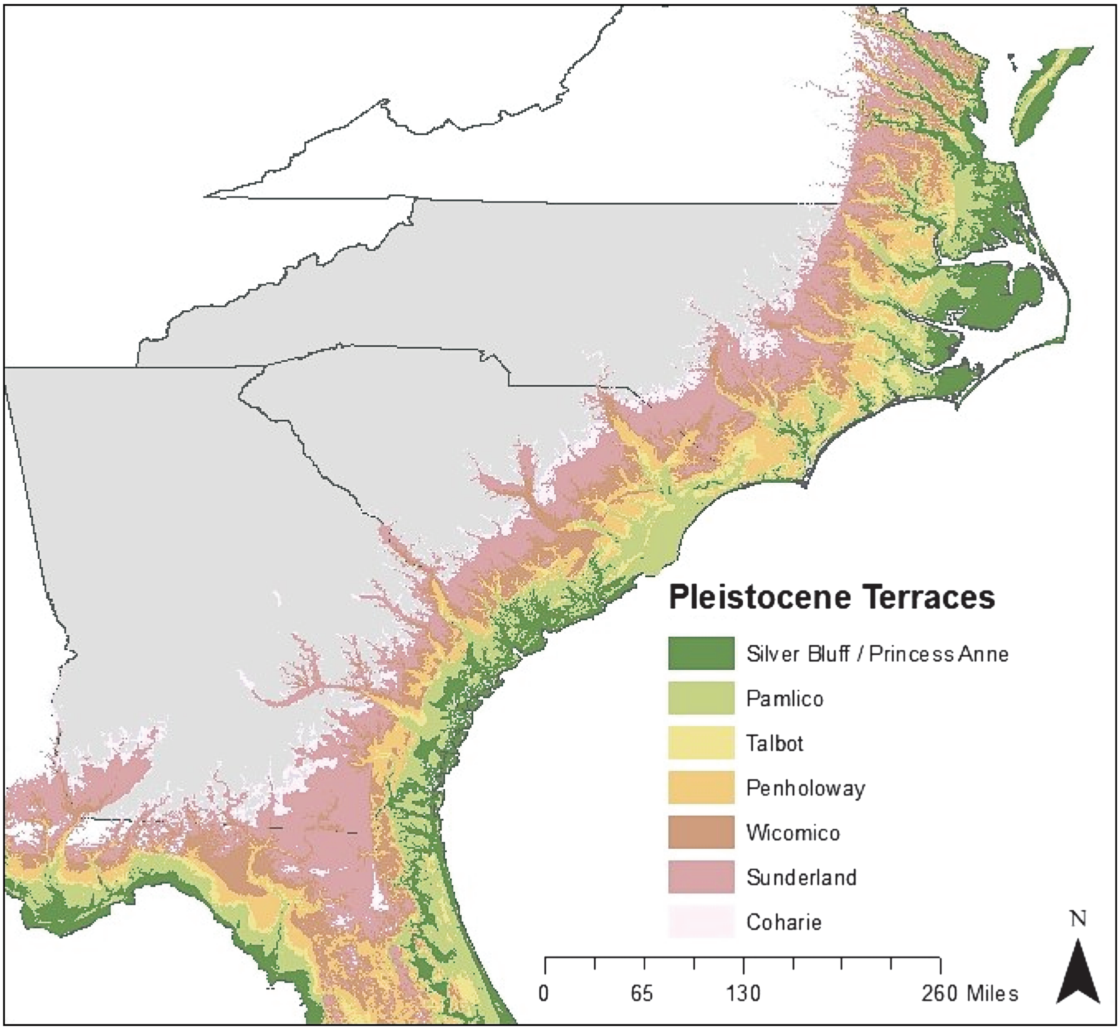

Figure 4. The Pleistocene Terraces along the coast of the southeastern United States are found between 30 and 215 feet in elevation. Loblolly pine on these terraces are found to be limited by nitrogen, phosphorus, potassium, and micronutrients.

Vegetation Control × Fertilization

Although responses to fertilization were becoming clearer, juvenile to midrotation loblolly pine responses to weed control after canopy closure were not well documented in the 1990s, and several questions remained: To what degree does competing vegetation limit pine response to fertilization? Can vegetation control and fertilization substitute for one another? Under complete weed control and fertilization, what is the maximum productivity after ameliorating all growth limitations? In collaboration with the Auburn University Silvicultural Herbicide Cooperative, the RW 17 (established in 1996) investigated the effects of a one-time application of midrotation vegetation control and fertilization in a 2 × 2 factorial across 13 sites, 10 loblolly pine and 3 slash pine (Albaugh et al. 2012).

In general, the combined treatment effects were additive, resulting in the following order of absolute volume response: fertilizer plus vegetation control > fertilizer > vegetation control. Responses varied widely. There was evidence that the duration of the positive response from vegetation control was limited by the regrowth of the vegetation. This diminishing trend was across study sites, demonstrating that a long-term, positive response from a one-time application of vegetation control and fertilization can be elusive, but when complete and sustained weed control is accomplished along with fertilization, it can yield substantial results (Borders and Bailey 2001, Miller et al. 2006).

Thinning × Fertilization

It was long hypothesized among those in the FPC that there would be an interacting effect of thinning

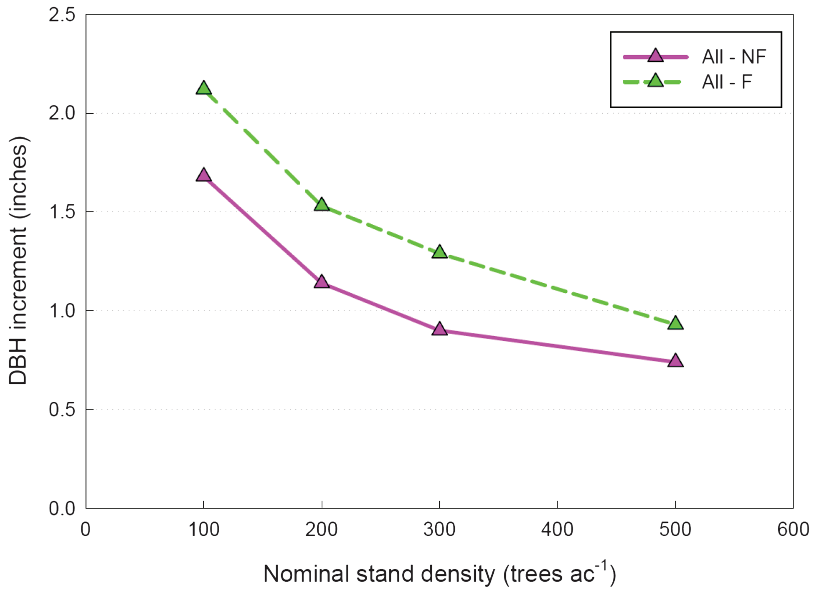

Figure 5. Results from one site in the regionwide 19 thinning × fertilization study. DBH = diameter at breast height; F = fertilized; NF = not fertilized.

and fertilization on diameter growth over different levels of stand stockings: an upward shift in the response curve for the fertilized treatment, relative to the nonfertilized treatment. Insufficient study designs and difficulties in coordinating thinning regimes with landowners yielded inconsistent results from early attempts to test this hypothesis (RWs 5, 9, and 11). The RW 19, however, established in 2006 in collaboration with the Virginia Tech Forest Modeling Research Cooperative, demonstrated the hypothesized effect was possible, on certain sites. Although some sites with an LAI >3.5 ft^2 ft^{-2} prior to treatment were not responsive to the fertilization treatment, those that were yielded the anticipated results (Figure 5). On responsive sites, the annual increment of diameter at breast height (DBH) in the fertilized treatment was found to be generally increasing at an accelerated rate over decreasing levels of stand stockings relative to the nonfertilized treatment three years after treatment installation (Figure 5). The rate of DBH increase between stocking levels (trees per acre [TPA]) was often greater under fertilization (F) compared with nonfertilized (NF): 500 to 300 TPA: F = 0.36-inch increase in DBH versus NF = 0.16-inch increase in DBH; 300 to 200 TPA: F and NF were equal, 0.24-inch increase in DBH; 200 to 100 TPA: F = 0.59-inch increase in DBH versus NF = 0.54 inch increase in DBH. Ultimately, this result means it is possible to accelerate the development of chip-n-saw and sawtimber size classes, although there is a tradeoff between individual tree volume growth and stand-level volume growth and its value (Albaugh et al. 2018).

FPC in South America

Nearly 30 years ago, Cartón de Colombia joined the FPC, marking the beginning of the FPC's international reach. Today, 15 South American companies or domestic companies with South American landholdings are members of the Cooperative in Colombia, Chile, Argentina, Brazil, Uruguay, and Venezuela. As this membership has expanded, so too have the research efforts, as nearly as many RW plots have been installed in South America with consistent experimental designs as those found in North America. RW trials 21 through 27 are unique to South America. Some of the most recent advancements made by the FPC in South America have been reviewed by Rubilar et al. (2018) and will not be further discussed here given this review's focus on the United States. The U.S. members of the FPC have benefited from the scientific imports born from this international partnership, showing the value of research collaboration on fundamental questions into applied research.

South America has presented a great opportunity to learn from short rotation, clonal plantations. Additionally, the rapid growth rates experienced in South America (570 ft^3 ac^{-1} yr^{-1} versus 215 ft^3 ac^{-1} yr^{-1} in the United States; Albaugh et al. 2018) mean the research yields answers to stand developmental questions and long-term sustainability more quickly than they could be answered here in the United States.

The RW 20 was established in 2007 to address questions regarding optimal management of clonal varieties of loblolly pine compared with open- or control-pollinated growing stock. The study is also intended to increase our understanding of the mechanistic underpinnings responsible for the greater growth rates and carrying capacities experienced in South America. Plantations were established in Virginia, North Carolina, and Brazil examining genetics × silviculture × spacing interactions (for details, see Vickers et al. 2012). This experimental design provides unique insight into the effects of environmental variables across these three locations by using the same genetic entries across all three sites. Today, these trials are at midrotation and have been the focus of intense study. We have measured peak LAIs and stem volume growth rates in Brazil (LAI of 7.5 and 500 ft^3 ac^{-1} yr^{-1}) that are more than double of what is measured in the United States (LAI of 3.5 and 250 ft^3 ac^{-1} yr^{-1}). To date, results from studies exploring the mechanisms behind the accelerated growth rates found in Brazil indicate that differences in leaf area distribution, specific leaf area, crown architecture (Albaugh et al. 2020), and Brazil's relatively mild climate (Albaugh et al. 2018) contribute to growth rates observed in Brazil. Conversely, foliage longevity (Albaugh et al. 2010b) and light-use efficiency (Albaugh et al. 2018) have been found to not differ among sites. Additional questions regarding soil microbial communities, foliar acclimatization, and diffuse light levels, among others, are expected to be answered before the study concludes. The possibility exists that differences among sites could inform management in the United States to further increase loblolly pine productivity, domestically.

The "Lost" RW Trials

Several early RW trials did not yield publishable results. During this time, FPC scientists were developing methods for field experimental design for pine plantations. Proper measurement and treatment plot size, buffer sizes, and coordination among members were developed through an iterative process. Today, thanks to the work of previous researchers, the FPC has streamlined this process and produced widely repeatable study designs that provide robust inference. These study designs are considered an additional export among our bundle of goods available to domestic and international members.

FPC Products and Future Directions

Over the last 50 years, the FPC has installed 28 RW trials, with 327 installations in North America and 271 installations in South America. This prolific research has yielded 125 graduate students (57 PhDs, 66 Master of Science degrees, 2 Master of Forestry), 534 peer-reviewed publications, and numerous theses and dissertations. Additionally, the FPC has and continues to provide professional workshops where research is disseminated to professionals. During this time, the FPC also participated in or took the lead of key research programs including the National Acidic Precipitation Assessment Program (NAPAP); the Southern Global Climate Change Program; the Pine Integrated Network: Education, Mitigation, Adaptation Project (PINEMAP); the National Science Foundation's Center for Advanced Forest Systems; the Chilean Woody Biomass & Bioenergy Consortium (BIOENERCEL); and the Eucalyptus Water Sustainability Project (EUCAHYDRO). These activities kept the program at the forefront of scientific research and leveraged the value of the FPC-member-installed research trials.

During this time, the FPC has withstood personnel changes, market fluctuations, natural disturbances, corporate restructuring, and globalization. We remain committed to exploring new methods and technologies, from remote sensing to stable isotopes, to manage site resources more precisely and accurately at multiple spatial scales. Our research intentions are to usher in new solutions to the issues faced by the forest products industry, today and in the future, and find new ways to sustainably increase productivity in intensively managed plantations in the southeastern United States and beyond.

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