Available online at www.sciencedirect.com
ScienceDirect
Biomass and Bioenergy 30 (2006) 1001–1010
BIOMASS & BIOENERGY
www.elsevier.com/locate/biombioe

Energy trade-offs between intensive biomass utilization, site productivity loss, and ameliorative treatments in loblolly pine plantations

D. Andrew Scott[a,*], Thomas J. Dean[b]

[a]*Southern Research Station, USDA Forest Service, 2500 Shreveport Highway, Pineville, LA 71360, USA*
[b]*Louisiana State University Agricultural Center, Louisiana State University, Baton Rouge, LA 70803, USA*

Received 9 December 2004; received in revised form 5 May 2005; accepted 12 December 2005
Available online 2 October 2006

Abstract

Loblolly pine plantations are the most important source of forest products in the US and the slash remaining after conventional harvest represents a significant potential source of bioenergy. However, slash removal in intensive harvests might, under some circumstances, reduce site productivity by reducing soil organic matter and associated nutrients. Two complimentary studies in the Gulf Coastal Plain of the southeastern US were designed to test whether harvest intensity (level of biomass removal) could have a negative long-term impact on site productivity. Harvesting tree crowns in addition to the merchantable bole had a negative impact (18%) on pine biomass accumulation by age 7–10 years on 15 of 19 research blocks. Sites at risk of harvest-induced reductions in productivity were relatively unproductive prior to harvest and had low soil phosphorus (P) concentrations. Intensive harvesting, fertilization, and chemical control of non-crop vegetation were all energy efficient; the additional biomass energy gained through these practices was two-orders of magnitude greater than the energy needed to conduct the activities. Harvest of slash for bioenergy in the Gulf Coastal Plain of the southeastern US has the potential to reduce productivity on infertile soils, but fertilization has the potential to restore and even improve productivity on those sites in an energy-efficient way.
Published by Elsevier Ltd.

Keywords: Bioenergy; Whole-tree harvesting; Energy efficiency; Fertilization; Long-term soil productivity

1. Introduction

In southeastern US pine forests, over 100 MWh ha^{-1} of potential bioenergy remains on-site as tree tops and slash after harvesting operations. Additionally, many stands throughout the Southeast are overstocked and in need of thinning to improve productivity and reduce fire danger, but thinning is often delayed due to a lack of commercial value. Biomass energy is a potential market for such stands. However, tree crowns and small-diameter trees contain a disproportionately greater quantity of site nutrients compared to their biomass, and the removal of these small trees and tree crowns may reduce long-term site productivity. Furthermore, in many commercial harvesting operations in the southern pine region, whole-tree harvesting occurs by default since much of the tree crown biomass and slash is often concentrated near landings, even when efforts are made to redistribute the material through the stand.

The southern pine region of the US encompasses over 36 million ha [1] and accounts for almost 60% and 16% of the industrial wood production in the US and the world, respectively [2], yet little research has been conducted to determine the impact of whole-tree harvesting on long-term site productivity in this region. Several studies have been conducted in diverse locations throughout the world to document the impacts of forest harvesting on soil nutrient pools and processes, but few have documented its impact on long-term site productivity in a way that is clear and not confounded with climate, soil physical disturbances, and competing vegetation [3,4].

*Corresponding author. Tel.: 1 318 473 7204; fax: 1 318 473 7273.
E-mail address: andyscott@fs.fed.us (D. Andrew Scott).

0961-9534/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.biombioe.2005.12.014

Forest industry and some private landowners routinely improve forest productivity through fertilization, physical site preparation, and chemical competition control, whereas public forest management agencies and many non-industrial private landowners manage their lands by relying on inherent site productivity. Land managers that do not ameliorate site productivity constraints face the risk that the cumulative impacts of harvesting biomass during thinnings and final harvests might reduce site productivity. Managers capable of offsetting nutrient depletions with fertilization could be well served by understanding the energy efficiency of fertilization to facilitate continued economic efficiency and by recognizing how the practices affect carbon sequestration.

In the 1990s, two studies were initiated in the Gulf Coastal Plain of the southeastern USA to address the general impacts of forest management practices on soil, site, and forest productivity. The first study was installed as part of a nationwide USDA Forest Service program called the Long-Term Soil Productivity (LTSP) study [3] that now includes 62 sites in the USA and Canada. Its main objectives were to (1) determine if organic matter removal and soil compaction at harvest had lasting impacts on site productivity, (2) determine if impacts were universal, regional, or site-specific, and (3) to develop, validate, and verify monitoring criteria to ensure that site productivity was maintained. A secondary objective was to assess the influence of competing vegetation on treatment responses and site productivity. The study was installed between 1990 and 1997 at 13 locations in the southeastern USA, with 10 of the locations in the Gulf Coastal Plain region (Fig. 1). In 1994, a regional cooperative study was initiated by researchers from the Louisiana State University Agricultural Center, the USDA-Forest Service, and several forest industry companies to extend the LTSP design and to answer more applied questions regarding the impact of operational harvesting practices and various cultural treatments [5]. This study, named Cooperative Research in Sustainable Silviculture and Soil Productivity (CRiSSSP), has grown to six installations in the Gulf Coastal Plain (Fig. 1).

These two cooperative studies encompass 29 replicate blocks in nine individual studies in four southern states (Fig. 1). Three soil orders are represented (Alfisols, Ultisols, and Vertisols) (Table 1). All sites are moderately well to somewhat poorly drained and lie within the southern Coastal Plain physiographic province. Precipitation ranges from 1676 to 1191 mm, near the lower limit for commercial loblolly pine (*Pinus taeda* L.). Native vegetation on the sites would have been either longleaf (*Pinus palustris* L.), loblolly, or loblolly and shortleaf (*Pinus echinata* P. Mill.) pines with associated understory plants. These studies represent the largest sub-regional study of the potential impacts of bioenergy production on potential soil productivity in the USA.

The objectives of this paper are to: (1) determine if harvest intensity has an impact on the early productivity of loblolly pine stands in the Gulf Coastal Plain; (2) determine if productivity responses were related to easily measured and monitored site variables; and (3) analyze the relative energy balance of stem-only versus whole-tree harvesting, fertilization, and chemical competition control in Gulf Coastal Plain southern pine forests. For this paper, productivity is defined as cumulative crop tree biomass.

2. Materials and methods

2.1. Study 1: Long-Term Soil Productivity study

2.1.1. Site descriptions

Ten locations of the LTSP study are located in the humid-temperate-subtropical Southern Mixed Forest or

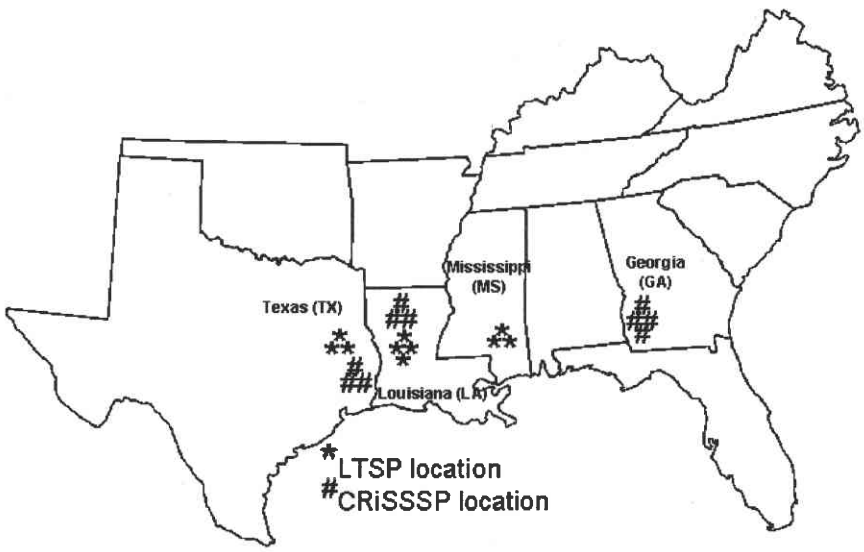

Fig. 1. Study locations of LTSP and CRiSSSP installations in the Gulf Coastal Plain of the southern USA.

Table 1
Site and soil characteristics of 13 harvesting impact study sites in the Gulf Coastal Plain

Study site[a]	Latitude/longitude	Precipitation (mm yr^{-1})	Soil series	Soil suborder
LA 1	31.0 N/92.7 W	1524	Malbis	Fine-loamy, siliceous, subactive, thermic Plinthic Paleudults
LA 2	31.3 N/92.5 W	1473	Glenmora	Fine-silty, siliceous, active, thermic Glossaquic Paleudults
LA 3	31.3 N/92.5 W	1473	Metcalf	Fine-silty, siliceous, semiactive, thermic Aquic Glossudalfs
LA 4	31.3 N/92.5 W	1473	Mayhew	Fine, smectitic, thermic, Chromic Dystraquerts
MS 1-3	31.5 N 88.9 W	1498	Freest	Fine-loamy, siliceous, active, thermic Aquic Paleudalfs
TX 1-3	31.1 N/95.1 W	1191	Kurth	Fine-loamy, siliceous, semiactive, thermic, Aquic Glossudalfs
Bainbridge, GA	30.9 N/84.7 W	1668	Hornsville	Fine, kaolinitic, thermic, Aquic Hapludults
Bryceland, LA	32.4 N/90.8 W	1372	Mahan	Fine, kaolinitic, thermic Typic Hapludults
Fred, TX	30.6 N/94.4 W	1364	Kirbyville	Fine-loamy, siliceous, semiactive, thermic, Oxyaquic Paleudults

[a]LTSP sites are known by their state abbreviation, i.e., LA 1 is Louisiana site 1, MS 2 is Mississippi site 2, etc. The CRiSSSP sites are known by the closest town to the study sites, i.e., Bainbridge, Georgia; Bryceland, Louisiana; Fred, Texas.

Outer Coastal Mixed Forest Province [6] (Fig. 1). Four sites were installed in the Kisatchie National Forest in Louisiana, and three sites each were installed in the DeSoto National Forest in Mississippi and in the Davy Crockett National Forest in Texas. The soils were Ultisols and Alfisols commonly found on Coastal Plain uplands and terraces formed from marine and alluvial sediments (Table 1). All soils were loams or silt loams over heavier textured subsoils. The understory on the Louisiana and Texas plots was characterized by shrubs and small trees common across much of the southern Coastal Plain, including sweetgum (*Liquidambar styraciflua* L.), wax myrtle (*Myrica cerifera* L.), yaupon holly (*Ilex vomitoria* Ait.), and assorted oaks (*Quercus* spp.). The understory in Mississippi was dominated by gallberry (*Ilex glabra* L.).

2.1.2. Experimental design

At each site, nine treatments were imposed in a 3×3 factorial design following a clear-cut harvest of the existing stand, with organic matter removal and compaction as the main treatment factors. The three organic matter removal treatments were stem-only harvest, whole-tree harvest, and whole-tree harvest plus forest floor removal. Compaction was evaluated with plots with no compaction (no mechanical equipment allowed on plots during harvesting), moderate compaction, and severe compaction, the latter defined as 80% of the root-growth limiting bulk density as determined from soil texture [7]. Moderate compaction was defined as the geometric mean bulk density between no compaction and severe compaction. The two compaction levels were induced by pulling a multi-tire road compactor with 2 levels of ballast across the sites six times, which increased bulk density and soil strength substantially well below planting depth (unpublished data). After treatments, containerized loblolly pine seedlings were planted at a 2.5×2.5-m spacing. Each 0.4-ha treatment plot was split into two 0.2-ha subplots, one of which was kept clear of competing vegetation by manual removal and directed-spray herbicide applications (primarily glyphosate, imazapyr and/or sufometuron, depending on site and vegetation). Competing vegetation was allowed to grow freely on the other subplot. Volunteer pines were removed on all plots. Measurement areas were the interior 0.1 ha of each subplot.

On an extra plot at one Mississippi (MS 3) and two Louisiana locations (LA 1, LA 3), conventional whole-tree harvesting was conducted, and then 280 kg ha^{-1} of diammonium phosphate (18% N, 46% P_2O_5, 0% K_2O) was applied to half of each 0.4 ha plot at age 3, supplying 50 kg nitrogen (N) ha^{-1} and 56 kg P ha^{-1}.

2.1.3. Measurements

Prior to harvest, stand inventories were taken and biomass of all pine and hardwood stems and pine tree crowns determined. Heights of dominant and co-dominant trees at age 25, i.e., site index, were determined from stem analysis [8] of at least 10 trees per site. After planting, we measured tree height and diameter at breast height in the 0.1-ha measurement plot with laser hypsometers and calipers. Stand biomass (bole and crown including bark) was calculated using stem [9] and crown [10] equations. Prior to study establishment, five soil samples were collected to 15 cm with a push probe sampler on each of 3 transect lines across each measurement plot and bulked by transect line. Mehlich III available soil P [11] and exchangeable calcium (Ca), magnesium (Mg), and potassium (K) [12] were determined for each sample with a Hewlett-Packard 8453 colorimetric spectrophotometer and a Perkin-Elmer 2100 Atomic Absorption spectrophotometer, respectively.

2.2. Study 2: Cooperative Research in Sustainable Silviculture and Soil Productivity

2.2.1. Site descriptions

Six installations of the CRiSSSP study were installed in the western Gulf Coastal Plain from 1995 to 2004. Unlike the LTSP study, in which individual blocks were not contiguous with each other, the three blocks of each CRiSSSP installation were all located in a contiguous area. Data from the three oldest installations are used for this paper. The three sites were located on dissimilar site types: an upland old-field site near Bainbridge, Georgia; an upland cutover site near Bryceland, Louisiana; and a wet

site near Fred, Texas. These sites were located within the same ecoregions as the LTSP sites, and the understories were similar to the Louisiana and Texas LTSP sites, except at the Georgia site, which had only grasses due to recent agriculture.

2.2.2. Experimental design

The CRiSSSP installations were similar to the LTSP installations in that the main two treatments were organic matter removal and compaction. However, instead of applying these two treatments factorially, they were applied simultaneously to simulate the extremes of operational forest harvest practices. The minimum disturbance treatment consisted of hand-felling the trees with power saws and lifting the merchantable stems from the treatment plots by hand or with cranes. The maximum disturbance treatment used mechanical feller-bunchers and grapple skidders to harvest the entire tree. Therefore, the stem-only and whole-tree organic matter removal treatments were confounded with operational soil compaction. After harvest, each disturbance level was treated in a factorial manner with one of three or four cultural treatments: chemical control of woody and/or herbaceous vegetation, fertilization, prescribed burning, and bedding. At each site, the "control" site preparation was a single aerial broadcast herbicide prior to planting. The plots on the Texas and Louisiana sites were 0.14 ha in size planted at a 2×3 m spacing; plots at the Georgia site were 0.26 ha and planted at a 2.4×2.4 m spacing. Only data from the "control" plots, i.e. herbicide only, were used for this paper.

2.2.3. Measurements

Tree heights and diameters were measured with height poles and diameter tapes, on all measurement trees at the Georgia site at age 7 years. At the Louisiana and Texas sites, height was measured on all trees and diameter on a 20-tree subplot at age 7 years. Biomass was estimated as described for the LTSP study sites.

2.2.4. Statistical analysis

Analysis of variance was used to compare the main effects of harvest intensity and weed control on biomass response in the LTSP study, and Duncan's Multiple Range Test was used to separate means. Because the whole-tree + forest floor removal treatment in the LTSP study was implemented in order to create a greater range of organic matter removal rather than simulate an actual biomass for energy harvest, only the biomass responses of the stem-only and whole-tree treatments were analyzed. The means for harvest treatment and weed control were compared across all three levels of compaction, which had no significant main or interaction effect on biomass production at $P<0.05$ (data not shown). Linear regression analysis was used to compare the relative biomass response of whole-tree and stem-only treatments to the pre-harvest site index, mean annual increment (MAI) of the pine and hardwood stems, and soil nutrients. The main effects of the minimum disturbance and maximum disturbance harvest intensity treatments on the CRiSSSP sites were compared using analysis of variance. Only plots receiving the null cultural treatment and no fertilizer were analyzed to focus on the harvest intensity effect.

2.3. Energy balance

Energy balances were determined for harvesting intensity, herbicide application, and fertilization from published values for each and several assumptions to limit the scope of the analysis to directly observable sinks. The energy value for pine wood biomass was assumed to be 20.3 GJ Mg^{-1} and converted to MWh using a factor of 0.27778 MWh GJ^{-1}. The energy required to manufacture and apply an average pesticide is 0.07 MWh kg^{-1}(263 MJ kg^{-1}). The energy required to produce, package, transport, and apply P and N fertilizer is 0.0021 MWh kg^{-1} (7.565 MJ kg^{-1}) and 0.022 MWh kg^{-1} (78.1 MJ kg^{-1}), respectively [13].

Although weed control was applied to half of all main plots on the LTSP sites and fertilizer was applied at three sites on extra plots, the plot at LA 3 was located in an area not representative of the study site, and as such had less than half the biomass as the other plots on the site (data not shown), and was determined to have little value for this exercise. Similarly, the plot at MS 3 was suspect due to changes in the plot design at the time of fertilizer treatment that precluded accurate data collection. Therefore, the energy balance was calculated using only data from LA 1, which was moderately productive and had moderate responses to treatments. Herbicide (glyphosate) was applied annually at approximately 1 kg ha^{-1} for about 5 years, which took, based on the preceding assumptions, 0.35 MWh ha^{-1}, which was rounded to 1 MWh ha^{-1} for convenience and conservatism. The fertilizer application of 50 kg ha^{-1} N and 56 kg ha^{-1} P on the extra LTSP plots similarly amounted to approximately 1.2 MWh ha^{-1}. While the CRiSSSP studies also included herbicide and fertilizer treatments, the variation in treatments, younger age of the stands, and smaller plot sizes made similar energy balances difficult to achieve and compare.

3. Results and discussion

3.1. Site productivity

Prior to study establishment, the sites ranged in productivity from 2.2 Mg ha^{-1} yr^{-1} of pine stem biomass on the Mississippi LTSP blocks to 7.0 Mg ha^{-1} yr^{-1} on the Georgia CRiSSSP site, and ranged in age from 27 years at the Texas CRiSSSP site to 57 years on the Texas LTSP sites (Table 2). Hardwood biomass ranged from 0 Mg ha^{-1} on the Georgia CRiSSSP site and on one Louisiana LTSP sites (LA 1) to 72.7 Mg ha^{-1} on another of the Louisiana LTSP sites (LA 4) (data not shown). The Georgia CRiSSSP site had no hardwood biomass because it had previously been

Table 2
Harvested stand biomass (Mg ha^{-1}) on seven replicated harvest impact studies sites and early growth responses

Study site	Pre-harvest site biomass			Post-harvest growth response		
	Age (yr)	Stem (Mg ha^{-1})	Crown (Mg ha^{-1})	Age (yr)	Stem-only[a] stand biomass (Mg ha^{-1})	Whole-tree stand biomass (Mg ha^{-1})
Louisiana	50	151.1	20.0	10	49.1a[b]	45.2a
Mississippi	56	123.9	21.0	10	39.1a	28.7b
Texas	57	202.2	20.6	5	3.0a	2.2b
Bainbridge, GA	30	210.1	28.2	7	23.9a	21.6a
Bryceland, LA	31	118.6	11.4	7	30.0a	22.4a
Fred, TX	27	104.8	18.3	7	18.1a	20.8a

[a]Stem-only and whole-tree treatments on the Louisiana, Mississippi, and Texas LTSP sites were averaged across three levels of soil compaction, which had no significant main or interaction effect, and confounded with soil disturbance on the Bainbridge, Bryceland and Fred CRiSSSP sites.
[b]Means within a row followed by the same letter are not significantly different at $P<0.05$.

an old-field site, whereas LA 1 had no hardwoods due to frequent burning and cattle grazing.

The pine tree crown biomass was quite similar across all the LTSP study sites (Table 2), averaging 20.5 Mg ha^{-1} (115 MWh ha^{-1}) across all three states despite an almost 50 Mg ha^{-1} variation in merchantable stem biomass. The three industry study sites had more variability in the amount of wood available for energy, ranging from 11.4 Mg ha^{-1} (64.4 MWh ha^{-1}) to 28.2 Mg ha^{-1} (159 MWh ha^{-1}). The relative variability was due to stand age, history, and productivity. The LTSP sites were fully mature sites over 50 yr old (except for LA1, which was 37 yr old), all had been thinned twice previously, and ranged in pine biomass productivity from 2.2 to 3.6 Mg ha^{-1} yr^{-1}. The CRiSSSP sites, however, ranged in age from 27 to 31 yr and productivity from 3.8 to 7.0 Mg ha^{-1} yr^{-1} and were either thinned once (Texas and Georgia sites) or thinned twice (Louisiana site). Across all sites, however, the biomass available for energy averaged 19.3 Mg ha^{-1} (115 MWh ha^{-1}), similar to the LTSP mean. These values are also quite similar to the 19.9 Mg ha^{-1} reported for a 22-yr-old loblolly pine stand in the Piedmont of North Carolina [14] and 17.5 for a 22-year-old loblolly pine in the Coastal Plain of Alabama [15].

3.2. Biomass response to harvest intensity

The biomass response to the stem-only and whole-tree harvest treatments on the LTSP study sites varied widely. Whole-tree harvesting resulted in biomass growth reductions compared to stem-only harvested treatments on eight of 10 locations, ranging from −17% at LA 1 to −56% at one of the Texas LTSP sites (TX 1) (Fig. 2). The average biomass growth reduction for the eight sites exhibiting a loss was 27%. Across the Louisiana LTSP plots, the relative biomass growth response of whole-tree harvested plots compared to the stem-only harvested plots varied from a 9% (4.0 Mg ha^{-1}) increase in biomass on LA 3 to a 25% loss (11.6 Mg ha^{-1}) on LA 2. On average, however, the treatments did not affect biomass response on the Louisiana LTSP sites at $p<0.05$ (Table 2). On the Mississippi sites the whole-tree harvested plots averaged

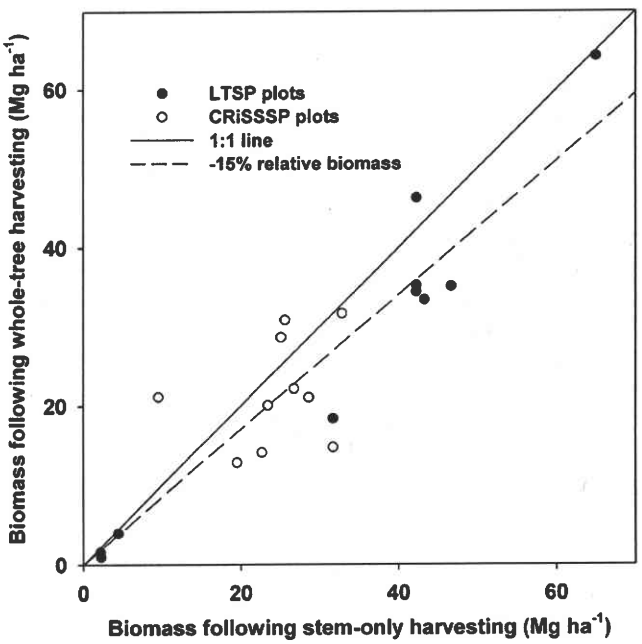

Fig. 2. Comparison of biomass growth following stem-only and whole-tree harvesting across 20 replicate blocks of the LTSP and CRiSSSP studies in the Gulf Coastal Plain.

26% less biomass at age 10 than the stem-only harvested treatments. The stem-only plots at the Mississippi sites were relatively unproductive, producing only 39.1 Mg ha^{-1}. In Texas, where the LTSP stands had reached only their fifth year of growth, harvesting the crowns also reduced biomass growth response by 26%. Responses at both the Texas and Mississippi LTSP sites were significant at $p<0.05$. Across the 10 LTSP locations, only the LA 3 location had a positive relative biomass response to whole-tree harvesting. The LA 4 location showed no difference in response between the harvesting treatments.

On the CRiSSSP sites, whole-tree harvesting had negative impacts on biomass growth compared to stem-only harvesting on seven of 10 replicate blocks ranging from −53% on the Louisiana site, block 1 to −3% on the Louisiana site, block 4 (Fig. 2). On these seven blocks, whole-tree harvesting reduced productivity compared to

stem-only harvesting by an average of 33%. Harvesting intensity with the null site preparation treatment had no statistically significant impact on biomass growth at any site (Table 2). The Texas site had two blocks that exhibited positive responses to whole-tree harvesting relative to stem-only harvesting, as evident from the site means (Table 2). However, one block had a positive relative biomass growth increase on the whole-tree harvested plot compared to the stem-only harvested plot of 130%. The stem-only harvested plot had less than half the biomass of any other plot studied at that site, indicating that factors other than the treatment effect on soil quality, such as survival, were probably important on these plots. Whole-tree harvesting has been linked to improved survival in other studies, especially on productive sites, where remaining slash is an impediment to planting and can immobilize nutrients [16].

For all six LTSP and CRiSSSP study sites encompassing 20 replicate blocks, harvesting logging slash through whole-tree harvesting reduced site productivity by an average of 12% compared to stem-only harvesting, with a reduction on 16 of the 20 blocks (Fig. 2). Excluding the one extraordinary block, the average response was a 19% reduction. The USDA Forest Service defines a significant reduction in productivity as a 15% reduction [17]. On this basis, whole-tree harvesting caused significant reductions in productivity on 14 of the 20 blocks studied. It is unknown at this early stage whether these productivity declines will continue throughout the end of the planned rotation, which ranges from 25 years on industry sites to 60 years on the LTSP plots. The longevity of the declines is probably related to the causes of the decline. As with fertilization-caused growth gains, growth losses caused by reductions in N availability may follow a Type I response [18,19]; N can be renewed over time from deposition and fixation, although the net increase or decrease in available N is subject to a myriad of climatic, site, and management factors. Growth losses caused by reductions in nutrients with small external inputs, i.e., P and cations may be long-term and follow a Type II response [18,19]. Furthermore, the responses to harvest intensity were quite variable across these sites, especially on the operational CRiSSSP sites. Monitoring commercial operations will be quite difficult given the relative effect of specific soil nutrients and variable responses; this underscores the importance of the rigorously designed LTSP study for determining monitoring surrogates and criteria.

While studies have reported the nutrient budgets following whole-tree harvesting of southern pine sites [20], few have reported on the impacts of harvest intensity on the subsequent rotation. Other studies in the southeastern USA that reported on the growth of the subsequent rotation include a study of several harvest intensity and site preparation treatments on multiple-rotation growth of loblolly pine on the Coastal Plain of Alabama [15], an additional LTSP study on the Coastal Plain of North Carolina, and a study of stem-only and whole-tree harvesting on the Piedmont of South Carolina [21]. Data have not been reported for the relative impact of harvest intensity on productivity on the Alabama study site, but nutrient uptake was substantially lower in the second rotation compared to the first rotation [15]. The North Carolina LTSP plots, which are also located on Coastal Plain soils, have shown no significant losses in productivity due to whole-tree harvesting, although soil nutrient concentrations in the upper 10 cm of soil were reduced significantly following whole-tree harvesting [22]. The study on the Piedmont site exhibited a 17% loss in volume production on the whole-tree harvested plots compared to stem-only harvested plots at age 16 [23]. The same site had a 23% reduction in productivity at age 5 [21], indicating the loss of productivity may indeed be long-term. On this Piedmont study, one cause given for the loss of productivity was the abundance of herbaceous and woody competition on the site [21], but this is indicative of a reallocation of site resources to non-crop vegetation and not a reduction in site productivity.

Non-crop competition had substantial impacts on crop tree productivity on the Louisiana and Mississippi LTSP sites and affected the biomass response to harvest intensity treatment on the Mississippi plots (Table 3). Stand biomass was 20.7 and 13.3 Mg ha^{-1} (56 and 49%) greater in the sub-plots in Louisiana and Mississippi, respectively, that were treated with herbicides relative to untreated subplots. In Louisiana, the stem-only and whole-tree harvests reduced productivity equally, although not significantly at $P<0.05$. On the Mississippi plots, the sub-plots with no competition control had a 12% reduction in biomass response due to the whole-tree harvest, whereas the split-plots with weed control had a 30% reduction in biomass production. On the Texas LTSP sites at age 5, no differences were detected in the weed control effect or for the weed control by harvest intensity interaction. Based on this information, the results from the Gulf Coastal Plain LTSP sites indicate that factors in addition to understory competition have reduced productivity following whole-tree harvesting.

Table 3
Impact of chemical vegetation control on biomass response to whole-tree and stem-only harvesting on the Gulf Coastal Plain LTSP sites

Location	Understory vegetation	Pine biomass (Mg ha^{-1})		
		Stem-only	Whole-tree	Mean
Louisiana	Natural vegetation	38.4 Ba[a]	35.2 Ba	36.8 B
	Chemical control	59.7 Aa	55.3 Aa	57.5 A
Mississippi	Natural vegetation	30.6 Ba	23.9 Bb	27.3 B
	Chemical control	47.6 Aa	33.6 Ab	40.6 A
Texas	Natural vegetation	2.87 Aa	1.99 Aa	2.43 A
	Chemical control	3.07 Aa	2.41 Aa	2.74 A

[a]Means within columns followed by the same capital letter are not significantly different at $P<0.05$. Means within rows followed by the same lowercase letter are not significantly different at $P<0.05$.

3.3. Site gradients and biomass response to harvest intensity

Because the seven LTSP locations in Louisiana and Mississippi had all reached their tenth year following treatment and had exhibited diverse responses to treatment, we conducted additional analyses on these sites to identify site characteristics indicative of potential productivity declines.

At age 5 years, productivity loss due to whole-tree harvesting was clearly related to site factors that affected the inherent site productivity; productivity loss on the whole-tree harvested plots was greatest on the sites that had the lowest inherent productivity [22]. However, this measure would not be useful in assessing stands prior to harvest for potential declines. Site index values are commonly used to assess potential productivity and are thought to be more indicative of actual site quality than biomass or volume production measures. The relative crop tree biomass response of whole-tree-harvested plots compared to stem-only-harvested plots was not linearly related to the pre-harvest site index on these sites (Fig. 3). The general trend was for the sites with the highest site index (MS 1–3) to exhibit the greatest productivity loss following whole-tree harvesting. Site index, at least on these sites, was not indicative of biomass production at harvest, nor regenerating biomass production.

The relative biomass response was positively linearly related ($p<0.04$, $R^2=0.62$) to the pre-harvest MAI (Fig. 4) on six of the seven sites. The relationship between the pre-harvest MAI and the potential productivity loss provided an excellent method to assess stands of similar ages and structures for their susceptibility to productivity loss by whole-tree harvesting. It appears from our analysis that mature sites with MAI less than $3\,Mg\,ha^{-1}\,yr^{-1}$ may be susceptible to significant losses in productivity due to whole-tree harvesting as compared to stem-only harvesting. Because these stands were mature and well past the culmination of MAI, $3.0\,Mg\,ha^{-1}\,yr^{-1}$ is valid only for stands of similar age (37–56 yr in this study). Relationships could be determined to relate the site productivity of stands at other stages of development to their suitability for whole-tree harvest. In Sweden, where logging slash is bundled and harvested specifically for energy wood, logging contractors assess the feasibility of slash harvesting during the harvesting operation (Swedish logging contractor, personal communication). If the stands are relatively unproductive, the logging contractors do not pile the slash for harvest, thus maintaining the nutrients and organic matter to conserve site quality. A similar system may work for southern pine plantations.

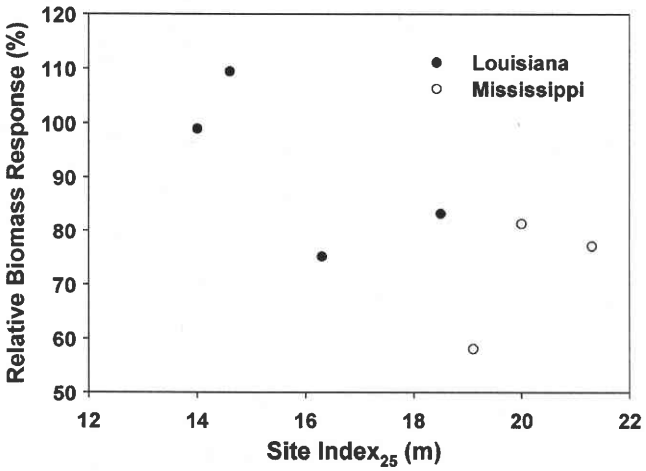

Fig. 3. Relative biomass response of whole-tree harvested plots to stem-only harvested plots as a function of site index on seven locations of the LTSP study in the southern USA.

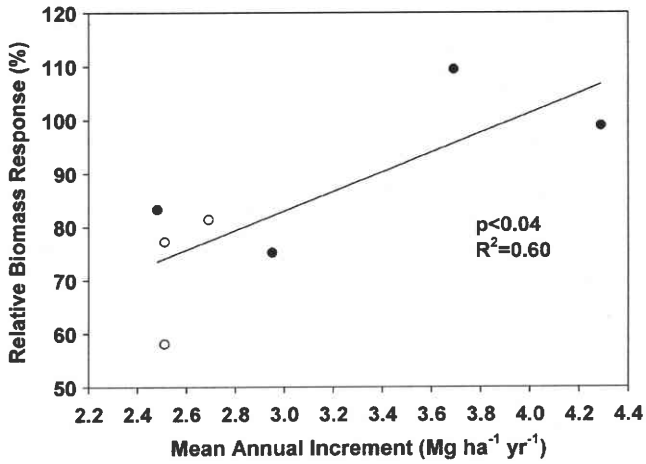

Fig. 4. Relative biomass response of whole-tree-harvested plots to stem-only harvested plots as a function of pre-harvest mean annual increment on seven locations of the LTSP study in the southern USA.

Table 4
Soil nutrients on seven LTSP locations in Louisiana and Mississippi and their relationship to relative biomass response following stem-only or whole-tree harvesting

Site	Mehlich III P ($mg\,kg^{-1}$)	Ca ($mg\,kg^{-1}$)	Mg ($mg\,kg^{-1}$)	K ($mg\,kg^{-1}$)
LA 1	3.43	151	31.4	21.5
LA 2	2.11	165	44.9	20.4
LA 3	5.30	481	169	63.7
LA 4	4.43	830	164	182
MS 1	1.75	80.0	25.1	19.4
MS 2	2.69	110	27.8	23.8
MS 3	2.22	177	46.3	17.8
p value[a]	0.0015	0.0443	0.0089	0.1512
R^2	0.89	0.59	0.77	0.36

[a]Simple linear relationship.

We also studied the relationship between surface soil nutrients and productivity loss. The concentrations of Ca, Mg, and P in the upper 15 cm of the mineral soil were clearly related to the relative biomass response (Table 4), but soil P was most closely related to the relative biomass response. The soils were essentially either fertile or infertile with respect to Ca and Mg. The linear relationship between

pre-harvest soil P concentrations and the relative biomass response was highly significant ($p<0.0015$) and explained almost 90% of the variation (Fig. 5). Whole-tree harvesting reduced productivity by 15% or more on the sites with less than 3.3 mg kg^{-1} of Mehlich III available P. This is very similar to the 3 mg kg^{-1} soil critical level reported for determining sites in the southeastern USA responsive to P fertilizer [24].

Coastal Plain soils, while ranging in texture from coarse sands to heavy clays, have widespread nutrient limitations. While soil N limitations are more widespread and have been of more concern with respect to harvesting intensity, P deficiencies are also common across the southeastern USA [25]. On soils with low inherent soil nutrient availability due to parent material, weathering, and land use history, organic matter decomposition and nutrient release is of even greater importance. Research from Australia [26,27] and New Zealand [16] has indicated that harvest residues should be maintained on sandy sites to ensure productivity associated with N availability. Soil texture has been considered a primary variable in determining the role of organic matter retention in sustaining forest productivity [28], but data from the loamy Gulf coast LTSP and CRiSSSP sites show that soil texture is not exclusively indicative of low fertility in this region.

3.4. Energy balance

Energy balance has previously been determined for various harvesting systems utilizing entire trees. Energy harvesting had a 11.5:1–15.7:1 ratio of energy produced per energy expended for three systems including a system in which commercial stems were removed for fiber utilization [29]. The energy required to ameliorate P deficiencies caused by whole-tree harvesting and control non-crop vegetation with herbicides is almost inconsequential compared to the additional energy produced when these treatments are applied (Table 5). Fertilizing stands with elements other than P can have slightly different energy balances. Potassium (K) fertilizer takes only about 80% the energy to produce, package, transport, and apply as P fertilizer, whereas N fertilizer takes 4.5-fold more energy than P fertilizer. Additionally, N fertilizer often must be applied 2–4 times throughout a rotation to maintain improved growth, and common application ratios for N:P are between 2:1 and 10:1 [24]. However, assuming an N fertilization regimen as intensive as 200 kg N ha^{-1} applied 4 times throughout a rotation, the energy associated with this treatment would only be ~70 MW h ha^{-1}. Furthermore, although soil and foliar N are low on some of these sites [22], none of these sites or other study sites throughout the South have exhibited growth losses due to N deficiencies that can be attributed to whole-tree harvesting. Therefore, nutrient deficiencies caused by whole-tree harvesting can be ameliorated in a highly energy-efficient manner.

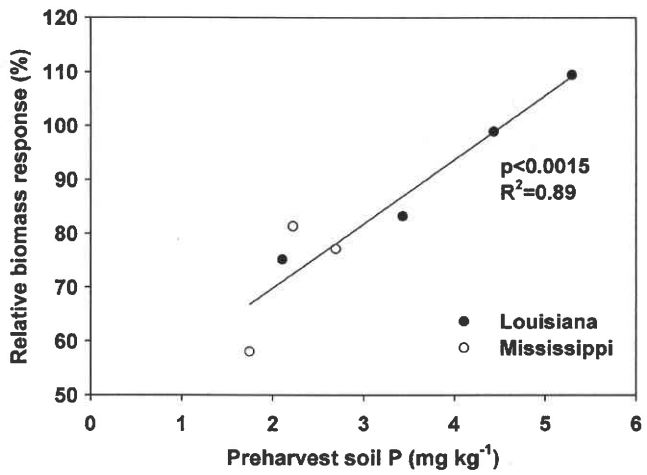

Fig. 5. Relative biomass response of whole-tree harvested plots to stem-only harvested plots as a function of pre-harvest surface soil (0–15 cm) P availability on seven locations of the LTSP study in the southern USA.

Table 5
Biomass and energy analysis of harvesting intensity and site and forest productivity improvement treatments on the LA 1 LTSP location

Treatment	Biomass (Mg ha^{-1})	Energy (MW h ha^{-1})			
		Direct gain[a]	Indirect gain[b]	Loss	Net
Stem-only harvest	35.6	0		0	0
Whole-tree harvest	28.0	115		−43[b]	+72
WTH + herbicide	42.5	115	82	−1[c]	+196
WTH + fertilizer	52.3	115	137	−1.2[d]	+252

[a]Energy value of slash harvested for bioenergy.
[b]Biomass energy response to whole-tree harvesting compared to stem-only harvesting with no herbicides of fertilizers applied.
[c]Energy value of manufacturing and applying common forestry herbicides.
[d]Energy value of manufacturing and applying 56 kg P ha^{-1} and 50 kg N ha^{-1}.

4. Conclusions

Biomass energy represents a significant potential market for both industrial and private landowners in the Gulf Coastal Plain of the southeastern US. Conventional harvesting techniques in the region remove or concentrate much of the crown biomass, thereby replicating the effects of whole-tree harvest even if the material is not harvested. Therefore, in order to sustain productivity in this region, we must understand the impact of organic matter removal on subsequent soil productivity.

Whole-tree harvesting reduced productivity on over 75% of the study blocks in these two studies by an average of 18%. The magnitude of the response was clearly related to the inherent productivity of the site and to the soil P availability as assessed before harvest. While competing

vegetation had a strong influence on pine productivity, it did not mask the impacts of whole-tree harvesting. On the LTSP site that had a fertilized plot, a relatively small one-time application of N + P fertilizer maintained productivity of whole-tree harvested plots and increased productivity by an additional 47% above the stem-only harvest level. This indicates that for similar soils in the Gulf Coastal Plain, soil analyses could be used to identify sites at risk of harvesting-induced productivity loss, and fertilization of these sites could fully restore any productivity loss caused by whole-tree harvesting. While soil P limitations were most important on these sites, other soil nutrients should be monitored and ameliorated when necessary to maintain productivity following whole-tree harvest.

At age 10 years, the energy gained from harvesting tree crowns is still greater than the potential energy lost due to growth losses. However, fertilization and weed control greatly increased potential energy gains and were highly energy-efficient.

Acknowledgments

The CRiSSSP research study was funded in part by a Challenge Cost-Share grant from the USDA Forest Service Southern Research Station with participation by International Paper Company, Temple-Inland Forest Products Corporation, and Weyerhaeuser Company. Rick Stagg was instrumental in developing the energy budgets. We thank Allan Tiarks, Rick Stagg, Michael Elliott-Smith, and Morris Smith, Jr. for installing and measuring the LTSP studies. We thank Mason Carter, Ray Newbold, and many others for installing and measuring the CRiSSSP study. We thank Chris Allen for his help with the CRiSSSP database. We also thank Michael Blazier for a review of an earlier draft of manuscript.

References

[1] Wear DN. Land use. In: Wear DN, Gries JG, editors. Southern forest resource assessment. Asheville, NC: USDA For Serv So Res Sta Gen Tech Rep SRS-53; 2002. p. 153–74.

[2] Prestemon JP, Abt RC. Timber products supply and demand. In: Wear DN, Gries JG, editors. Southern forest resource assessment. Asheville, NC: USDA For Serv So Res Sta Gen Tech Rep SRS-53; 2002. p. 299–326.

[3] Powers RF, Alban DH, Miller RE, Tiarks AE, Wells CG, Avers PE, et al. Sustaining site productivity in North American forests: problems and prospects. In: Gessel SP, Lacate DS, Weetman GS, Powers RF, editors. Sustained productivity of forest soils. Proceedings of the seventh North American forest soils conference. Vancouver, BC: University of British Columbia; 1990. p. 49–79.

[4] Morris LA, Miller RE. Evidence for long-term productivity change as provided by field trials. In: Dyck WJ, Cole DW, Comerford NB, editors. Impacts of forest harvesting on long-term site productivity. London: Chapman & Hall; 1994. p. 41–80.

[5] Carter MC, Dean TJ, Zhou M, Messina MG, Wang Z. Short-term changes in soil C, N, and biota following harvesting and regeneration of loblolly pine (*Pinus taeda* L.). Forest Ecology and Management 2002;164:67–88.

[6] Bailey RG. Description of the ecoregions of the United States. 2nd ed. Misc Pub No 1391, Map scale 1:7,500,000. Washington DC: USDA Forest Service; 1995.

[7] Daddow RL, Warrington GE. Growth-limiting soil bulk densities as influenced by soil texture. Group Rep WSDG-TN-00005; 1983.

[8] Fabbio G, Frattegiani M, Manetti MC. Height estimation in stem analysis using second differences. Forest Science 1994;40:329–40.

[9] Baldwin Jr. VC, Feduccia DP. Loblolly pine growth and yield prediction for managed west gulf plantations. New Orleans, LA: USDA For Serv So Exp Sta Res Pap SO-236; 1987.

[10] Baldwin Jr. VC, Peterson KD, Burkhart HE, Amateis RL, Dougherty PM. Equations for estimating loblolly pine branch and foliage weight and surface area distributions. Canadian Journal of Forest Research 1997;27:918–27.

[11] Mehlich A. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis 1984;15:1409–16.

[12] Gillman GP. A proposed method for the measurement of exchange properties of highly weathered soils. Australian Journal of Soil Research 1979;17:129–39.

[13] Fluck RC. Energy in farm production. In: Stout BA, editor. Energy in world agriculture, vol. 6. Amsterdam: Elsevier; 1992.

[14] Tew DT, Morris LA, Allen HL, Wells CG. Estimates of nutrient removal, displacement and loss resulting from harvest and site preparation of a *Pinus taeda* plantation in the Piedmont of North Carolina. Forest Ecology and Management 1986;15:257–67.

[15] Rubilar RA. Biomass and nutrient accumulation comparison between successive loblolly pine rotations on the upper Coastal Plain of Alabama. Dissertation. Raleigh, NC: North Carolina State University; 2003.

[16] Smith CT, Lowe AT, Skinner MF, Beets PN, Schoenholtz SH, Fang S. Response of radiata pine forests to residue management and fertilisation across a fertility gradient in New Zealand. Forest Ecology and Management 2000;138:203–23.

[17] USDA Forest Service. Soil quality monitoring. In: Forest service handbook FSH 2509.18 Soil management handbook. Washington, DC: USDA For Serv; 1991 [Chapter 2].

[18] Snowdon P, Waring HD. Forest fertilisation and thinning practice. In: Proceedings of the IUFRO regional thinning meeting. Economics and techniques of thinned plantations in Australia and New Zealand. Canberra: CSIRO Division of Forest Research; 1981. p. 159–62.

[19] Snowdon P, Waring HD. Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. In: Grey DC, Shönau APG, Shutz CJ, editors. Proceedings of the IUFRO symposium on site and productivity of fast growing plantations. Pretoria: Forest Research Institute; 1984. p. 701–11.

[20] Mann LK, Johnson DW, West DC, Cole DW, Hornbeck JW, Martin CW, et al. Effects of whole-tree and stem-only clearcutting on postharvest hydrologic losses, nutrient capital, and regrowth. Forest Science 1988;34:412–28.

[21] Cox SK, Van Lear DH. Biomass and nutrient accretion on Piedmont sites following clearcutting and natural regeneration of loblolly pine. In: Shoulders E, editor. Proceedings of the third biennial southern silvicultural research conference. New Orleans, LA: USDA For Serv So Exp Sta Gen Tech Rep SO-54; 1985. p. 501–6.

[22] Scott DA, Tiarks AE, Sanchez FG, Elliott-Smith ML, Stagg R. Forest soil productivity on the southern long-term soil productivity sites at age 5. In: Conner KF, editor. Proceedings of the 12th biennial southern silvicultural research conference. Asheville, NC: USDA For Serv So Res Sta Gen Tech Rep SRS–71; 2004. p. 372–7.

[23] Johnson DW, Knoepp JD, Swank WT, Shan J, Morris LA, Van Lear DH, et al. Effects of forest management on soil carbon:results of some long-term resampling studies. Environmental Pollution 2002;116:201–8.

[24] Wells CG, Crutchfield DM, Berenyi NM, Davey CB. Soil and foliar guidelines for phosphorus fertilization of loblolly pine. Asheville, NC: USDA For Serv Southeast Exp Sta Res Pap RP-SE-110; 1973.

[25] Allen HL. Forest fertilizers. Journal of Forestry 1987;85:37–46.
[26] Keeves A. Some evidence of loss of productivity with successive rotations of Pinus radiata in the southeast of South Australia. Australian Forestry 1966;30:51–63.
[27] Farrell PW. Radiata pine residue management and its implications for site productivity on sandy soils. Australian Forestry 1984;47:95–102.
[28] Vance ED. Agricultural site productivity: principles derived from long-term experiments and their implications for intensively managed forests. Forest Ecology and Management 2000;138:369–96.
[29] Watson WF, Miller DE, Stokes BJ, Broussard ML. Energy budget for an energywood harvesting system. In: Proceedings of the 1986 southern forest biomass workshop. Norris, TN: Tennessee Valley Authority; 1987. p. 103–5.