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Technical, allocative, and total profit efficiency of loblolly pine forests under changing climatic conditions

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ABSTRACT

Forest ecosystem services (ES) provide significant value to society. Without means to adequately capture that value, societal ES values have little influence on landowners' management decisions, leading to inefficiencies in forest-based ES provision. To understand these inefficiencies, we employ data envelopment analysis (DEA) to assess three types of efficiency – technical, allocative and total profit – of planted pine forests using loblolly pine (*Pinus taeda* L.) in the Southern US as an example. Field data from $n = 28$ plots are used to assess stand-level efficiency in the production of timber, carbon sequestration, and species richness considering inputs such as site index, age and number of trees, precipitation and temperatures. Given the impacts of climate change on key inputs, we also assess efficiency under climate scenarios representing moderate (RCP4.5) and high (RCP8.5) greenhouse gas emissions pathways. We find that 96% of forest plots are technically efficient in providing timber, carbon sequestration and species richness and 75% are allocative or total profit efficient. With climate change, allocative or total profit efficiency remains similar to the initial conditions, and total profit substantially increases (42.8% and 45.6% for RCP4.5 and RCP8.5). These findings highlight the increasingly important role that forests play in providing socially valuable ES.

1. Introduction

Forests provide myriad ecosystem services (ES) to society, including timber, carbon sequestration, water quality, habitat for a variety of plant and animal species, aesthetics, and recreation. For example, in the Southern United States (US), forests provide around 62% of national timber harvested (Smith et al., 2009), have the potential to sequester 23% of regional emissions of greenhouse gases (Han et al., 2007), produce 34% of the regional water yield (Lockaby et al., 2013), and host over 1000 native terrestrial vertebrates with highest species richness occurring in the Mid-South and Coastal Plain areas that are dominated by planted pine forests (Trani Griep and Collins, 2013). These forests also play a critical role in providing economically-important outdoor recreation and ecotourism opportunities, with 75 million people age 16 years or older participating in forest-based recreation each year (Cordell et al., 2013).

Sustainable forestry to ensure the continued provision of these vitally important ecosystem services has become a significant societal priority (Matta et al., 2007). This is particularly relevant in the case of nonindustrial private forest landowners who own around 49 million ha in the Region (68% of private timberlands) (Smith et al., 2009), whose lands are needed to sustain the flow of ES and enhance the resilience of forest-connected ecosystems in light of changing climatic conditions. Market mechanisms such as government payment programs, mitigation markets, and other incentives programs are a promising approach to incentivize these private forest landowners to conserve ES (Deal et al., 2012). In this context, valuation of forest ES in monetary units becomes critical since it permits analyzing tradeoffs and synergies in the production of ES, and estimating the societal benefits of forest ES in units that can be easily understood by a broad audience to help garner public support (Costanza et al., 2014).

Numerous studies have assessed the provision of forest-based ES but very little work has attempted to assess multiple ES simultaneously (Tallis et al., 2008). Failing to incorporate the relationships among ES may incur unwanted tradeoffs and limit the opportunities to take advantage of synergies and create unexpected changes in the provision of ES (Bennett et al., 2009). The lack of scientific research on multiple

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provisions of ES is a significant shortcoming in the literature, and one that presents a substantial challenge that is only just beginning to yield way. For example, see the work by Schwenk et al. (2012) who applied multi-criteria decision analysis and forests simulation models to determine the tradeoffs among carbon sequestration, wood production, and biodiversity in northern forests in the US.

The effects of climate change on forest-based ES are also a major policy concern. Continued anthropogenic emissions of greenhouse gases is expected to exacerbate Earth's warming and changes to weather patterns (IPCC, 2013). In the Southeastern US, mean temperatures are expected to increase up to 3 °C (Kirtman et al., 2013), and mean precipitation is expected to rise between 10 and 20% in winter months by 2100 (IPCC, 2013). These changing climate conditions are expected to significantly affect the production of forest-based ES. For example, timber productivity in southern forests is expected to increase with warmer temperatures and higher levels of carbon dioxide (Wertin et al., 2012), and the viable growing region for several southern pine species may shift farther north generating both gains and losses in the timber industry (Sohngen et al., 2001). However, these gains in productivity may be offset by increased water stress from higher temperatures and associated water loss by evapotranspiration (Lockaby et al., 2013). Climate change may also increase decomposition of organic matter thus releasing more carbon to the atmosphere (Peterson et al., 2014). Additionally, increased frequencies and magnitudes of natural disturbances to forests (e.g., wildfires, pests and hurricanes) as the climate warms are expected to negatively impact the provision of ES (Peterson et al., 2014).

Although natural forests play a pivotal role in the provision of biodiversity, plantation forests can also provide benefits to biodiversity. Plantation forests may provide forest habitats and also help reduce the pressure on natural forests (Pawson et al., 2013). Overall biodiversity is enhanced with mixed plantations over successive rotations (Jeffries et al., 2010). Planting different tree species plantations can be desirable to support tree species richness and other wildlife species (Andreu et al., 2008). Furthermore, societal demands for non-timber forest products such as biodiversity from forest plantations in the southeastern US are increasing (Andreu et al., 2008).

In the Southeastern US, research on economic valuation of multiple forest ES is limited, particularly in the context of climate change. Notable studies in the Southeastern US that have engaged both forest ES and climate change include work on climate change and the economics of timber production and carbon sequestration (Stainback and Alavalapati, 2002; Susaeta et al., 2014); and the impact of bioenergy markets on amenity production of southern forests from a social and private perspective (Hallmann and Amacher, 2014).

The main goal of this study is to economically assess the provision of multiple ES – timber production, carbon sequestration, and biodiversity – from planted loblolly pine forest (*Pinus taeda* L.) plots in the state of Florida under climate change. Loblolly pine was selected given its role as the main dominant commercial species in the South, occupying >13 million of ha (Susaeta et al., 2014). The effects of climate change on this species could cause significant impacts on the provision and value of forest-based ES.

We use a non-parametric approach known as data envelopment analysis (DEA) (Charnes et al., 1978) for the estimation of the economic revenues of ES associated with loblolly pine forests. In DEA, the basic unit of analysis is the decision making unit (DMU) that requires the same inputs to produce the same outputs. DEA is a mathematical optimization technique that identifies the production technology frontier on which the relative performance of each DMU is compared to the most efficient DMUs (Cooper et al., 2006). Originally designed to measure the relative efficiency of a decision making unit (DMU), DEA has been also employed to determine proficient efficiency of DMUs (Cooper et al., 2011). The main advantage of DEA is that a mathematical specification for the production function is not required; and the main limitations of DEA are that its efficiency measures can be strongly affected by the sample size and it is more sensitive to measurement error than parametric approaches (Avkiran, 2013).

DEA has been widely applied to forestry industry, particularly in the context of logistics and transportation of timber (Marinescu et al., 2005), the operation of wood processing facilities (Upadhyay et al., 2012), and forest management (Bogetoft et al., 2003). However, few studies have employed DEA to assess forest ES. For example, Macpherson et al. (2013) used DEA to analyze the efficiency of environmental policies and resource allocations by examining the impacts of climate, hydrology and topography on forest fragmentation within the Southern US. Bosetti and Locatelli (2006) used this approach to determine the efficiency of natural parks in wilderness protection using biodiversity indicators in Italy. In general, these DEA based studies do not address the economic implications of changes in the efficiency of the provision of ES.

Our study adds to the existing literature by evaluating the technical, allocative and profit efficiencies of loblolly pine forests' ES under changing climatic conditions, and by applying a DEA based additive model. We use plot-level Forest Inventory and Analysis (FIA) data (U.S. Department of Agriculture Forest Service, 2014) to assess the economic performance of planted loblolly pine forests in the production of timber, biodiversity, and carbon sequestration under current and future changes in forest productivity conditions and levels of precipitation and temperatures associated with climate change. Changes in future forest productivity conditions due to climate change are simulated based on the scenarios proposed within the context of the Pine Integrated Network: Education, Mitigation and Adaptation Project (PINEMAP) (Teskey, 2014). PINEMAP is a Coordinated Agricultural Project funded in 2011 by the USDA National Institute of Food and Agriculture that aims to increase carbon sequestration by loblolly pine plantations by 15% by 2030 (http://pinemap.org/). Future climatic conditions (temperatures and precipitations) are simulated using the Multivariate Adaptive Constructed Analogs (MACA) approach (http://maca.northwestknowledge.net/). The rest of the paper is as follows. Section 2 outlines how the theoretical additive DEA models determine the technical and overall profit efficiencies. Section 3 describes the empirical additive models, climatic scenarios and the applicability of the DEA models. Results of the economic efficiency of forest plots under current and future climatic conditions are discussed in Section 4. Section 5 provides our concluding remarks, study limitations and future research considerations of our study.

2. Theoretical data envelopment analysis (DEA) additive models

Each DMU is assumed to require the same inputs to generate the same outputs. Inputs and outputs can be affected (discretionary) or not affected (non-discretionary) by management decisions. Examples of non-discretionary and discretionary inputs related to land management are climatic variables, and amount of fertilizers, respectively, whereas example of discretionary and non-discretionary outputs are timber production, and water surface levels. We extend the additive models proposed by Cooper et al. (2011) to determine the lost profits due to technical, allocative and overall inefficiencies by incorporating the use of discretionary and non-discretionary variables as suggested by Charnes et al. (1987). The main advantage of additive models over a traditional output or input oriented model is that it allows simultaneously maximizing outputs and minimizing inputs (Cooper et al., 2011).

The performance of a DMU can be typically analyzed from a technical and allocative perspective. Cooper et al. (2011) refer to technical efficiency when it is not possible to increase an output or decrease an input without increasing other outputs or decreasing other inputs; allocative (price) efficiency as the gain of a technically efficient DMU in terms of combinations of inputs and outputs given their costs and prices; and overall efficiency as the product of allocative and technical efficiencies. The following theoretical framework follows Cooper et al.

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(2011). For simplicity, we present only the technical and overall profit models. Let's assume we have n DMUs, where each DMUj ($j=1,\ldots,n$) needs the same x inputs v_{ij} ($i=1,\ldots,x$), to produce the same y outputs q_{rj} ($r=1,\ldots,y$). The technical additive model is for a specific DMUk presented as follows:

$$\begin{aligned}&\text{Max}\sum_{r=1}^{y} z_{rk}^{+}+\sum_{i=1}^{x} z_{ik}^{-}\\&\text{subject to}\\&\sum_{j=1}^{n} q_{rj}\lambda_j - z_{rk}^{+}=q_{rk}(r=1,2,\ldots,y)\\&\sum_{j=1}^{n} v_{ij}\lambda_j + z_{ik}^{-}=v_{ik}(i=1,2,\ldots x)\\&\sum_{j=1}^{n}\lambda_j=1\\&z_{rk}^{+}\le\alpha_r q_{rk}(r=1,2,\ldots,y)\\&z_{ik}^{-}\le\beta_i v_{ik}(i=1,2,\ldots,x)\\&\lambda_j,\ z_{rk}^{+},\ z_{ik}^{-}\ge 0,\ \forall i,\ j,\ r.\end{aligned}\tag{1}$$

In Eq. (1), λ_j represents the shadow price or the proportion given by DMUj to evaluate DMUk, z_{rk}^{+}, z_{ik}^{-} represent the slacks variables (output shortfalls and input excesses, respectively, for the evaluated DMU), and α_r,β_i represent the degree of discretion to outputs and inputs. Setting $\alpha_r=0$ characterizes a non-discretionary output r while $\alpha_r\approx\infty$ implies that output r is completely discretionary. Assigning $\beta_i=0$ represents a completely non-discretionary input i while $\beta_i=1$ characterizes a discretionary input i (Cooper et al., 2006). By solving Eq. (1) for the evaluated DMU, we obtain optimal slack values z_{rk}^{+*}, z_{ik}^{-*} and shadow prices λ_j^*, and can determine optimal values of outputs $\hat{q}_{rk}$ and inputs $\hat{v}_{ik}$. These new values for output $\hat{q}_{rk}$ and input $\hat{v}_{ik}$ are located on the efficiency frontier. A DMUk is said to be technically efficient (Pareto-Koopmans efficient) if the optimal slacks z_{rk}^{+*}, $z_{ik}^{-*}=0$ (Cooper et al., 2011). Weights for inputs and outputs are not considered for this technical efficiency model. Thus:

$$\begin{aligned}&\hat{q}_{rk}=q_{rk}+z_{rk}^{+*}\ge 0,\quad (r=1,2\ldots,y)\\&\hat{v}_{ik}=v_{ik}-z_{ik}^{-*}\le 0,\quad (i=1,2,\ldots,x).\end{aligned}\tag{2}$$

The allocative efficiency model for a DMUk when costs of inputs and prices of outputs are available is presented as follows:

$$\begin{aligned}&\text{Max}\sum_{r=1}^{y} p_r\hat{z}_{rk}^{+}+\sum_{i=1}^{x} c_i\hat{z}_{ik}^{-}\\&\text{subject to}\\&\sum_{j=1}^{n} q_{rj}\lambda_j - \hat{z}_{rk}^{+}=\hat{q}_{rk}(r=1,2,\ldots,y)\\&\sum_{j=1}^{n} v_{ij}\lambda_j + \hat{z}_{ik}^{-}=\hat{v}_{ik}(i=1,2,\ldots,x)\\&\sum_{j=1}^{n}\lambda_j=1\\&\hat{z}_{rk}^{+}\le\alpha_r\hat{q}_{rk}\ (r=1,2,\ldots,y)\\&\hat{z}_{ik}^{-}\le\beta_i\hat{v}_{io}\ (i=1,2,\ldots,x)\\&\lambda_j\ge 0,\ \forall j;\ \hat{z}_{ik}^{-},\ \hat{z}_{rk}^{+}\ \text{free}\ \forall i,\ r\end{aligned}\tag{3}$$

In Eq. (3), p_r is the unit price to the output slacks $\hat{z}_{rk}^{+}$ and c_i is the unit cost to the input slack $\hat{z}_{ik}^{-}$. Contrary to the technical efficiency model, the slacks can take positive or negative values, a necessary condition to allow for substitution between inputs and outputs to reach profit efficiency (Cooper et al., 2011). The overall efficiency model is as follows:

$$\begin{aligned}&\text{Max}\sum_{r=1}^{y} p_r z_{rk}^{+}+\sum_{i=1}^{x} c_i z_{ik}^{-}\\&\text{subject to}\\&\sum_{j=1}^{n} q_{rj}\lambda_j - z_{rk}^{+}=q_{rk}(r=1,2,\ldots,y)\\&\sum_{j=1}^{n} v_{ij}\lambda_j + z_{ik}^{-}=v_{ik}(i=1,2,\ldots,x)\\&\sum_{j=1}^{n}\lambda_j=1\\&z_{rk}^{+}\le\alpha_r q_{rk}\ (r=1,2,\ldots,y)\\&z_{ik}^{-}\le\beta_i v_{io}\ (i=1,2,\ldots,x)\\&\lambda_j\ge 0,\ \forall j;\ z_{ik}^{-},\ z_{rk}^{+}\ \text{free}\ \forall i,\ r\end{aligned}\tag{4}$$

The profit model provides a measure of the profits foregone due to overall inefficiency which is represented by the objective function of Eq. (4). The overall profits lost (OPL) caused by inefficient DMUs can be due to technical and/or allocative inefficiencies(Cooper et al., 2011). The profits foregone due to technical (TPL) and allocative inefficiencies (APL) are, respectively, $\sum_{r=1}^{y} p_r z_{rk}^{+*}+\sum_{i=1}^{x} c_i z_{ik}^{-*}$ and $\sum_{r=1}^{y} p_r\hat{z}_{rk}^{+*}+\sum_{i=1}^{x} c_i\hat{z}_{ik}^{-*}$, where z_{rk}^{+*}, z_{ik}^{-*}, and $\hat{z}_{rk}^{+*}$, $\hat{z}_{ik}^{-*}$, represent the optimal slacks values obtained by solving Eqs. (1) and (3). Thus, the overall profits lost (OPL) is:

$$\begin{aligned}\text{Max}\sum_{r=1}^{y} p_r z_{rk}^{+}+\sum_{i=1}^{x} c_i z_{ik}^{-} &= \sum_{r=1}^{y} p_r\hat{z}_{rk}^{+*}+\sum_{i=1}^{x} c_i\hat{z}_{ik}^{-*}\\&+\sum_{r=1}^{y} p_r\hat{z}_{rk}^{+*}+\sum_{i=1}^{x} c_i\hat{z}_{ik}^{-*}\end{aligned}\tag{5}$$

3. Empirical DEA additive model

We employ data from planted loblolly pine forest plots[1] (DMUs) surveyed by the Forest Inventory and Analysis (FIA) research program in the state of Florida between 2002 and 2004 (U.S. Department of Agriculture Forest Service, 2014) to determine our DMUs for the additive models. A total of $n = 28$ FIA forest plots are selected which is in line with the rule of thumb of selecting a sample size at least three times larger than the total number of inputs and outputs (Edirisinghe and Zhang, 2010). The geographical location of the planted loblolly pine forest plots are presented in Fig. 1.

We assume that a loblolly pine forest plot requires forestry and climatic-related inputs to produce the following outputs: wood production, carbon sequestration, and biodiversity. Wood production reflects different standing wood assortments (sawtimber, chip-n- saw, and pulpwood) typically obtained when southern forests are harvested. Carbon sequestration is considered in the belowground and aboveground portion of the tree. We employ tree species richness as a proxy for biodiversity. Higher tree species richness may reflect a low vulnerability of planted forests to pest or insects (Bauhus and Schmerbeck, 2010) and contribute to ecosystem services such as water flow regulation (Bremer and Farley, 2010), improving the overall productivity of plantation (Jeffries et al., 2010). We select the following forest-related inputs that influence loblolly pine forest outputs: age of the trees, productivity conditions (site index), and tree density. We also include climatic observations that affect the performance of loblolly pine forests such as total annual precipitation, and average minimum and maximum temperatures. The inputs and outputs and their descriptive statistics are summarized in Table 1.

The empirical technical, profit efficiency models, and profits foregone due to technical, allocative and total inefficiencies, for a DMU$_k$, with the definition of the key parameters, are shown in Table 2. A relevant feature of the empirical additive models is the level at which inputs and outputs can be changed at the discretion of managers. Intuitively, the weights of temperatures (β_{mx}, β_{mn}), precipitation (β_p), and age of the trees (β_a) = 0, since they cannot be controlled (non-discretionary) by forest landowners or managers (Table 2). As such, the monetary costs associated to the same inputs are ruled out from the allocative and overall profit model, and not considered in profits foregone due to technical, allocative and overall inefficiencies (Eqs. (6b)–(6f)).

In the case of tree density we assume a $\beta_d=1$ since it can be completely varied at the discretion of forest landowners/managers. In the case of site index – measured as the average height of dominant

[1] Each loblolly pine forest plot (0.068 ha) consists of 4 subplots with a 7.3 m radius where all trees with diameters >0.13 m are measured (O'Connell et al., 2014). All loblolly pine forest plots are privately owned, artificially regenerated, show no indication of disturbance damage, and present some evidence of site preparation, fertilization and weed control (O'Connell et al., 2014).

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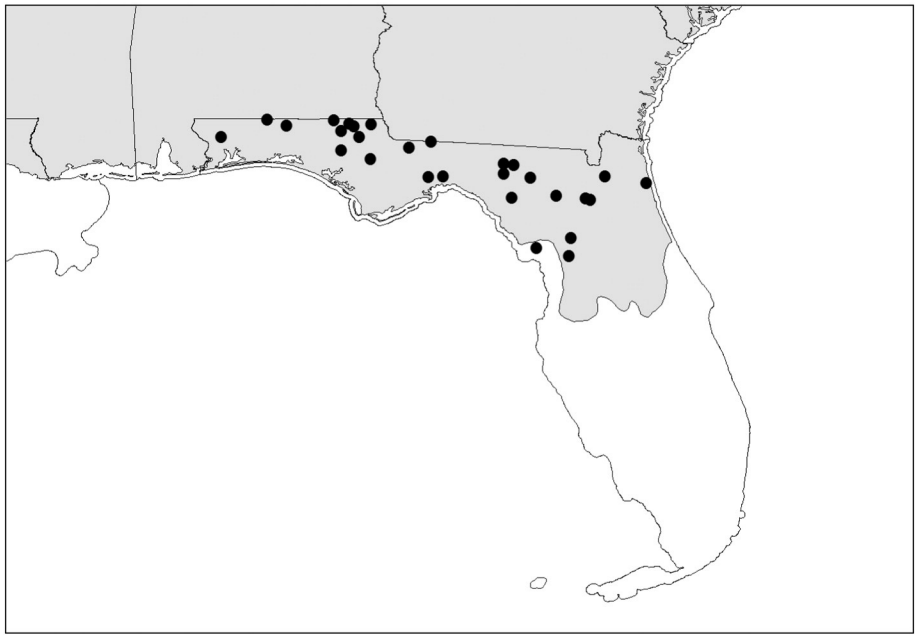

Fig. 1. Geographical location of loblolly pine plots in Florida.

Table 1
Inputs and outputs per loblolly pine forest plot ($n = 28$) and descriptive statistics.

Inputs	Mean	Standard deviation	Minimum	Maximum
Site index (m)	27.3	3.6	19.5	32.0
Age of the forest stand (years)	26.5	11.0	14	65
Number of trees	23 (338)	17.5 (258)	3 (44)	73 (1073)
Average annual maximum temperature (°C)	26.8	1.0	25.2	28.9
Average annual minimum temperature (°C)	13.8	1.1	11.5	16.6
Total annual precipitation (mm)	1617.0	138.2	1365.7	1887.3
Outputs				
Timber production (m^3)	5.4 (78.9)	3.3 (47.9)	0.49 (7.2)	14.4 (211.3)
Carbon sequestration (Mg)	0.09 (1.33)	0.06 (0.86)	0.25 (3.66)	0.01 (0.1)
Species richness	4.6 (67.2)	3.3 (48.4)	1 (14.7)	14 (205.9)

Notes: in parentheses, values at the hectare level.

and co-dominant trees at a base age – this indicator of forest productivity depend on soil quality and climatic conditions but it also can be affected by silvicultural treatments. For example, site index for loblolly pine has been increased by 35% after 25 years of intensive forest management in the Southern US (Jokela et al., 2010). Therefore we assign a $\beta_s = 0.5$ for site index to illustrate that it can be considered as both discretionary and non-discretionary input (Table 2). In the case of outputs, we assume that wood production and sequestered carbon outputs are discretionary ($\alpha = \infty$). Silvicultural management and tree genetic programs can increase significantly timber production; and the use of fertilizers and herbicides, can also increase carbon sequestration (Jokela et al., 2010). In the case of tree species richness, it may also be affected by site preparation, tree species, stand density management, and rotation lengths (Bauhus and Schmerbeck, 2010). For example, the removal of competing non-wood species may favor tree species richness and ameliorate negative impacts of climate change like pest outbreaks. Controlling tree species richness is desirable in forest plantations since it may increase the forest productivity (Jeffries et al., 2010). Thus we assign an $\alpha = \infty$ for tree species richness (Table 2).

We assume hand planting costs (c_d) of \$0.125 per loblolly pine seedling (Dooley and Barlow, 2013) to represent the cost of tree density per plot. We then determine the costs associated with site index (c_s) by assessing the costs incurred in two silvicultural treatments for loblolly pine forest stands to achieve the site indexes of 20 m and 26 m reported by Jokela et al. (2010).[2] Our analysis considers both loblolly pine forest stands annually fertilized from age 1 year until age 10 years and loblolly pine forest stands without any fertilization treatments (control) at the hectare level. Site preparation and fertilization costs of \$324 ha^{-1} and \$173 ha^{-1} are assumed respectively (Dooley and Barlow, 2013). Thus, the total costs of the annually fertilized and control loblolly pine forest stands are, respectively, \$1398 ha^{-1} (\$95 $plot^{-1}$) and \$324 ha^{-1} (\$22 $plot^{-1}$). We divide the costs per plot of each treatment by the site indexes of 26 m and 20 m respectively to obtain a cost per meter of site index (\$3.6 m^{-1} $plot^{-1}$ and \$1.1 m^{-1} $plot^{-1}$, respectively). Finally, we average both cost estimates and determine a site index cost for loblolly pine (c_s) of \$2.4 m^{-1} to cover the wide spectrum of forest productivity conditions.

Wood production per forest plot represents different assortments of standing timber (stumpage), thus we determine a weighted price of "in situ" wood (price of standing timber or stumpage price, p_w) using the proportion of sawtimber, chip and saw and pulpwood — traditional forest products obtained when pines are harvested. We use average annual stumpage prices for the state of Florida in 2014 (Timber Mart-South, 2014) to determine the price associated with wood production per forest plot — \$34.2 m^{-3}, \$27.1 m^{-3} and \$17.8 m^{-3} for sawtimber,

[2] Intensified forest management in the Southern U.S. has caused an increased in the site index for loblolly pine after a rotation length of 25 years, from 20 m (no silvicultural treatments) to 26 m (use of fertilization treatments) (Jokela et al., 2010).

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Table 2
Empirical DEA models and losses in technical (TPL), allocative (APL) and overall profitability (OPL).

Technical model (TPL) (6a)	Allocative model (APL) (6b)	Overall profit model (OPL) (6c)
Max $z_{wk}^{+}+z_{ck}^{+}+z_{bk}^{+}+z_{ak}^{-}+z_{sk}^{-}+z_{dk}^{-}+z_{pk}^{-}+z_{mxk}^{-}+z_{mnk}^{-}$	Max $p_w\hat{z}_{wk}^{+}+p_c\hat{z}_{ck}^{+}+p_b\hat{z}_{bk}^{+}+c_s\hat{z}_{sk}^{-}+c_d\hat{z}_{dk}^{-}$	Max $p_wz_{wk}^{+}+p_cz_{ck}^{+}+p_bz_{bk}^{+}+c_sz_{sk}^{-}+c_dz_{dk}^{-}$
subject to	subject to	subject to
$\sum_{j=1}^{n}q_{wj}\lambda_j-z_{wk}^{+}=q_{wk}$	$\sum_{j=1}^{n}q_{wj}\lambda_j-\hat{z}_{wk}^{+}=\hat{q}_{wk}$	$\sum_{j=1}^{n}q_{wj}\lambda_j-z_{wk}^{+}=q_{wk}$
$\sum_{j=1}^{n}q_{cj}\lambda_j-z_{ck}^{+}=q_{ck}$	$\sum_{j=1}^{n}q_{cj}\lambda_j-\hat{z}_{ck}^{+}=\hat{q}_{ck}$	$\sum_{j=1}^{n}q_{cj}\lambda_j-z_{ck}^{+}=q_{ck}$
$\sum_{j=1}^{n}q_{bj}\lambda_j-z_{bk}^{+}=q_{bk}$	$\sum_{j=1}^{n}q_{bj}\lambda_j-\hat{z}_{bk}^{+}=\hat{q}_{bk}$	$\sum_{j=1}^{n}q_{bj}\lambda_j-z_{bk}^{+}=q_{bk}$
$\sum_{j=1}^{n}v_{aj}\lambda_j+z_{ak}^{-}=v_{ak}$	$\sum_{j=1}^{n}v_{aj}\lambda_j+\hat{z}_{ak}^{-}=\hat{v}_{ak}$	$\sum_{j=1}^{n}v_{aj}\lambda_j+z_{ak}^{-}=v_{ak}$
$\sum_{j=1}^{n}v_{sj}\lambda_j+z_{sk}^{-}=v_{sk}$	$\sum_{j=1}^{n}v_{sj}\lambda_j+\hat{z}_{sk}^{-}=\hat{v}_{sk}$	$\sum_{j=1}^{n}v_{sj}\lambda_j+z_{sk}^{-}=v_{sk}$
$\sum_{j=1}^{n}v_{dj}\lambda_j+z_{dk}^{-}=v_{dk}$	$\sum_{j=1}^{n}v_{dj}\lambda_j+\hat{z}_{dk}^{-}=\hat{v}_{dk}$	$\sum_{j=1}^{n}v_{dj}\lambda_j+z_{dk}^{-}=v_{dk}$
$\sum_{j=1}^{n}v_{pj}\lambda_j+z_{pk}^{-}=v_{pk}$	$\sum_{j=1}^{n}v_{pj}\lambda_j+\hat{z}_{pk}^{-}=\hat{v}_{pk}$	$\sum_{j=1}^{n}v_{pj}\lambda_j+z_{pk}^{-}=v_{pk}$
$\sum_{j=1}^{n}v_{mxj}\lambda_j+z_{mxk}^{-}=v_{mxk}$	$\sum_{j=1}^{n}v_{mxj}\lambda_j+\hat{z}_{mxk}^{-}=\hat{v}_{mxk}$	$\sum_{j=1}^{n}v_{mxj}\lambda_j+z_{mxk}^{-}=v_{mxk}$
$\sum_{j=1}^{n}v_{mnj}\lambda_j+z_{mnk}^{-}=v_{mnk}$	$\sum_{j=1}^{n}v_{mnj}\lambda_j+\hat{z}_{mnk}^{-}=\hat{v}_{mnk}$	$\sum_{j=1}^{n}v_{mnj}\lambda_j+z_{mnk}^{-}=v_{mnk}$
$\sum_{j=1}^{n}\lambda_j=1$	$\sum_{j=1}^{n}\lambda_j=1$	$\sum_{j=1}^{n}\lambda_j=1$
$z_{wk}^{+}\le\alpha_wq_{wk}$	$\hat{z}_{wk}^{+}\le\alpha_w\hat{q}_{wk}$	$z_{wk}^{+}\le\alpha_wq_{wk}$
$z_{ck}^{+}\le\alpha_cq_{ck}$	$\hat{z}_{ck}^{+}\le\alpha_c\hat{q}_{ck}$	$z_{ck}^{+}\le\alpha_cq_{ck}$
$z_{bk}^{+}\le\alpha_bq_{bk}$	$\hat{z}_{bk}^{+}\le\alpha_b\hat{q}_{bk}$	$z_{bk}^{+}\le\alpha_bq_{bk}$
$z_{ak}^{-}\le\beta_av_{ak}$	$\hat{z}_{ak}^{-}\le\beta_a\hat{v}_{ak}$	$z_{ak}^{-}\le\beta_av_{ak}$
$z_{sk}^{-}\le\beta_sv_{sk}$	$\hat{z}_{sk}^{-}\le\beta_s\hat{v}_{sk}$	$z_{sk}^{-}\le\beta_sv_{sk}$
$z_{dk}^{-}\le\beta_dv_{dk}$	$\hat{z}_{dk}^{-}\le\beta_d\hat{v}_{dk}$	$z_{dk}^{-}\le\beta_dv_{dk}$
$z_{mxk}^{-}\le\beta_{mx}v_{mxk}$	$\hat{z}_{mxk}^{-}\le\beta_{mx}\hat{v}_{mxk}$	$z_{mxk}^{-}\le\beta_{mx}v_{mxk}$
$z_{mnk}^{-}\le\beta_{mn}v_{mnk}$	$\hat{z}_{mnk}^{-}\le\beta_{mn}\hat{v}_{mnk}$	$z_{mnk}^{-}\le\beta_{mn}v_{mnk}$
$\lambda_j,\ z_{wk}^{+},\ z_{ck}^{+},\ z_{bk}^{+},\ z_{ak}^{-},\ z_{sk}^{-},\ z_{dk}^{-},\ z_{mxk}^{-},\ z_{mnk}^{-}\ge0,\ \forall j$	$\lambda_j\ge0,\ \forall j;\ \hat{z}_{wk}^{+},\ \hat{z}_{ck}^{+},\ \hat{z}_{bk}^{+},\ \hat{z}_{ak}^{-},\ \hat{z}_{dk}^{-},\hat{z}_{pk}^{-},\hat{z}_{mxk}^{-},\hat{z}_{mnk}^{-}$ *free*	$\lambda_j\ge0,\ \forall j,\ z_{wk}^{+},\ z_{ck}^{+},\ z_{bk}^{+},\ z_{ak}^{-},z_{dk}^{-},z_{pk}^{-},z_{mxk}^{-},z_{mnk}^{-}$ *free*
$\mathrm{TPL}=p_wz_{wk}^{+*}+p_cz_{ck}^{+*}+p_bz_{bk}^{+*}+c_sz_{sk}^{-*}+c_dz_{dk}^{-*}$ (6d)	$\mathrm{APL}=p_w\hat{z}_{wk}^{+}+p_c\hat{z}_{ck}^{+}+p_b\hat{z}_{bk}^{+}+c_s\hat{z}_{sk}^{-}+c_d\hat{z}_{dk}^{-}$ (6e)	$\mathrm{OPL}=p_wz_{wk}^{+}+p_cz_{ck}^{+}+p_bz_{bk}^{+}+c_sz_{sk}^{-}+c_dz_{dk}^{-}$ (6f)

Notes: z_w^{+}, α_w, p_w; z_c^{+}, α_c, p_c; and z_b^{+}, α_b, p_b are, respectively, the slacks, weights and prices of timber production (q_t), carbon sequestration (q_c), tree species richness (q_b); z_s^{-}, β_s, c_s; and z_d^{-}, β_d, c_d, are, respectively, the slacks, weights and costs associated with site productivity and tree density; z_a^{-}, β_a; z_p^{-}, β_p; z_{mx}^{-}, β_{mx}; and z_{mn}^{-}, β_{mn}, are, respectively, the slacks and weights for age of the trees, precipitation, maximum temperature and minimum temperature; α_w, α_c, $\alpha_b=\infty$; $\beta_s=0.5$, $\beta_d=1$; β_a, β_p, β_{mx}, $\beta_{mn}=0$.

chip and saw, and pulpwood, respectively. Since forest management impacts the proportion of different forest products, we determine an average proportion of sawtimber, chip and saw and pulpwood for a forest plot aging between 1 and 50 years by combining site indexes of 14, 20 and 26 m, and initial planting densities of 750, 1500, and 2250 tree per ha using a growth and yield model for loblolly pine (Carbon Resource Science Center, 2014). Thus, we multiply the average proportion of sawtimber, chip and saw and pulpwood by the average stumpage price associated with each forest product to obtain the price of "in-situ" wood production per forest plot for ages between 1 and 50 years (p_w). Finally, we match the price of wood production with the age of forest plot at the time of the FIA observation.

Different prices of carbon sequestration have been reported by governmental and private organizations. The California Environmental Protection Agency Air Resources Board and Quebec's Ministry of Sustainable Development, Environment and the Fight against Climate Change have set a mean price of carbon to enter a cap and trade program of \$12.5 $Mg^{-1}CO_2e$ in 2015 (megagram of carbon dioxide equivalent) (\$46.4 $Mg^{-1}C$) (California Environmental Protection Agency, 2014). The State of the Voluntary Carbon Markets 2015 reported an average worldwide market carbon offset price of \$3.8 Mg^{-1} CO_2e in 2014; and average prices of \$7.7 and \$8.5 Mg^{-1} CO_2e for tree planting and forest management projects, respectively, between 2007 and 2014 (Hamrick and Goldstein, 2015). In our analysis we set the price of sequestered carbon (p_c) to \$12.5 Mg^{-1} CO_2e (\$46.4 Mg^{-1} C) to reflect the actual market price for carbon sequestration in the U.S.[3]

Traditionally, non-market valuation methods have been used to determine the value of biodiversity. Costs related to enhance tree species richness in forestlands may range from \$62.5 to \$150 ha^{-1} depending on the silvicultural activity, e.g., prescribed burning or invasive species control (Matta et al., 2007). For our analysis we use an estimate of \$87 ha^{-1} (\$6 $plot^{-1}$; 1 plot = 0.068 ha), a value suggested by Matta et al. (2007) to reflect the price of species richness (p_b).

3.1. Climatic scenarios

We define two main climatic scenarios to ascertain the impacts of climate change on the profit efficiency of loblolly pine forest plots in the provision of ecosystem services: i) *Scenario A* in which a loblolly pine forest's inputs and outputs are measured at the time of FIA observation; and ii) *Scenario B* in which a loblolly pine forest faces changes in climatic conditions affecting outputs and inputs. *Scenario B* is divided into two sub-scenarios, defined according to two representative concentration pathways (RCPs) for greenhouse gas emissions: RCP4.5 (*Scenario* B_1) and RCP8.5 (*Scenario* B_2) for the time frame 2014–2030. These RCPs, widely used by the IPCC, represent, respectively, low and high greenhouse gas emission trajectories over time considering future changes related to energy and land use, socioeconomic and technological conditions, and emissions of greenhouse gases (IPCC, 2013).

We use the Multivariate Adaptive Constructed Analogs (MACA) approach and apply it to the second generation Canadian Earth system model CanESM2 to generate historical and forecast future climate data[4] for *Scenarios A* and *B*. Thus, for each loblolly pine forest plot, we obtain both historical and RCP projections, for average monthly maximum and minimum temperatures, and monthly total precipitation, at the time of FIA observation and the 2014–2030 time frame. Mean annual estimates for temperatures and precipitation are obtained by averaging the projections for the monthly climatic variables. Table 3 shows the

[3] Since carbon credits are treated as a commodity, we assume the same price for carbon sequestration in all the forest plots. The total price for carbon sequestration per plot will depend upon the characteristics and variability (e.g. number of trees and wood production) of each loblolly pine forest plot. Sellers and buyers of carbon credits can have different perceptions regarding the carbon purchase agreement, e.g. the duration of the contracts between carbon offset providers and buyers; however, this not the scope of our analysis.

[4] Strictly, the historical data should not be considered "observations". The MACA model baseline period (1950–2005) is a reference period for calculating future changes in climate; it has the same statistics as the actual years; and it means to represent recent climate conditions including averages and extremes; and it is used to compute future changes in climate to have minimal biases between the model and actual data (Heather Alridge, State Climate Office of NC, NC State University, May 1st 2015, personal communication).

Table 3
Descriptive statistics of temperatures and precipitation for baseline scenario and representative concentration pathways (RCPs), and changes in forest inputs and provision of ecosystem service for climatic scenarios during 2014–2030.

Climatic variables for time frame 2014–2030	RCP-Scenarios	Mean	Standard deviation	Minimum	Maximum
Average annual maximum temperature (°C)	*Scenario A*	26.8	1.0	25.2	28.9
	RCP4.5 − B_1	27.5	0.80	25.8	29.0
	RCP8.5 − B_2	28.7	0.71	27.2	30.1
Average annual minimum temperature (°C)	*Scenario A*	13.8	1.1	11.5	16.6
	RCP4.5 − B_1	14.6	0.92	12.8	17.2
	RCP8.5 − B_2	15.8	0.86	14.0	18.2
Total annual precipitation (mm)	*Scenario A*	1617.0	138.2	1365.7	1887.3
	RCP4.5 − B_1	1438.4	86.8	1311.0	1716.0
	RCP8.5 − B_2	1473.7	84.5	1352.3	1715.0

Levels of forest inputs and outputs	RCP-scenarios	Site index	Wood production	Carbon sequestration	Tree richness
	Scenario A	No change	No change	No change	No change
	RCP4.5 − B_1	+2 m	+25%	+25%	+2.5%
	RCP8.5 − B_2	+4 m	+30%	+30%	+5%

estimates for temperatures and precipitation for historical data (*Scenario A*) and RCPs (*Scenarios* B_1 and B_2).

The provision of ES is expected to change as climatic conditions are altered. For example, site index at base age 25 years is expected to increase, on average, by 3 to 6 m by 2030, and up to a 9 m increase by 2100 from the base site index assumed in 2030, in the Southern US (Teskey, 2014). Changes in site index will have a direct impact on timber production and carbon sequestration. A 35% increase in site index for loblolly pine stands may double the total stand volume (Jokela et al., 2010). The growth, yield and carbon balance model for loblolly pine developed by the Carbon Resources Science Center at the University of Florida suggests around 8% increase in total loblolly pine volume per 1 m increase in site index when this is increased from 20 to 25 m with 1500 trees ha^{-1} (Carbon Resource Science Center, 2014). On the other hand, climate change is expected to increase tree species richness up to 10% in the Southern US (Currie, 2001). Table 3 shows the percentage changes in site index, timber production, carbon sequestered and species richness due to changing climatic conditions used in this analysis. These changes in the provision of the ES are in the range already described for site index, timber production, carbon sequestration and tree richness.

3.2. Sensitivity analysis

We also conduct a sensitivity analysis to: i) quantify the impacts of an increase in the price of carbon sequestration and the price of species richness on the profit efficiency of loblolly pine forest plots, and ii) determine the robustness of our findings. We simulate a 30% increase in the price of carbon sequestration and species richness. For carbon sequestration, this assumed increase is in line with expected future values for the next decade reported by the California Environmental Protection Agency (2014) and the State of the Voluntary Carbon Markets 2015 (Hamrick and Goldstein, 2015). For species richness, the assumed increase is on the conservative side of the range provided by Matta et al. (2007) — up to \$150 ha^{-1}.

3.3. Application of the DEA additive model

Once the 28 loblolly pine forest plots are selected with their inputs and outputs we proceed to assess, for each DMU (forest plot), the technical efficiency by determining the optimal slack values (s_{ro}^{+*}, s_{io}^{-*}) and the optimal values of inputs and outputs ($\hat{x}_{io}, \hat{y}_{ro}$) (Eq. (6a)) at the initial climatic conditions at the time of the FIA observation (*Scenario A*). Then, using the weights (Table 2), costs and prices associated to inputs and outputs, we apply Eqs. (6b–6c) to determine the allocative and total profit efficiency of each forest plot (Table 2). Finally, we determine the profits foregone due to technical, allocative and total inefficiencies for each forest plot (Eqs. (6d–6f)). The same process is applied for *Scenario B*. Thus, results from all the scenarios are used to compare the losses in profitability of loblolly pine forest plots caused by technical, allocative, and overall inefficiencies due to changing climatic conditions, including the sensitivity analysis.

4. Results and discussion

4.1. Efficiency analysis

Table 4 shows a summary of the technical, allocative and total profit efficiency for all scenarios. In the case of *Scenario A* (no changes in climatic variables and forestry inputs and outputs), 96% of the forest plots (27) are technically efficient in providing timber, sequestering carbon and hosting different species (sum of slacks, $s_{ro}^{+}, s_{io}^{-} = 0$). From an economic perspective, i.e. once input costs and output prices are considered, 21 forest plots (75%) are allocatively and totally profit efficient.

Moderate changes in climatic conditions (*Scenario* B_1, increases in inputs and outputs related to RCP4.5) have a positive impact in terms of technical efficiency: 100% of the forest plots (28) are technically efficient; and 75% (21) of the forest plots are allocatively and totally profit efficient (Table 4). With increased changes in inputs and outputs due to climatic conditions associated to RCP8.5 (*Scenario* B_2), the technical, allocative and profit efficiencies are similar to those of *Scenario A*, only one loblolly pine forest plot is not technically efficient (96% efficient), and 21 forest plots (75%) are allocatively and totally profit efficient. Although two inefficient forest plots under *Scenario A* improve their allocative efficiency in *Scenarios* B_1 and B_2, two efficient plots worsen their allocative and total efficiency in Scenarios B_1 and B_2. Thus, there is no net impact on the number of allocatively and totally efficient forest plots associated with climate change.

4.2. Profit analysis

The average profit under the initial conditions (at the time of FIA observation) for all forest plots is \$77.6 $plot^{-1}$ (\$1141.2 ha^{-1}) (Table 4). Once optimal levels of forest inputs and ES are determined, the average total profit increases to \$79.8 $plot^{-1}$ (\$1173.5 ha^{-1}) (*Scenario A*) (Table 4). The average profitability of the forest plots increases with moderate (*Scenario* B_1) and high (*Scenario* B_2) changes in climatic conditions. At the optimum level the average total profits are \$110.9 $plot^{-1}$ (\$1630.9 ha^{-1}) and \$113.0 $plot^{-1}$ (\$1661.8 ha^{-1}) for *Scenarios* B_1 and B_2, respectively (Table 4). Compared to the initial conditions for *Scenario A*, moderate and high changes in climatic conditions increase the profitability of forestlands by 42.8% and 45.6%, respectively. Most of the forest plots show a positive profitability regardless of

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Table 4
Summary of efficiency and profit analysis of loblolly pine forest plots.

Efficiency analysis	*Scenario A*	*Scenario B_1*	*Scenario B_2*
Number of technically efficient loblolly forest plots	27	28	27
Number of allocatively efficient loblolly forest plots	21	21	21
Number of totally efficient loblolly forest plots	21	21	21
Profit analysis		\$ plot^{-1} (\$ ha^{-1})	
Average profit (initial conditions)	77.6 (1141.2)	107.8 (1585.3)	109.9 (1617.2)
Average foregone technical profit	0.5 (7.2)	0	0.04 (0.58)
Average foregone allocative profit	1.7 (24.3)	3.1 (45.6)	3.06 (52.9)
Average foregone total profit	2.2 (32.4)	3.1 (45.6)	3.1 (45.6)
Optimal average technical profit	78.1 (1148.4)	107.8 (1585.3)	110.0 (1617.6)
Optimal average allocative profit	79.3 (1166.2)	110.9 (1630.9)	112.9 (1661.2)
Optimal average total profit	79.8 (1173.5)	110.9 (1630.9)	113.0 (1661.8)

Notes: a complete table with efficiencies and profits for each forest plot is available from the authors upon request. Profits at initial conditions are determined with the initial levels of inputs and outputs for each scenario before determining their optimal levels.

the climatic scenario, with the majority of them having profits ranging between 0 and \$300 plot^{-1} (\$4411.7 ha^{-1}) (Table 4). These values are consistent with previous estimates of profitability of forestlands reported in the literature in the Southern US (Susaeta et al., 2014).

Yet changes in climatic conditions and forest management improve the total profitability of planted loblolly pine forest plots, and the impact of reducing technical and allocative inefficiencies of the initial conditions for those forest plots with negative economic returns have little impact on the distribution of the optimal level of total profits. Only 2 and 1 forest plots, respectively, change from having initial negative profits (*Scenario A*) to positive total economic returns in *Scenarios B_1* and B_2 (Table 5).

Changing climatic conditions tend to impact more heavily the distribution of forest plots that present greater positive economic returns. In *Scenarios B_1* and B_2, 10% (5) and 12% (6) of the forest plots with positive profits are, respectively, in the range of total profits greater than \$200 plot^{-1} (\$2941.2 ha^{-1}) (Table 5), while 0.2% (1) of the forest plots are in that range in *Scenario A*. Most of the forest plots show a positive profitability regardless of the climatic scenario, with the majority of them having profits ranging between 0 and \$300 plot^{-1} (\$4411.7 ha^{-1}) (Table 5). Furthermore, there are 4 and 5 more forest plots with profitability greater than \$200 plot^{-1} in *Scenarios B_1* and B_2, respectively, compared to *Scenario A* (1).

Our findings suggest that the profitability of forestlands is increased with changing climatic conditions. These results are consistent with expected increases in social welfare related to the US forest sector with climate change (Ochuodho and Lantz, 2014) and projected increases in forest productivity due to climate change expected in the Southern US (Susaeta et al., 2014). However, these results are region-specific. For example, the expected land values of European forestlands by 2100 are expected to decline between 14 and 50% of the current present land value (Hanewinkel et al., 2013).

On average, the total foregone profits are \$2.2 plot^{-1} (\$32.4 ha^{-1}) for *Scenario A*, and \$3.1 plot^{-1} (\$45.6 ha^{-1}) for *Scenarios B_1* and B_2. In the case of *Scenario B_1*, all losses in profitability of forest plots are due to allocative inefficiencies *while* in the cases of *Scenarios A* and B_2, 85% of foregone profits are due to allocative inefficiencies (Table 5). In addition, in *Scenarios A*, B_1 and B_2, 75% (21) of forest plots show zero total foregone profits (Table 5).

Table 5
Range of total and foregone profits of forest plots (π) under *Scenarios A*, B_1, and B_2.

Total profit π range \$ plot^{-1} (\$ ha^{-1})	*Scenario A*	*Scenario B_1*	*Scenario B_2*
	Number of plots		
0	7	5	6
$0 < \pi < 100$ ($0 < \pi < 1470.6$)	11	10	9
$100 < \pi < 200$ ($1470.6 < \pi < 2941.2$)	9	8	7
$200 < \pi < 300$ ($2941.2 < \pi < 4411.7$)	1	4	5
$\pi > 300$ ($\pi > 4411.7$)	0	1	1
Total foregone profit π range \$ plot^{-1} (\$ ha^{-1})	Number of plots		
$\pi = 0$	21	21	21
$0 < \pi < 10$ ($0 < \pi < 147.1$)	3	2	2
$10 < \pi < 20$ ($147.1 < \pi < 294.1$)	4	4	4
$\pi > 20$ ($\pi > 294.1$)	0	1	1

4.3. Sensitivity analysis

As expected, greater average technical, allocative and total profit efficiencies are obtained with increased prices of carbon sequestration and tree species richness (Table 6). On average, the average total profit efficiency is 40% greater for *Scenario A*, and 30% for *Scenario B* than those obtained with initial prices of carbon sequestration and tree species richness. Furthermore, compared to the initial conditions of *Scenario A*, increases in the prices of ecosystem services increase the profitability of forest plots by 47.2% and 50.1%, respectively, in the case of moderate and high changes in climatic conditions. The distribution, average foregone technical, allocative and profit efficiency, range and total foregone profits, of the loblolly pine forest plots with increased prices of carbon sequestration and tree species richness are similar to those obtained with initial prices (Tables 4 and 5).

Our findings suggest that the total inefficiency of forest plots is mainly allocative. Thus, forest management practices that tend to minimize the inputs required by forestlands may not have a significant impact on the economic value of forest ecosystems when the production of ES is considered. With the development of forest-based ES incentive programs and markets, we should see landowners increasingly and explicitly managing for ES production. As this happens, forest landowners and land managers will need to achieve a balance between the cost of silvicultural management and the benefits of ES, or more specifically how to use the adequate level of inputs to generate the optimal level of outputs given their costs and prices. In this context, we know that timber and carbon prices becomes critical to determining the optimal age of harvesting that maximizes the economic retunes for landowners. As incentives for other forest ES become available, the role of ES synergies (C and timber production) and tradeoffs (C and water yield) will affect optimal rotations and land management in dynamic ways not yet fully understood.

These results are useful for understanding the economic aspects of forest-based ES provision, but we caution against over-interpretation. Results of economic valuation studies should be considered as part of a broader conversation that involves non-economic factors (e.g., environmental, social, and political/administrative) in the decision making process. This is particularly important given the diversity of views about the importance of ES, which can lead to some of them

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Table 6
Profit analysis of loblolly pine forest plots with increased prices of carbon sequestration and tree species richness.

Profit analysis	*Scenario A*	*Scenario B_1*	*Scenario B_2*
	$ plot^{-1} ($ ha^{-1})		
Average profit (initial conditions)	80.7 (1186.8)	111.1 (1633.8)	113.4 (1667.6)
Optimal average technical profit	81.3 (1195.6)	111.1 (1633.8)	113.4 (1667.4)
Optimal average allocative profit	82.4 (1211.8)	114.2 (1679.4)	116.5 (1713.2)
Optimal average total profit	82.9 (1219.1)	114.2 (1679.4)	116.5 (1713.2)

being undervalued or ignored in certain cases (Balmford et al., 2011). We also recognize that economic valuation of ES is somewhat controversial. For example, biodiversity is a complex and abstract concept, and its monetary valuation involves subjective decisions about critical assumptions related to the different levels of biodiversity (e.g. gene, species, ecosystem), most appropriate valuation approaches, and alternative perspectives on biodiversity values (e.g., direct versus indirect values, monetary versus biological indicators) (Nunes and Van den Bergh, 2001). These factors can also lead to ES being undervalued or excluded from the analysis altogether (Balmford et al., 2011).

5. Conclusions

We use additive data envelopment analysis (DEA) models to assess the technical, allocative and total profit efficiency of loblolly forest plots in the provision of timber, carbon and species richness under altered temperatures and precipitations in the state of Florida. Our findings indicate that almost all loblolly forest plots are technically efficient in providing timber, carbon sequestration and tree species richness.

Interestingly, our results indicate that despite the efficiency of loblolly forest plots being improved with moderate climatic conditions, once costs of forestry inputs and prices of ES are considered, forest plots remain allocative and totally profit efficient. In the case of climate *Scenario B_1* (RCP4.5), the allocative and total inefficiencies occur within 15% of the total forest plots. With significant changes in climatic conditions (*Scenario B_1*, RCP8.5), our results suggest that allocative and total profit efficiencies are similar to those of the initial conditions. Overall we see zero improvements in allocative and total profit efficiency with climate change — around 10% of the allocatively and totally efficient forest plots improve and worsen their performance with changing climatic conditions. Altered climatic conditions also have a moderate–strong, positive impact on the profitability of loblolly pine forest plots. At the optimal level of total efficiency, the profitability of forest plots is increased by 42.8% and 45.6% with moderate and high levels of precipitation and temperature increases, respectively. Increased prices of carbon sequestration and species richness increase the profitability of forest plots by 47.2% and 50.1%, for the same climatic scenarios — yet with no further improvement in the profit inefficiencies of the forest plots. Thus, if effective, policies should develop stronger markets for non-timber products such as carbon sequestration, and also to make forest landowners aware of the importance of biodiversity in their lands in order to improve the economic sustainability of southern forestlands.

While our findings suggest increases in the profitability of southern pines with changing climatic conditions and positive impacts for forest-based ES production under moderate climate change, we urge caution against interpreting the findings too broadly given several limitations of our research. First, there are limitations of the DEA approach, e.g., efficiency measures cannot be compared across different studies (de Lancer Julnes, 2008). The reason is that DEA estimates the relative efficiency but not the global efficiency, i.e., it compares the performance of a DMU with respect to other DMUs in the dataset, but not to the best theoretical performance — in our study, and given the high level of efficiency, it seems that the forest plots are rather homogenous. Furthermore, it is highly sensitive to data errors due to misspecification problems such as exclusion of inputs/outputs, overstatement of outputs and understatement of inputs (de Lancer Julnes, 2008). The use of parametric techniques such as econometric methods together with the development of DEA software packages can ameliorate the weakness of DEA (de Lancer Julnes, 2008). Second, one significant question for future research not considered here is the role of disturbance risks that are expected to be exacerbated with climate change such as pest outbreaks, wildfires or hurricanes. These disturbances are expected to negatively affect the provision of forest-based ES thus reducing the economic benefits of forestlands. Our analysis also does not incorporate climate change mitigation and adaptation-related forest management strategies, which are seen as a necessary aspect of society's response to climate change, and may significantly affect the economic values of forestlands and forest-based ES. These questions are fertile ground for future research related to the sustainable provision of ES in forestlands.

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