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Abstract: The export of wood pellets from the southeastern United States (USA) has grown significantly in recent years, following rising demand from Europe. Increased wood pellet demand could lead to spatially variable changes in timberland management and area in the USA. This study presents an assessment of the impacts of increasing wood pellet demand (an additional 11.6 Mt by 2030) on land-use dynamics, taking into account developments in other wood product markets as well as expected changes in other land uses. An economic model for the forest sector of the southeastern USA (SRTS) was linked to a land-use change model (PLUC) to identify potential locations of land-use change following scenarios of demand for pellets and other wood products. Projections show that in the absence of additional demand for wood pellets, natural timberland area is projected to decline by 450–15 000 km^2 by 2030, mainly through urbanization and pine plantation establishment. Under the high wood pellet demand scenario, more (2000–7500 km^2) natural timberland area is retained and more (8000–20 000 km^2) pine plantation is established. Shifts from natural timberland to pine plantation occur pre-

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dominantly in the Atlantic coastal region. Future work will assess the impact of projected transitions in natural timberland and pine plantations on biodiversity and carbon storage. This modeling framework can be applied for multiple scenarios and land-use projections to identify locations of timberland area changes for the whole southeastern USA, thereby informing the debate about potential impacts of wood pellet demand on land-use dynamics and environmental services. © 2017 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Keywords: wood pellets; bioenergy; land-use change; spatial variation; modeling; southeastern USA

Introduction

Global wood pellet production has grown considerably over the last decades; from 1.7 Mt in 2000 to 29.7 Mt in 2015.[1] The European Union (EU) is the main user of wood pellets, responsible for about 80% of global pellet consumption in 2015.[1] Specifically, there has been a strong increase in the use of wood pellets for electricity production in the EU28, reaching a pellet consumption of 7.3 Mt in 2015,[1] with about 4.6 Mt (63%) being imported from the southeastern United States (USA).[2] Wood pellet production has risen strongly in the USA in recent years, mainly driven by an increase in European demand for wood pellets.[3] As a result, US exports to the EU have increased[4] and the USA is now the main supplier of wood pellets to Europe.[5] The southern part of the USA produces 98% of exported pellets from the USA.[6] Future increases in pellet production in this region are expected: of total announced wood-pellet producing capacity to be built in the USA in the coming years, 81% is located within the southeastern USA.[7] However, future development in pellet production in the region is uncertain; projections range from around 5.6 Mt[8] to 16 Mt[7] pellet production. The feedstock used to produce wood pellets originates from timberland, which comprises two subsets: natural timberland* and planted timberland (pine plantation).†

An increased demand for wood pellets from the southeast of the USA could lead to changes in both timberland area and management in this region. Changes in demand for wood product feedstocks such as timber (large roundwood) and pulpwood (small roundwood, which, with mill residues, is also the main feedstock for wood pellet production[9,10]) affect feedstock prices. High prices for wood feedstocks can lead to an increase in timberland establishment.[6,11] Strong markets for forest products can motivate private forest owners to keep their land in forest cover, which may shift the expansion of urban areas – projected to be the largest driver of deforestation in this region in the near future – toward agricultural land rather than timberland.[12] Shifts in prices have also been shown to lead to changes in forest management. High prices for small roundwood promote forest investment and increased management intensity in terms of shorter rotations,[13,14] higher density planting, increased thinning practices, and fertilizer use.[15] Currently, southern pine plantations are among the most intensively managed forests in the world.[16] The largest share (86%) of timberland in the southeastern USA (both natural and planted) is privately owned by corporations and families, who are responsible for 96% of large roundwood harvesting.[12,17] Market forces can influence private landowner decisions on forest management and harvest.[18–20]

Changes in timberland area and management can have an impact on the provision of ecosystem services, such as biodiversity conservation and carbon storage. The increased production of wood pellets has fueled debate about its potential impacts on land-use change[21–23] and its implications for biodiversity[24–27] and carbon storage.[8,28–31] As a result of uncertainty about the sustainability of the use of wood pellets, several European countries have put forward sustainability guidelines,[32] which could restrict the supply of wood pellets from the USA to Europe.[9] The South is thought to be the largest carbon sink across the conterminous United States.[33] Changes in forest area determine variation in carbon storage across the landscape. Forest management also influences carbon stocks, as was shown

*Natural timberland is defined as 'Productive forests composed of trees established by natural regeneration of existing seed sources, root suckers, stump sprouts, etc. Establishment may be either afforestation on land that until then was not classified as forest or by reforestation of land classified as forest after a disturbance or following harvest' following the Forest Inventory and Analysis National Program (for instance, Oswalt *et al.*[76]).

†Planted timberland is defined as 'Productive forests composed of trees established through planting and/or seeding of native or introduced species. Establishment may be either afforestation on land that until then was not classified as forest, or by reforestation of land classified as forest after a disturbance or following harvest' following the Forest Inventory and Analysis National Program (for instance, Oswalt *et al.*[76]).

for different plantation management strategies in the southeastern USA (Jonker *et al.*, unpublished data). Additionally, while natural forests generally provide a more suitable habitat for a wider range of species than pine plantations, pine plantation establishment can provide habitats for a number of forest species and increase connectivity and landscape diversity.[34,35] The net benefits of managed timberlands depend on the reference system and the assumed alternative management practices. These effects might not be distributed evenly over the region.[31] Historical trends in land-use change vary across the landscape in the southeastern USA.[36] Timberland area and management dynamics in the southeastern USA are expected to be non-uniform due to the variation in spatially explicit characteristics, such as potential agricultural yields, water availability, and urbanization pressure.[37] Therefore, changes in timberland area and management intensity, as well as subsequent environmental impacts, are expected to be location specific. To answer questions related to the sustainability of pellet production in the southeastern USA, it is necessary to take into account spatial variability. To date, limited research has taken into account spatial variability in land-use dynamics following increased pellet demand for the whole southeastern region. Previous studies on the impact of wood pellet demand on land use have provided insights into potential changes in land use, but were mostly not spatially explicit.[6,7,9,38,39] Those analyses that were spatially explicit were conducted either at low resolution (state level) on a large scale (several states in the southeast),[22] or provided detailed information of high resolution (100 m or less) but on a small local scale (woodshed[26] and state[23]).

The aim of this research is to create a spatial assessment of the impact of increasing wood pellet demand on land-use dynamics, while taking into account demand for other wood products (i.e., saw timber and pulp and paper), as well as development of other land uses (e.g. urban land and cropland). This study does not quantify the environmental impacts of wood pellet production, but provides an important first step for environmental impact assessment by providing projections of potential land-use change. By identifying where and how much timberland area is projected to change under different pellet demand scenarios, we can inform the debate about the potential impacts of wood pellet demand on land-use dynamics.

Methods

The southeastern USA is defined as in previous studies of the forestry sector in the area [9,39–41] and includes the states of Florida, Georgia, South Carolina, North Carolina, Virginia, Tennessee, Alabama, Mississippi, Louisiana, and Arkansas, as well as the western parts of the states of Texas and Oklahoma. The landscape patterns in the southeastern USA today were created through large-scale deforestation for agriculture in the eighteenth and nineteenth centuries, followed by land abandonment and subsequent forest regeneration in the late nineteenth and twentieth century.[42] The area of natural timberland in the southeastern USA decreased by almost 20 000 km² between 1990 and 2010, while the area of pine plantation increased by more than 50 000 km².[17] These land-use changes have been attributed to the driving forces of urbanization, increased commercial forestry and competition with agriculture.[43] Between 2001 and 2011, urbanization resulted in over 7000 km² additional developed land in the southeastern USA, while agricultural land decreased by over 2000 km².[44,45]

A modeling approach was applied to assess potential future changes in land use in the southeast of the USA resulting from an increasing wood pellet demand between 2010 and 2030 and taking into account developments in other wood markets (i.e., saw timber and paper products) and dynamics of other land uses. The methodology consisted of the combination of a partial-equilibrium economic wood market model (SRTS) [41,46] and a spatial land-use change model (PLUC).[47,48] The wood market model determined the volume and area of timberland needed to satisfy an exogenously set demand scenario for wood products. The land-use model spatially allocated the projected changes in timberland area, as well as changes in other land uses. The development in demand for non-forest land (e.g. urbanization, agriculture) was exogenously set, based on the 2010 Resources Planning Act Assessment of the US Forest Service[49] and included in the PLUC model. Figure 1 provides an overview of the modeling approach. The spatial model generates maps of annual projected land use between 2010 and 2030 at a 2x2 km resolution. These maps can be used to model and project environmental impacts in a spatially explicit way for the entire southeastern region of the USA.

Scenarios

Demand from different markets for different wood feedstocks is divided into softwood (from pine and mixed forests) and hardwood (from mixed forests, upland, and lowland hardwood forests), as well as large roundwood (timber) and small roundwood (pulpwood). Between 2006 and 2011 in the USA, 19–25% of wood harvested was used as sawtimber, 49–55% was used by the pulp and paper sector, 15–17% was used to produce wood based panels, and

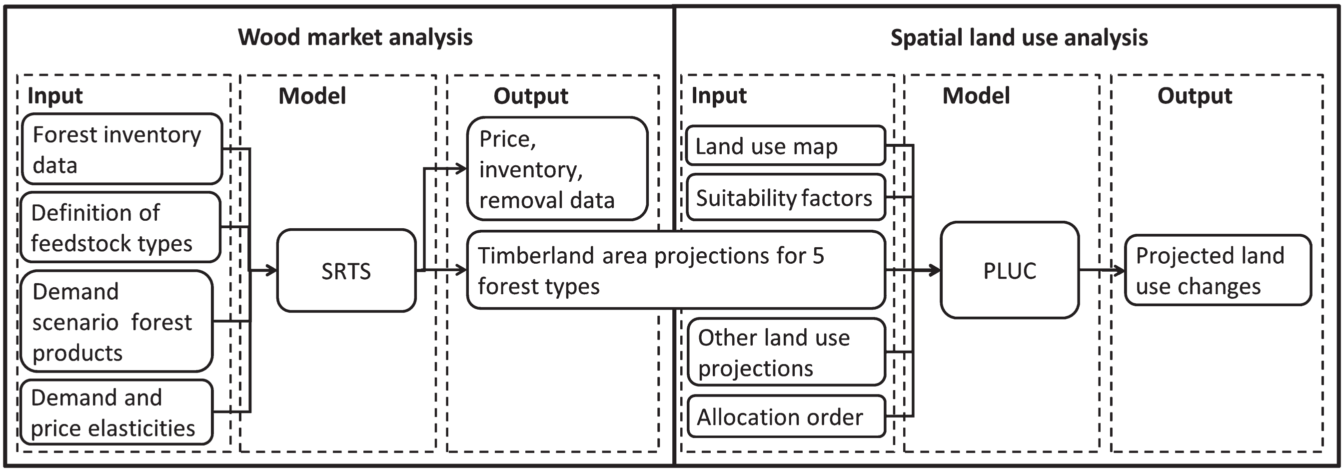

Figure 1: Overview of the methodology, showing a combination of the SRTS (in the component 'wood market analysis') and the PLUC model (in the component 'spatial land use analysis'). For each model, input data and output data are listed. Forest area projections are both an output of the SRTS model and an input to the PLUC model.

9–11% of wood harvested was used for energy production (including energy used in running the mills).[10] Because an acre of timberland generally contains both small and large roundwood, harvests of small and large roundwood are often linked. The future development of wood markets is uncertain; therefore, four scenarios for future demand for woody biomass were constructed to assess the consequences of potential future market development on land use. The wood pellet sector is strongly influenced by developments in other larger wood-using sectors, such as the saw timber and pulp and paper markets. The scenarios therefore included projections for wood pellet markets in conjunction with pulp and paper markets and the domestic housing market in the USA.

A scenario of relatively high future pellet demand was derived from projections of future EU imports of wood pellets[50] and the proportion of imports originating from the USA.[51] This scenario assumed a gradual increase in pellet demand from the southeast of the USA, reaching a plateau of an additional 11.6 Mt in 2020 from a starting point of about 0.5 Mt in 2010 (based on Abt et al.[7] and Pelkmans et al.[52]). This scenario was compared to a scenario with no increased demand for wood pellets from 2010. The demand for wood pellets was translated into demand for small roundwood. This was done by assigning 20% of demand for pellets to hardwood small roundwood feedstock, and 80% to softwood small roundwood feedstock. The small roundwood category also includes 15% (for softwood) and 30% (for hardwood) harvest residues from the large roundwood category. Two scenarios for rates of recovery of the domestic housing market, which crashed in 2008, were constructed based on Ince and Nepal.[53] All scenarios include a slowly growing demand for small roundwood from the pulp and paper sector of under 2% a year up to 2030, also based on Ince and Nepal.[53] Figure 2 provides an overview of demand volumes in the different scenarios (also Annex 1). The two scenarios for the wood pellet market and the two scenarios for the US domestic housing market were combined to formulate four scenarios based on a combination of demand for small roundwood (from both the pellet and paper sector) and large roundwood (from the housing sector; Fig. 3): HhHp for high housing and high pellet demand, HhLp for high housing and low pellet demand, LhHp for low housing and high pellet demand, and LhLp for low housing and low pellet demand.

Wood market analysis

The influence of the demand for different wood products on the area of timberland was assessed using an economic model of the forestry market in the US South: the Sub Regional Timber Supply (SRTS) model. The SRTS model was developed by Abt *et al.*[41,46] to assess timber supply and demand in the US South on a medium timescale (5–25 years). SRTS is a partial equilibrium model, i.e., it takes into consideration one sector (in this case the forestry sector, which contains several markets), but not the dynamics in other sectors. About 14% of total timberland in the area is found on public lands.[17] Harvest decisions on public lands (such as national forests) are not driven by market forces, and only 4% of timber harvest takes place on public lands.[54] Therefore public lands were excluded from the analysis, as in other studies.[12,41,55] Timberland area included in the analysis follows the USDA definition of timberland: 'forest land that is producing or is capable of producing crops of

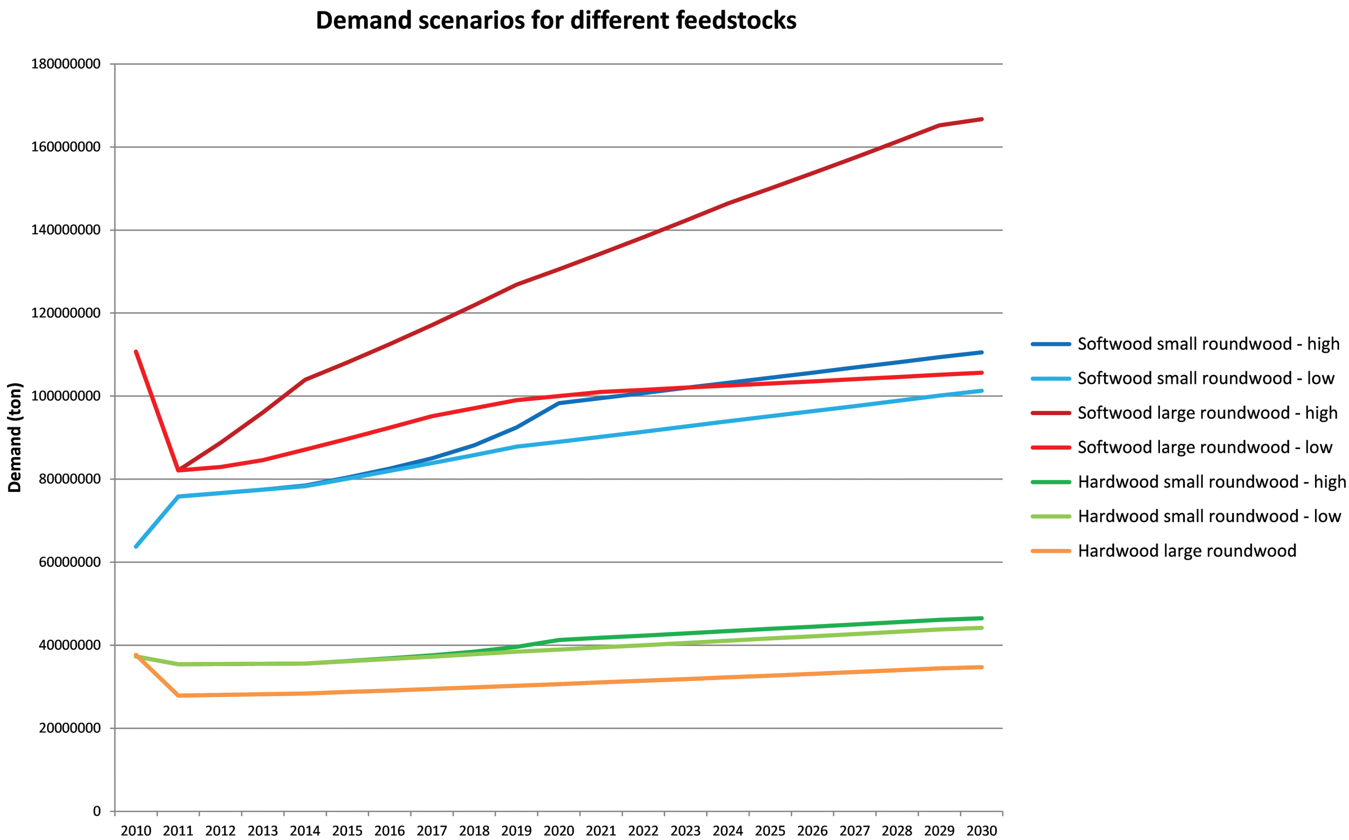

Figure 2: Overview of demand scenarios for the different feedstocks, with demand in tons per year between 2010 and 2030. The changes between 2010 and 2011 reflect the TPO adjustment (see Annex 2).

industrial wood.'[56] SRTS was run in demand mode, which means that harvest, price and forest areas respond endogenously to an exogenous development in demand.

SRTS simulates the economic market for wood products based on Forest Inventory & Analysis (FIA) data, definitions of feedstock types, and demand scenarios for forest products. The demand scenarios described earlier were used as input in the SRTS model. The SRTS model calculates timberland dynamics for spatial units with the size of an FIA survey unit level, which consists of several counties and is on average 25 000 km^2 in size (area ranges from 11 296 to 48 558 km^2). Forest inventory data used in SRTS includes data on area per forest type, stand age, and removals and is based on FIA[17] and Timber Product Output (TPO) data[57] (Annex 2 has a more detailed explanation of TPO adjustment). SRTS also requires a definition of feedstock types, which defines the class boundary between small and large roundwood. It also defines a percentage of large roundwood that ends up in the small roundwood pool, such as tops and branches.[‡] Finally, elasticity values are required to calculate price responses of the feedstock types. The output of SRTS includes projections of large and small roundwood price, forest inventory and removals, as well as expected timberland area for five different forest types: pine plantation, natural pine, mixed forest, upland hardwood, and lowland hardwood.

SRTS was run with a time step of 1 year from 2010 to 2030. We used the version of SRTS based on FIA data for start year 2010 (SRTS version 28b). In SRTS, changes in timberland area are calculated at each time step for five different forest types. Hardie *et al.* have shown that timberland area can increase based on relative changes in agriculture and forest rents.[58] SRTS uses the Hardie empirical model to calculate timber rents based on endogenous timber price changes, while assuming a constant rate of increase in agriculture rents based on a historical average (Table 1). An overview of the processes in SRTS is shown in Fig. 4. Input data on demand from the saw timber, pulp and paper, and wood pellet markets are compared to inventory data. At the first time step, inventory data from the FIA are used as input. In subsequent time

‡This percentage was 15% for softwood and 30% for hardwood.

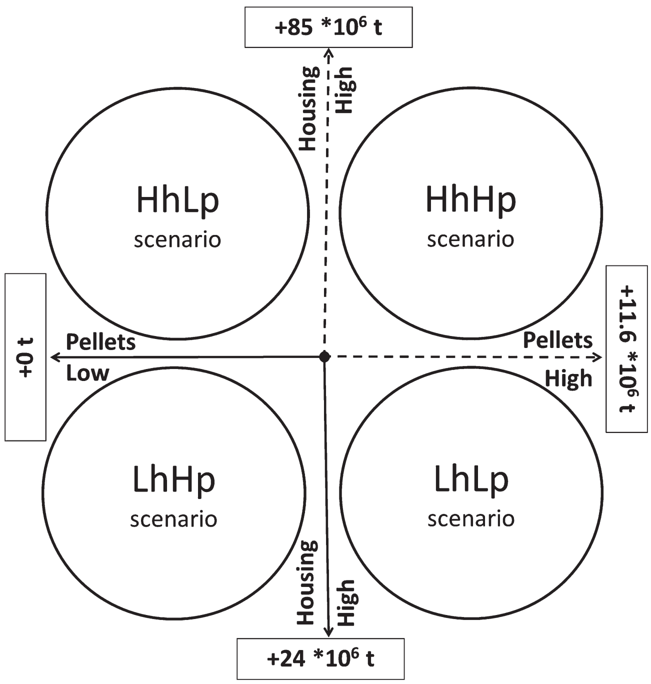

Figure 3: Overview of scenarios used in the analysis. 'High housing' stands for a high demand for large roundwood. The volumes presented on either side of the vertical arrow depict the additional demand for large roundwood in 2030. 'High pellets' stands for a high demand for small roundwood. The volumes presented on either side of the horizontal arrow depict the additional demand for small roundwood in 2030.

steps, these inventory data are adapted based on calculated removals (item I in Fig. 4) and regrowth (II). Regrowth is a slow process and therefore has a time lag in the model. Changes in timberland inventory trigger changes in small and large roundwood prices based on elasticity values. (III) Small and large roundwood prices are used to calculate timber land rents based on a Net Present Value calculation.[§](IV) Timber rents are compared to agricultural rents to calculate the area per forest type that is projected to be established or lost. (V) Price responsiveness is assumed to differ per forest type, with pine plantations being most price responsive.** The projected changes in timberland area affect the inventory of small and large roundwood; in the case of timberland area expansion, this process occurs with a time lag. (VI) SRTS creates yearly projections of timberland area per forest type, which were used as land-use projections in a spatial land-use analysis.

A sensitivity analysis was carried out for the assumptions made in SRTS. The parameters included in the sensitivity analysis are related to product definition, elasticities of price and inventory, and agricultural rent. Table 1 shows all variables included in the sensitivity analysis and their ranges. SRTS has a static definition of feedstock types throughout the runs. In reality, however, these definitions are expected to shift and vary with relative changes in prices for large and small roundwood depending on local circumstances such as proximity to pellet mills. Therefore, the cut-off point between large and small roundwood was varied in the sensitivity analysis. In addition, assumptions are made in SRTS about the percentage of large roundwood that is expected to be of low quality and as a result not usable as saw timber; this includes tops and branches, crooked or diseased trees (Table 1 gives an overview of SRTS input parameters). Consequently, a percentage of large roundwood is expected to end up in the small roundwood pool. The influence of this assumption was tested in the sensitivity analysis. The influence of assumptions about demand and supply elasticities was tested because a range of potential values was found in previous studies (Table 1). Finally, the effect of agricultural rent developments on timberland area was tested, because the developments of agricultural rents are uncertain.

Spatial land use analysis

Future land use was projected spatially using the PCRaster Land Use Change (PLUC) model. PLUC is a spatial land-use change model developed by Verstegen *et al.*[47,48] and often applied in case studies on land-use dynamics and bioenergy.[48,59,60] PLUC is a cellular automaton that spatially allocates land use per time step based on current land use, yearly projections of demand for different land uses for the region, the suitability of land for different land uses, and the allocation order. In PLUC, land-use classes are divided into dynamic, passive, and static. Dynamic land-use classes can actively expand or contract based on changes in relative demand, leading to a net change in area for competing dynamic land classes. Passive land-use classes only change as a result of changes in the area of dynamic land-use categories. Static land uses do not change over time. The allocation order determines in which order land uses get assigned a location of expansion or contraction. For a more detailed description of the PLUC model, we refer to earlier studies that introduce the PLUC model.[47,48]

[§]Large roundwood starts off 4x the price of small roundwood, and is discounted at 4% for 10 years.
**Pine plantation was assumed to be 2.5 times more price responsive than other forest types. Lowland hardwood was assumed to be 0.5 times less price responsive because of hydrological and geographical restrictions in allocation.

Table 1. Parameters included in the sensitivity analysis with their upper and lower boundaries. Source lists the rationale behind choosing these values. Rw = roundwood

Parameter	Input type	Softwood small rw	Softwood large rw	Hardwood small rw	Hardwood large rw	Source
Demand price elasticity	Default	0.3	0.3	0.3	0.3	Default values SRTS
	Low	0.2	0.2	0.2	0.2	Based on literature[7]
	High	0.5	0.5	0.5	0.5	Based on literature[38,39,41,72]
Supply price elasticity	Default	0.3	0.5	0.3	0.5	Default values SRTS, for softwood also see literature[7]
	Low	0.23	0.42	0.23	0.42	Based on literature: small roundwood,[73,74] large roundwood[73]
	High	0.35	0.55	0.35	0.55	Estimation[b]
Supply inventory elasticity	Default	1	1	0.7	0.7	Default values SRTS, for softwood also see literature[7]
	Low	0.9	0.9	0.6	0.6	Estimation,[b] for hardwoods based on literature[7]
	High	1	1	0.8	0.8	Estimation[b]
Large to small roundwood (%)	Default	15%		30%		Default values SRTS
	Low	13.5%		27%		Estimation[b]
	High	16.5%		33%		Estimation[b]
Cut-off point small and large roundwood (inch)	Default	9		11		Based on literature[54,c]
	Alternative value	11		X		Estimation[d]
	Alternative value	13		X		Estimation[d]
Agricultural rent (% increase)	Default	2.28				Based on literature[e,75]
	Low	0				Estimation[b]
	High	3.81				Based on literature[f]

[a]Found in US Department of Energy report [73]
[b]For parameters for which no values were found in literature, estimations were made.
[c]Based on classification of feedstock by Forest Inventory Assessment
[d]The authors assume that 11 inches currently is a realistic cut-off point in areas with higher demand, while 13 inches could become realistic in the future under scenarios of increased demand.
[e]Based on an average of historical agricultural rent data from 1994 to 2015 for all states within the project area.
[f]Based on the state with the highest historical agricultural rent increase between 1994 and 2015 for all states within the project area – which was Georgia.

PLUC was adapted to the US southeast case study by including projections of the expansion or contraction of nine dynamic land-use classes (Annex 3 gives land-use projections used in PLUC). These are urban land, cropland, pasture, pine plantation, natural pine forest, mixed forest, upland hardwood forest, and lowland hardwood forest. Water and federal land are static land-use classes. Non-forest vegetation was included as a passive land-use class, this land-use class includes all non-forest vegetation land uses including wetlands and shrub lands (Annex 4 has a more detailed definition of land-use classes). PLUC was further adjusted for the southeastern US context by defining the allocation order (Table 2; Annex 6) and including land-use specific suitability factors applicable to the US case. A literature study was done to identify potential suitability factors. A binary logistic regression analysis was then carried out to select from these potential suitability factors, those factors, which significantly explained patterns of historical land-use transitions in the southeastern USA between 2001 and 2011. Historical land-use transitions were determined using land cover data from the National Land Cover Database (NLCD) from 2001 and 2011.[44,45] This timeframe was chosen because of the availability of spatial data. Each suitability factor was assigned a weight for each of the land-use classes (Table 2). Weights were calculated as the difference in R^2 created by leaving the factor out of the model. A higher R^2 value means more of the variation in historical land-use transitions was explained by the combined suitability factors. The relationship between

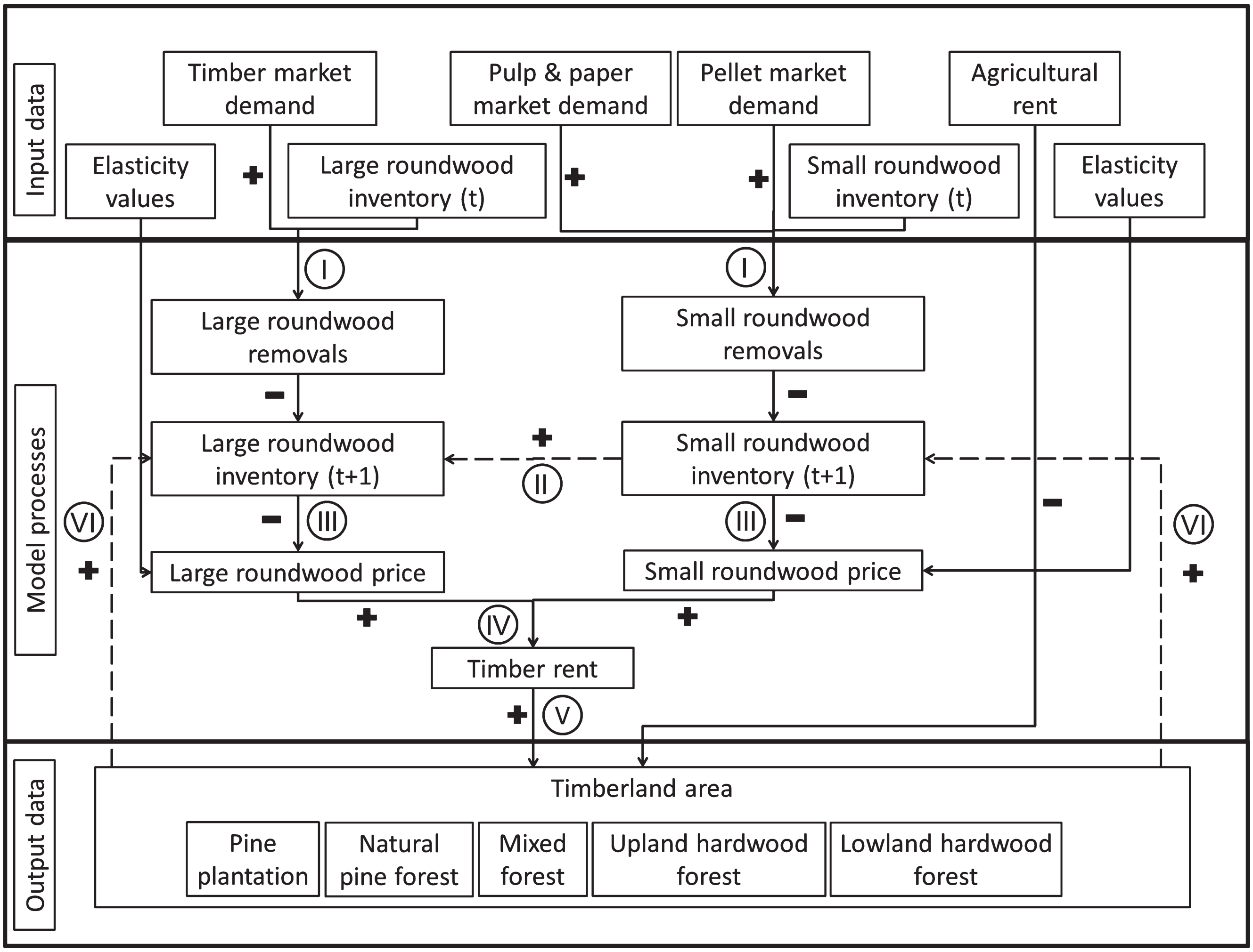

Figure 4: Linkages and feedback mechanisms in SRTS model. The type of the relationship between two model components is shown using plus (positive) and minus (negative) signs. Dashed lines show feedbacks subject to a time lag.

the suitability factor and the transition into each land use was determined to be either positive or negative. Due to a lack of spatial data that distinguishes between pine plantation and natural pine forests, suitability factors for these land-use classes were the same. Annexes 5 and 6 provide a description of the potential and final suitability factors respectively.

PLUC requires input of a land-use map for the start year (2010), which in this case was an initial land-use map developed specifically for this purpose. The initial land-use map was created using the method of Verstegen *et al.*[61] As input data for this method, data of the USDA National Resources Inventory[62] of land-use type per state in 2010 were combined with spatial input data from the National Land Cover Database (NLCD)[44,45] and the National Gap Analysis Program.[63] Annex 4 describes how the land-use categories of these data sources were translated into the categories used in this analysis. Projections of timberland area, including plantations, were based on SRTS output. Projections of urban, cropland and pasture demand were adapted from RPA 2010 scenario A1B.[64] RPA scenario A1B was selected because it is based on similar projections of future GDP growth as the scenario used in the SRTS analysis.[53]

The model was run from 2010 to 2030 with a time step of one year at a resolution of 2x2 km^2 and results were visualized using Aguila[65] and ArcGIS software. The spatial allocation of the different land uses by the adapted PLUC model was validated by running the model for the time frame 2000–2011 using NLCD data as input.[44] Modeling results for 2011 were compared to the observed 2011 NLCD map.[45] The accuracy of the results was quantified by calculating the Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)) between observed and

Table 2. Suitability factors per land-use type with corresponding weights as used as input in the PLUC model. The table also provides the allocation order of the land use types. The R^2 per land use shows the amount of variation in historical land-use change that was explained by the combination of significant suitability factors.

Suitability factors	Urban	Cropland	Pasture	Pine plantation	Natural pine forest	Mixed forest	Upland hardwood	Lowland hardwood
Allocation order	**1**	**2**	**8**	**3**	**6**	**7**	**5**	**4**
Elevation (m)			–0.09	–0.04	–0.04	–0.12		–0.02
Slope (degrees)	–0.03	–0.04		–0.04	–0.04	+0.10	–0.02	
Rainfall (mm)	+0.01	–0.05		+0.09	+0.09		–0.14	
Yield (kg DW/ha)	+0.03	–0.22		+0.05	+0.05	–0.12		
Growing season (days)		–0.10		+0.19	+0.19	+0.18	+0.09	+0.01
Soil type		0.15[d]	0.62[d]	0.15[d]	0.15[d]		0.22[d]	
Distance to main roads (km)	–0.03							+0.79
Distance to urban area (km)	–0.79			+0.05	+0.05		–0.03	
Distance to river (km)				+0.03	+0.03		+0,05	–0.05
Distance to wood mills[a] (km)		–0.07		–0.04	–0.04		–0.05	
Distance to main ports (km)		–0.10		–0.04	–0.04		–0.16	
Density of self[b]	–0.01		+0.15	+0.08	+0.08	+0.20	+0.04	
Density of urban area[c]	+0.10	–0.05		–0.05	–0.05	–0.08	–0.07	
Density of forest area[c]		–0.21	–0.14	+0.15	+0.15	–0.20	–0.13	+0.13
R^2	**0.644**	**0.324**	**0.100**	**0.272**		**0.401**	**0.275**	**0.343**

[a]Includes all wood using mills such as pellet mills, sawmills, and paper mills.
[b]Number of pixels of the investigated land use with in a square of 3x3 pixels (6x6 km^2).
[c]Number of pixels of urban area or any natural timberland forest type within a square of 10x10 pixels (20x20 km^2).
[d]Soil types are treated as separate variables in the regression, and each of 10 soil types has its own relative weight and direction.

modeled results per land-use class on different spatial levels: ecoregion, state, survey unit and county level. The CV(RMSE) was calculated using Eqn (1):

$$\mathrm{CV(RMSE)} = \frac{\sqrt{\sum_{n=1}^{12} (A_{\mathrm{observed}} - A_{\mathrm{modeled}}{}^{2})^{*} \mathrm{n}^{-1}}}{\bar{A}_{\mathrm{observed}}} \quad (1)$$

with $A_{observed}$ in Eqn (1) being the area per spatial unit of a certain land-use class in the NLCD map in 2011,[45] $\bar{A}_{observed}$ being the average area per spatial unit of a certain land-use class in the 2011 NLCD map, $A_{modeled}$ the area per spatial unit of a certain land-use class in the PLUC results for 2011, and n being the number of spatial units: 5 ecoregions, 12 states, 51 survey units and 949 counties. A map showing the different spatial levels can be found in Annex 7.

Results

The combined analysis using the SRTS and PLUC models results in projections of timberland area per forest type for the four different wood market scenarios and subsequent projections of changes in land use. First, a description of projected changes in timberland area is given, followed by an overview of spatial projections of land-use transitions. Land-use changes related to timberland are then discussed in more detail.

Timberland area projections

Modeling results from SRTS provide projections of timberland area per year for five forest types; pine plantations and four types of natural timberland (Fig. 5). Total timberland area is higher in 2030 compared to 2010 in all scenarios but the LhLp scenario. Increased pellet demand leads to projected higher timberland area compared to no additional pellet demand in 2030. However, increases in timberland area consist mainly of an increase in pine plantation area. Pine plantation area has an upward trend under the high housing scenarios, while in the low housing scenarios, it declines first before it starts increasing (Fig. 5). The area of natural timberland is projected to decrease by about 500 (HhHp scenario) to 15 000 km^2 (LhLp scenario) by 2030, especially natural pine and

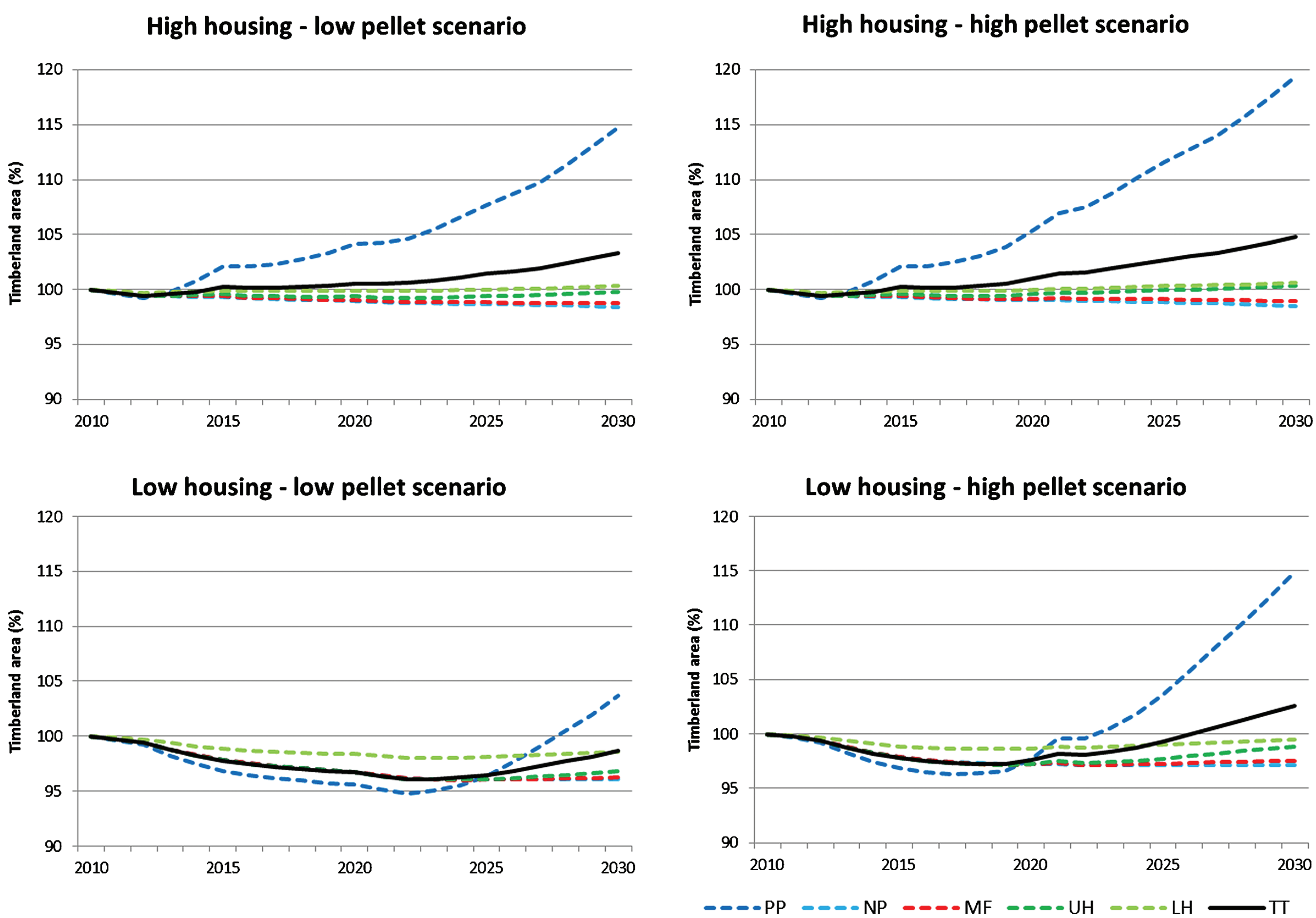

Figure 5: Timberland area per scenario in percentages with 2010 as base year. Forest type abbreviations - PP: planted pine forest, NP: natural pine forest, MX: mixed forest, UH: upland hardwood forest, LH: lowland hardwood forest, TT: total.

mixed forest. Changes in total timberland area (including pine plantation) between 2010 and 2030 range from an increase of 4.8% (HhHp scenario) to a decrease of 1.3% (LhLp scenario). Projected changes in total timberland area are mostly due to a change in plantation area, which increases by 4–19% under the different scenarios (LhLp and HhHp, respectively). When demand from the housing market is assumed to be high, additional wood pellet demand leads to projected establishment of approximately 8000 km^2 additional pine plantation (a change of 4.7%) and avoided loss of just under 2000 km^2 (a 0.1 to 0.5% decrease in total area) natural timberland by 2030 when compared to low pellet demand. For the low housing demand scenarios, increased wood pellet demand leads to the projected establishment of almost 20 000 km^2 of pine plantation (a change of 11.2%) and about 7500 km^2 less natural timberland lost by 2030 (a 1.5–3.0% decrease). Besides timberland area, SRTS also provides output on feedstock price, inventory, and removals for the user-defined demand scenarios, this data is shown in Annex 8.

Sensitivity analysis

A sensitivity analysis was done for the main assumptions made in SRTS related to parameters on product definition, elasticities, and agricultural rent. Of the different forest types, pine plantation proved to be most sensitive to shifts in parameter values, particularly for elasticities Fig. 6). This result is due to the assumption that pine plantation is more price responsive than natural timberland forest types. The cut-off point for the division between small and large roundwood had a smaller effect on pine plantation area, with shifts leading to up to a 3% change in the area of pine plantation. Variation in agricultural rents and the percentage of large roundwood that ends up in the small roundwood pool had no significant impact on timberland area.

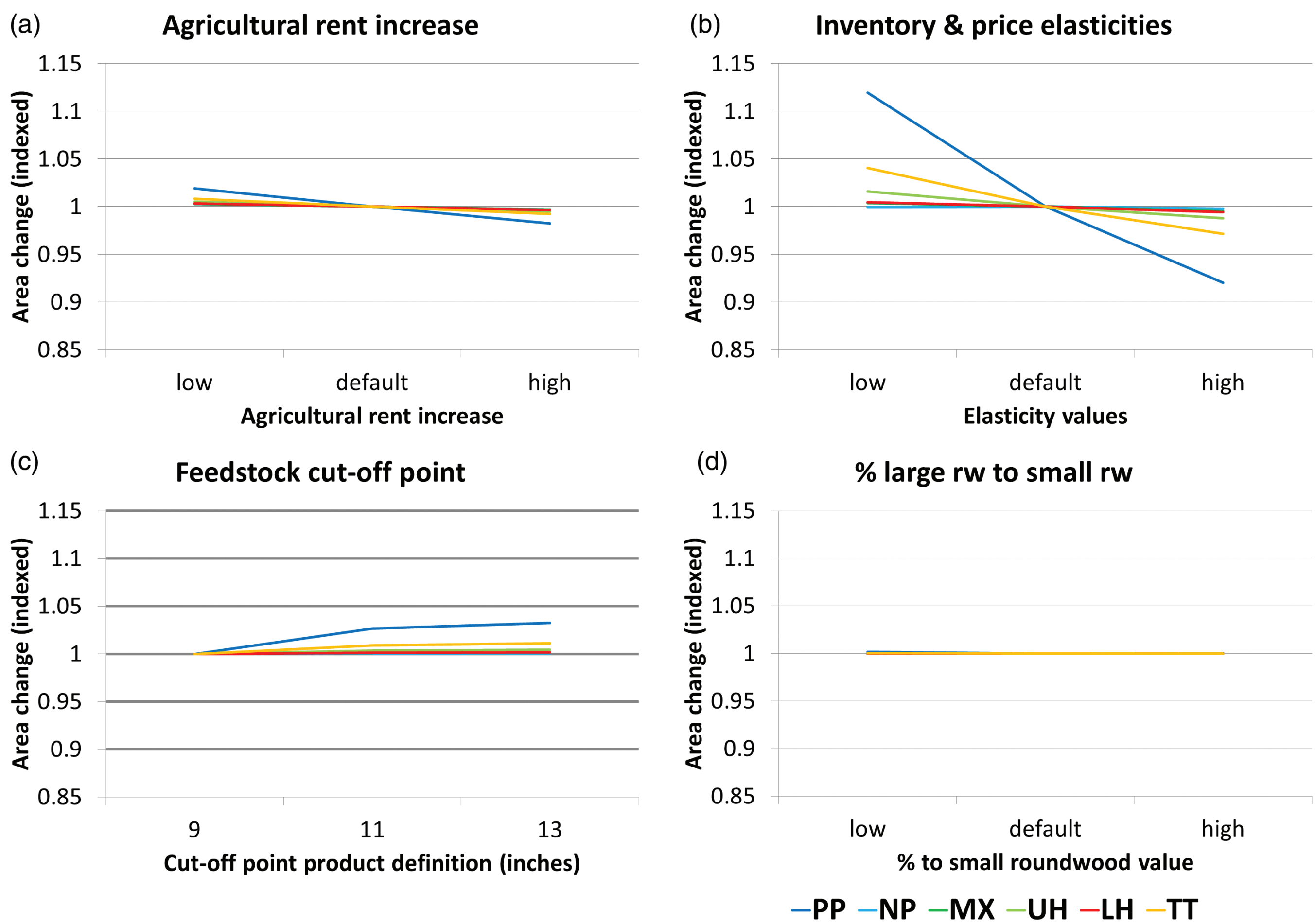

Figure 6: Sensitivity of total timberland area in the HhHp scenario to a) cut-off point between small and large roundwood, b) elasticity values for demand and supply c) annual increase in agricultural rent d) the percentage of large roundwood ending up in the small roundwood pool. For low, default and high values for elasticities, agricultural rent and % to small roundwood value, see Table 3. Results of the sensitivity analysis for the HhLp, LhHp and LhLp scenarios can be found in Annex 10. The abbreviation rw stands for roundwood. Abbreviations in the legend: pp = pine plantation, np= natural pine, mx= mixed pine, uh= upland hardwood, lh= lowland hardwood, tt= total.

Land-use transitions

Timberland area projections from SRTS were combined with projections from other land uses, which were used as input for PLUC to produce yearly maps of projected land use between 2010 and 2030 for the four wood market scenarios. Urban area is projected to expand around all main cities, particularly in the northern part of Alabama, Georgia, and South Carolina, the eastern part of Tennessee and the western part of North Carolina (Fig. 7). The establishment of new pine plantation is projected to occur mainly in the coastal parts of Virginia, North Carolina, South Carolina, Georgia, Alabama, and Mississippi. This is expected due to suitability of this area because of the proximity to existing forests, as well as suitable soil types and a longer growing season. New natural timberland regenerates in the coastal regions as well, often alongside pine plantations. The different scenarios provide similar patterns of land-use transitions (Annex 8 provides land-use transition results for the HhLp, LhHp, and LhLp scenarios). Pine plantations are established mainly at the expense of natural pine and pasture (Fig. 8). Some pasture is replaced by regeneration of natural pine and mixed forest. Some of the pasture area lost is restored by a transition from non-forest vegetation into new pasture area, particularly in Florida in the HhHp scenario. The two scenarios with high pellet demand lead to the largest cumulative amount of land-use transitions. This is due to the larger projected increase in timberland area for the high pellet demand scenarios compared to the low pellet demand

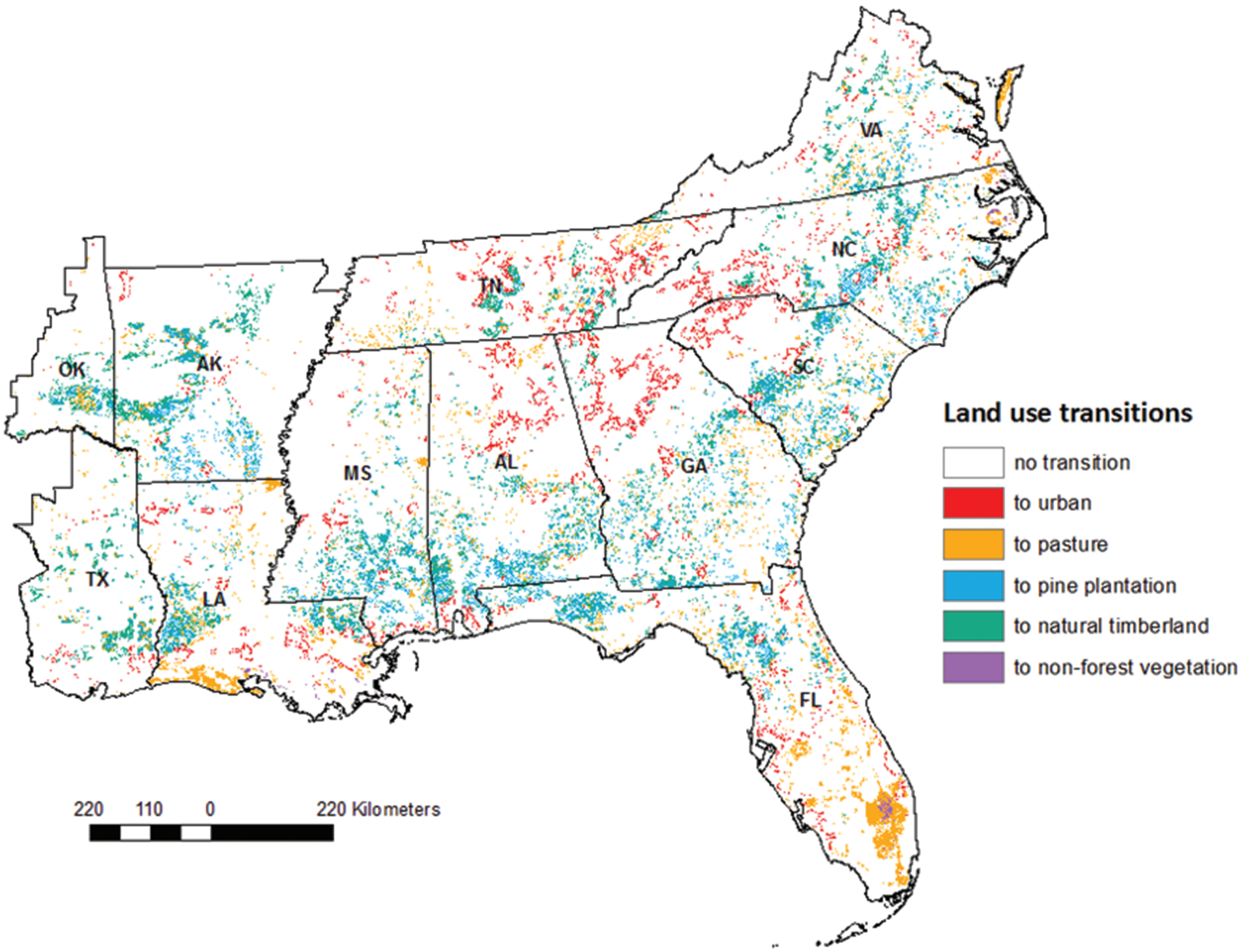

Figure 7: Transitions in land use between 2010 and 2030 for the HhHp scenario. Colours show the land uses in 2030. The natural timberland forest types were aggregated into one class.

scenarios. The additional increase in timberland area in the high pellet demand scenarios is established mainly at the expense of pasture area.

Pine plantations

Even in the absence of strong demand from the housing or pellet market, an increase in pine plantation area is expected in most states (Fig. 9). This increase becomes considerably larger, however, with increased pellet demand or high housing demand. Urbanization led to the loss of about 1850 km^2 of pine plantation, with the largest losses occurring in Alabama and Georgia. Besides Oklahoma and Texas, all states in the southeastern USA show a net gain in pine plantation in all scenarios, with many states showing a strong increase. The HhHp scenario leads to the strongest increase in pine plantation in all states except for Oklahoma, Tennessee, and Texas, which do not have a lot of pine plantation to begin with. When comparing the high and low pellet scenarios it becomes clear that pellet demand has a larger influence on pine plantation establishment in the absence of a strong housing market (i.e., the difference between the LhLp and LhHp scenario is larger than the difference between the HhHp and the HhLp scenarios). It also shows that even if the housing market is relatively strong, pellet demand can still have an added influence on pine plantation establishment, as can be seen from the difference between the HhHp and the HhLp scenarios. Pine plantation loss occurs mainly in the low housing scenarios, but in most states this loss is offset by gains in plantation area.

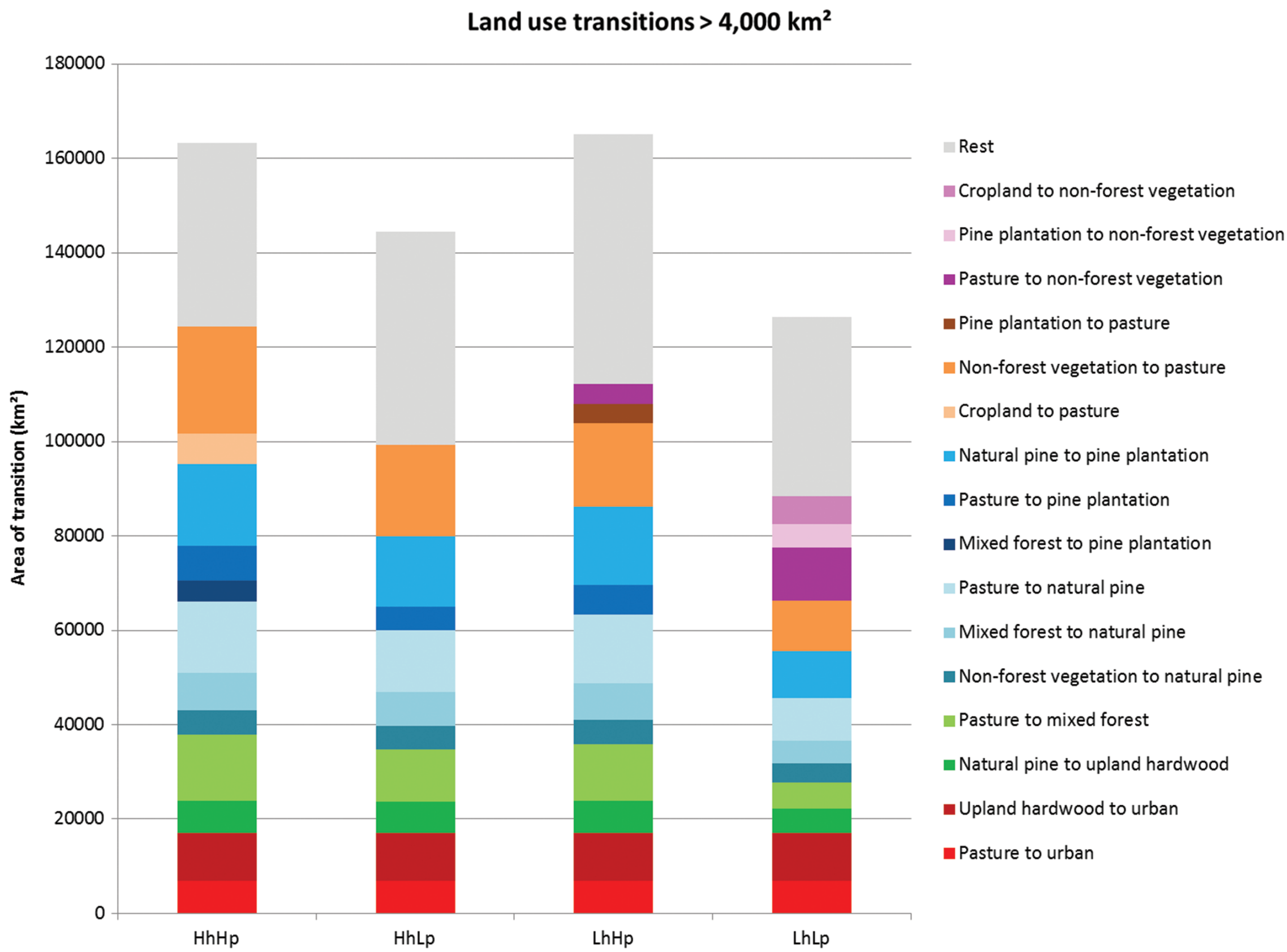

Figure 8: Area of transitions in land use (in km^2) between 2010 and 2030 for the different scenarios. The graph shows all transitions larger than 4,000 km^2 in area separately, all smaller transitions were aggregated into the category 'rest'.

For all scenarios, transitions into pine plantation occur mainly in the coastal parts of Virginia, North Carolina, South Carolina, Georgia, Alabama, and Mississippi (Fig. 10), where most of the pine plantations occur today. The new areas of pine plantations are spread out over this region, and are established mostly at the expense of natural pine – and to a lesser extent at the expense of pasture. Results for all scenarios show a similar pattern (Fig. 10 and A9). While the establishment of pine plantation is scattered across the region, some areas show relatively large increases in pine plantation area at the local level. Large differences in pine plantation establishment can be seen between the scenarios on a local scale, particularly along the Gulf coast. These locations seem to be suitable for pine plantations mostly because of the proximity of existing natural timberland and plantation forest area, as well as a longer growing season. We can conclude that establishment of pine plantation between 2010 and 2030 varies strongly over the region, but in many states net pine plantation area will increase considerably, mostly at the expense of natural timberland.

Natural timberland

In the absence of strong demand for wood products, natural timberland declines or stays relatively stable (Fig. 11). Increased pellet demand leads to a larger area of natural timberland lost to pine plantation, as well as a larger area of forest regeneration at the expense of pasture land. The amount of natural timberland lost to urbanization is 16 400 km^2, with most transitions occurring around major cities (Fig. 12 and A10). Arkansas and Texas show

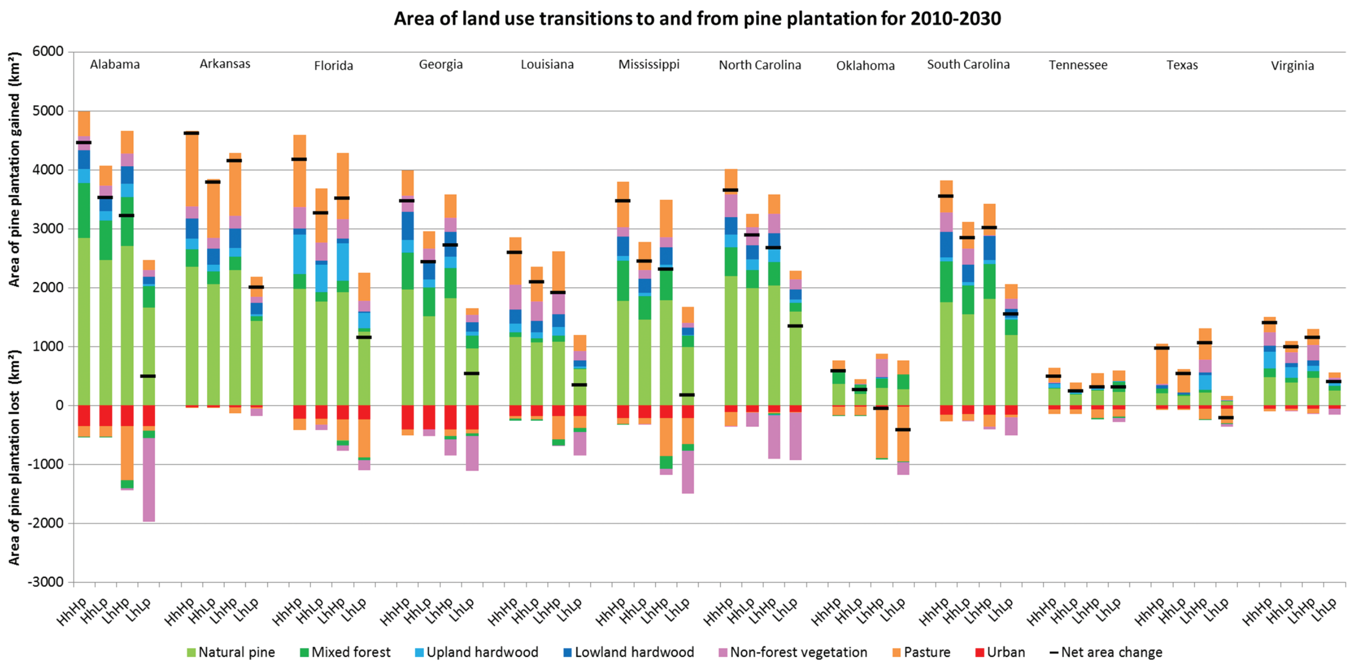

Figure 9: Area in km^2 of land use transitions involving pine plantations between 2010 and 2030, per state and for the different scenarios. Above the x-axis the area of pine plantation gained, colours show the land use type in 2010 that was replaced by pine plantation. Below the x-axis the area of pine plantation lost, colours show the land use type that replaced pine plantation by 2030. Black bars show the net gain or loss of natural timberland per state for each scenario.

very little transition of natural timberland to new urban land. For most states, the largest share of natural timberland lost transitions into pine plantations. This result is particularly prominent for the coastal parts of Virginia, North Carolina, South Carolina, Georgia, Alabama, and Mississippi, where the largest increases in pine plantation area are expected. For Florida and Oklahoma, a relatively large area of natural timberland is lost to new pasture areas (up to about 2500 km^2 and 1000 km^2, respectively, in the HhHp scenario). This is mostly due to loss of small remnants of upland hardwood in these areas. In the states Arkansas, Oklahoma, Texas, and Virginia, a net gain in natural timberland area is projected for all scenarios. In Louisiana and Tennessee, natural timberland area increases in all but the LhLp scenario. Natural timberland is gained mostly at the expense of pasture area and to a lesser extent non-forest vegetation. Reforestation occurs throughout the southeastern US, but mostly in the eastern states of Georgia, Arkansas, and Texas. This could be explained by a combination of proximity to existing forest area, steeper slopes, and relatively low suitability for other land uses. The states of Alabama, Florida, Georgia, Mississippi, North Carolina, and South Carolina show a net loss of natural timberland area under all scenarios.

Validation

Accuracy of results was evaluated by validating the spatial allocation of land-use change for the adapted PLUC model as well as a sensitivity analysis for the SRTS model. CV(RMSE) values were calculated for four spatial levels (Table 3). PLUC results are most accurate (i.e., a lower CV(RMSE) value) for the land-use types of lowland hardwood, urban, and cropland. This can be explained by the relatively high ranking in the allocation order of urban area and cropland, which means that these land uses get first pick of most suitable locations. Another explanation is the relatively high R^2 values in the regression analysis of the suitability factors for urban area and lowland hardwood, which means the model is able to capture spatial patterns that determined allocation of the land use better. Results are less accurate for mixed forest, pine forest, pasture, and non-forest vegetation. This result can be explained by the relatively low ranking in the allocation order of mixed forest, pasture, and non-forest vegetation, as well as low R^2 values of the suitability factors for pasture and pine forest. The accuracy of PLUC is reduced with increasing spatial resolution but remains relatively high for all land-use classes except non-forest vegetation up to a survey unit level – and for urban and lowland hardwood forest even up to a county

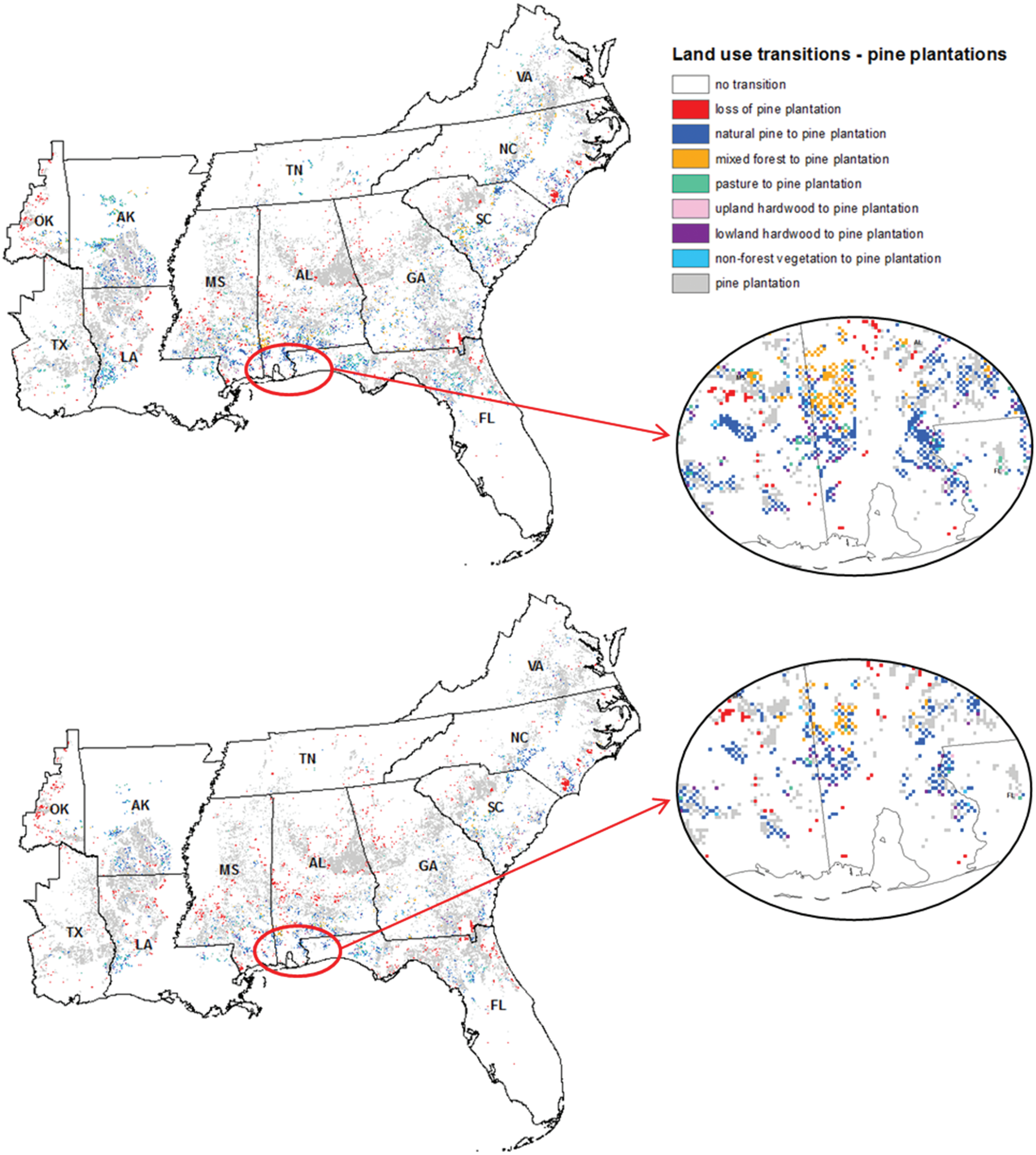

Figure 10: Land use transitions between 2010 and 2030 involving pine plantations for the LhHp (upper panel) and LhLp (lower panel) scenario. Circles show a close-up of the coastal area of Mississippi and Alabama.

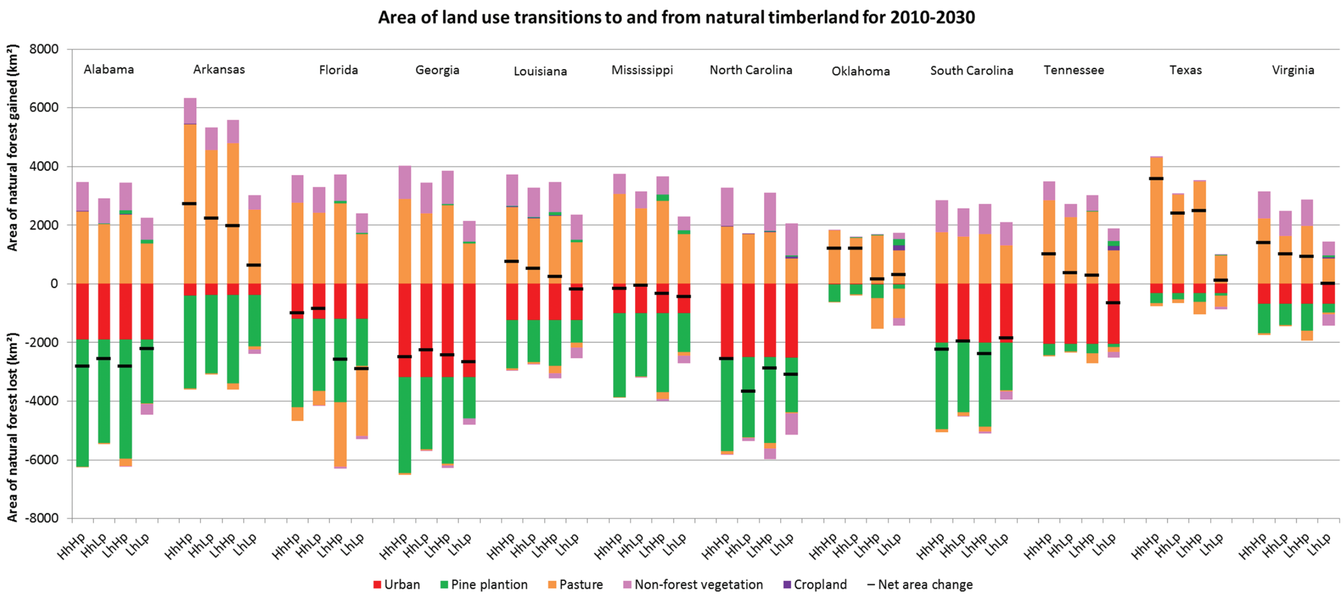

Figure 11: Area in km^2 of land use transitions involving natural timberland between 2010 and 2030, per state and for the different scenarios. Above the x-axis the area of natural timberland gained, colours show the land use type in 2010 that was replaced by pine plantation. Below the x-axis the area of natural timberland lost, colours show the land use type that replaced pine plantation by 2030. Black bars show the net gain or loss of natural timberland per state for each scenario.

level (similar to a study by Diogo *et al.*[59]). Because PLUC was able to successfully replicate historical land-use changes up to the survey unit level, we assume that our projections of future land use can be considered robust up to that level, assuming that future condition are the same as the past.

Discussion

This study quantified and spatially allocated the potential changes in land use in the southeastern USA for different scenarios of future demand for wood pellets and other wood products. Results show that an additional demand for wood pellets (of 11.6 Mt, from a starting point of about 0.5 Mt in 2010) and other wood products can have a considerable impact on timberland area in 2030. Increased wood pellet demand led to projections of establishment of approximately 8000 km^2 (high housing demand) to almost 20 000 km^2 (low housing demand) additional pine plantation area compared to stable pellet demand, which amounts to an increase of 4.7% and 11.2% in pine plantation area, respectively. It also resulted in projections of avoided loss of natural timberland of almost 2000 km^2 (high housing demand) or to a loss of just over 7500 km^2 (low housing demand), which amounts to 0.4% and 1.5% of the current natural timberland area respectively. Our projected timberland area changes are modest compared to previous research on the southeastern USA, which predict a change in pine plantation area in the range of -11% to +67% and a change in timberland area of -10% to +3%, depending on scenario assumptions, timeline and geographical extent[7,12,22,39,67] (Annex 11 gives an overview of previous findings on timberland and pine plantation expansion in the southeastern USA).

The innovative component of this study is the spatial allocation of these changes in timberland area. Projected establishment of new pine plantations occurs mainly in the coastal parts of Virginia, North Carolina, South Carolina, Georgia, Alabama, and Mississippi. This is in line with earlier findings on historical dynamics[37] as well as future projections[22] for this region. According to our results, pine plantations are often established at the expense of natural timberland, mainly natural pine and mixed forest. Projected forest regeneration occurs throughout the southeastern USA but is more concentrated in the eastern parts of Georgia, Arkansas, and Texas. Natural timberland cover was reduced in the areas where pine plantation expands, as well as around all major cities as a result of urbanization. Natural timberland cover was reduced in six states, while in six other states the area increased. This finding differs from Prestemon and Abt,[22] who find a loss of natural timberland for all states in their base scenario between 1995 and 2040. Similarly, however,

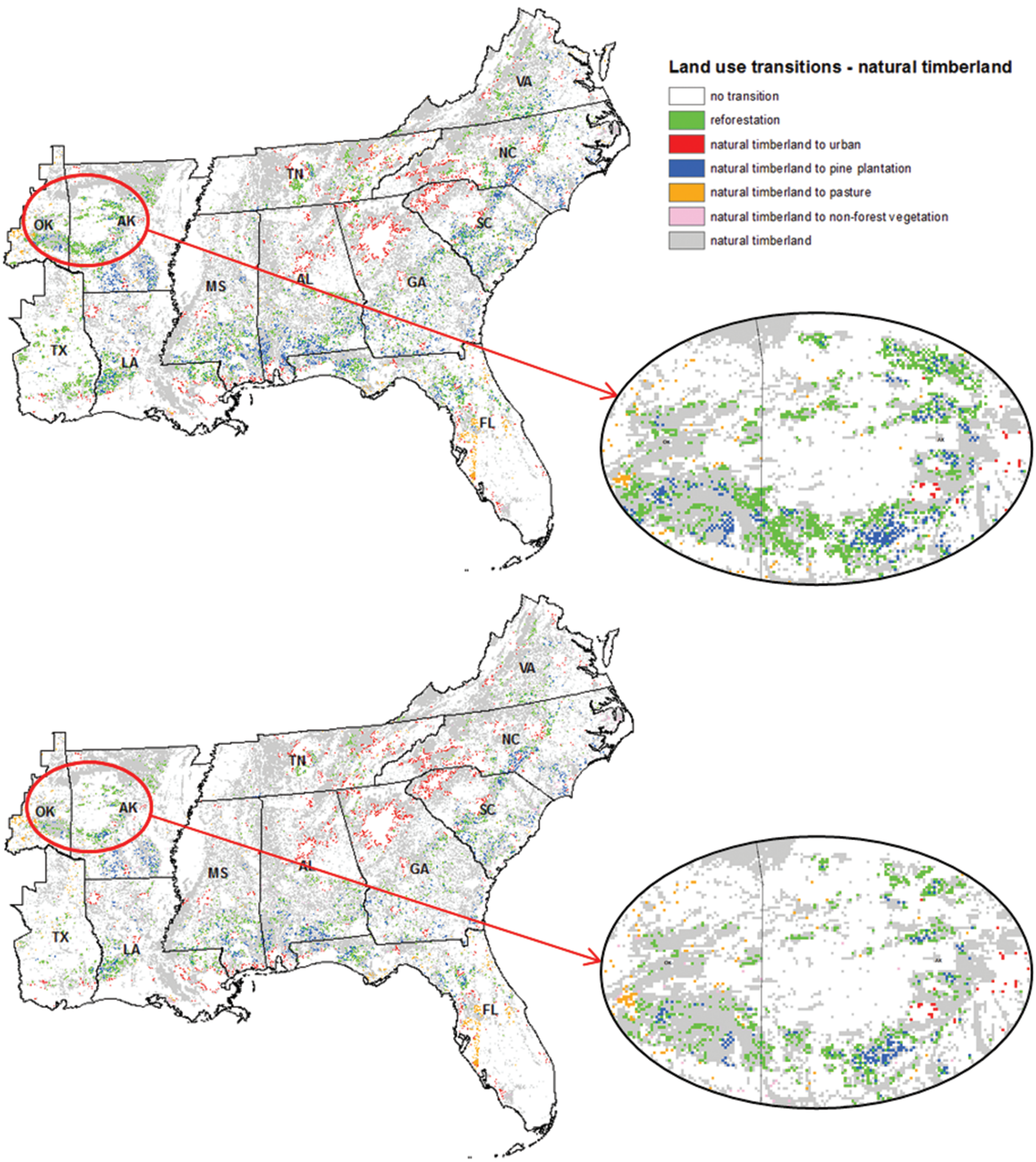

Figure 12: Land use transitions between 2010 and 2030 involving natural timberland for the LhHp (upper figure) and LhLp (lower figure) scenario. Circles show a close-up of central Arkansas and eastern Oklahoma.

they find a strong loss of natural timberland in North Carolina, South Carolina, Georgia, and Alabama (as well as Florida), as a result of pine plantation expansion and urbanization. Validation of the model shows that these results are robust up to the survey unit level (approximately 25 000 km^2 in size on average).

Table 3. Coefficient of variation of the RMSE values for the area of different land use types in 2011 at different spatial levels. The change in area (in km^2) for the input data is also given.

Land use types	Absolute area change NLCD 2001-2011 (km^2)	Ecoregion level	State level	Survey unit level	County level
		Coefficient of variation of the root mean squared error			
Urban	7,309	0.01	0.02	0.04	0.12
Cropland	2,299	0.00	0.05	0.10	0.35
Pasture	13,256	0.05	0.09	0.14	0.36
Pine forest	13,942	0.02	0.08	0.13	0.25
Mixed forest	7,224	0.07	0.07	0.12	0.16
Upland hardwood	8,626	0.04	0.05	0.10	0.18
Lowland hardwood	2,699	0.00	0.01	0.03	0.08
Non-forest vegetation	13,696	0.13	0.15	0.33	1.04

Several limitations of the modeling approach need to be taken into consideration when observing the findings presented here. The PLUC model is based on an extrapolation of historical land-use trends used to project future trends in land use. This may not reflect potential changes in drivers of land-use change over time.[68] The link between the SRTS and PLUC models presented here is based on input-output, without any feedback mechanism between the two models. This means that changes in forest area were only spatially allocated after SRTS was run, so spatial input data such as suitability factors did not influence the outcome of SRTS runs. In reality, there might be spatial variation in a number of input variables of SRTS, such as the cut-off point between small and large roundwood, and agricultural rent. A more robust integration of both models would improve the strength of results.[69] Furthermore, climate change may lead to a shift in land suitability or reduce land availability, particularly on a longer time scale. The impacts of climate change were not considered in this study because of the relatively short timeline of this study, as well as the uncertainty related to the impacts of climate change.

Several assumptions used in the individual models might also have influenced our results in a significant manner. In the SRTS model, forest productivity was fixed throughout the modeling period. However, in the presence of strong forest product markets, forest productivity could increase over time,[22,38] which could result in a lower expected increase in timberland area and a smaller shift from natural timberland to pine plantations. These increases in productivity could be the result of changes in forest management related to, for instance, harvest cycle or planting densities (Jonker *et al.*, unpublished data). Furthermore, the SRTS model is based on the assumption that land or forest owners respond to market prices. It has, however, been shown that other factors – including property size, and age, profession, and income of the land owner, as well as life events, such as the need to raise money for health, education, or retirement – also play a role in forest management and ownership decisions in the southeastern USA.[11,20,70,71] Finally, the SRTS model was also shown to be sensitive to assumptions on elasticity values. The values used in this study are default values for SRTS and in line with previous studies, but choosing different elasticity values would influence forest area projections significantly. Higher elasticity values of feedstock demand price, supply price and supply inventory lead to lower changes in timberland area, particularly for pine plantation.

The results of the PLUC model could be improved by resolving data constraints, for instance by the availability of more recent spatial data, particularly for pine plantations. It was impossible to perform a regression analysis for pine plantation and natural pine independently, because these categories were combined in the historical spatial land-use data. Therefore, planted pine and natural pine were pooled in the regression analysis, while these two land-use types may have different suitability factors. Pine plantation establishment could be more dependent on anthropogenic factors such as accessibility and distance to wood using mills, and, as a result, have a different allocation pattern than natural pine. A forthcoming update of the GAP land-use map could resolve this issue by providing additional spatial data on pine plantation locations. Furthermore, PLUC results at the local level provide an indication of the spatial patterns in that area; however, pixel values should not be considered precise predictions.

The results presented here include a distinction between pine plantations and natural timberland types. The projected shift from natural timberland to pine plantations is expected to have significant sustainability impacts, particularly for biodiversity and carbon storage. Even though natural timberland regenerates rapidly in most areas, it may take a few decades before new forests reach mature levels of carbon storage and biodiversity. However, the transition of pasture into pine plantation forest could increase carbon storage in the landscape. Environmental impacts are expected to differ across the landscape according to the dominant local land-use transition patterns and heterogeneity in biophysical characteristics. These environmental impact assessments will be the subject of further research.

Conclusion

This study provides a spatially explicit assessment of the impact of an increasing wood pellet demand on land-use dynamics, while taking into account demand for other wood products (i.e., saw timber and pulp and paper), as well as development of other land uses (such as urban land and cropland). The modeling approach presented here could be useful for determining land-use-change patterns and identifying the most prominent land-use transitions. This modeling approach can be applied for other scenarios of demand for forest products as well as other projections of land use. In this study, it was applied to determine the impact of increased demand for wood pellets (of 11.6 Mt) and other wood products by 2030. We conclude that an increase in wood pellet demand leads to an increase in pine plantation establishment and an increase in both loss (to pine plantation) and gain (through regeneration) of natural timberland. This results in a lower loss of natural timberland under high pellet demand scenarios. In some areas, increased demand for wood pellets is projected to result in an increased natural timberland cover, but in most locations, it will lead to a substantial shift from natural timberland to pine plantations. Future research could compare the delivery of environmental services for different stand ages for natural timberland and pine plantations, to understand potential impacts of a shift in forest types. The results on land-use transitions developed in this study will be used as input for further research on environmental impacts for carbon storage and biodiversity conservation. Projections created using this model and follow-up analyses of environmental impacts can inform the debate about the sustainability of wood pellets.

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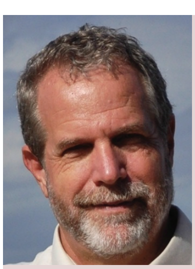

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