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RESEARCH

An Energy Analysis of Managed Forestry Systems: Accounting for Foregone Biomass as an Indicator of Ecosystem Impact Alongside Conventional Energy Metrics

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Abstract
Conventional energy analyses of forestry systems capture only human inputs and harvests, neglecting impacts to forest biomass stocks resulting from intensive management. This gap is addressed by extending the boundaries of forestry operations to the whole forest ecosystem. These new boundaries allow for the quantification of cumulative foregone biomass (ΔB_c, the difference between accumulated potential and existing forest biomass stocks over time) under differing management scenarios to supplement the interpretation of conventional energy metrics such as net energy (NE) and the ratio of energy return to energy invested (EROI). Like existing models in the literature, our results confirm that less intensive management approaches achieve higher EROI values due to lower inputs. However, more significantly, magnitudes of ΔB_c remain 1–2 orders of magnitude larger than NE over 100 years regardless of management scenario, and thus highlight an imbalance between the industrial and ecological energy dimensions of managed forests. This energy model begins to illustrate the overlooked role of ecological energy storage in forest management and offers insights to identify and design more sustainable management practices that can balance energy efficiency while minimizing resultant ecosystem impacts.

Keywords Forestry · Ecosystem impacts · Energy analysis · Net energy · EROI

Introduction

Energy plays a fundamental role in forestry systems. Through photosynthesis, atmospheric carbon dioxide is sequestered into biomass, which is the only renewable stored energy resource fueling the biosphere's food web of vast ecosystem biodiversity. However, through harvesting, forestry extracts a portion of this biomass to be used for various foods, fibers, and fuels (Bowyer et al. 2003; Easterling et al. 2007; Smil 2012). Such transactions require extramural technical energy inputs invested by humans to establish, manage, and harvest from the system where a key objective is to improve operational efficiencies by minimizing inputs and maintaining or increasing harvested outputs (Sundberg and Silversides 1988). As a result, energy analyses of managed forests predominantly focus on quantifying the amount of biomass produced and the energetic cost of obtaining that biomass.

Conventional energy analysis (e.g., net energy analysis, NEA), which quantifies the energetic performance of a system by comparing the useful outputs produced and the energy required to obtain those outputs, has been a key framework with which to assess the energetics of forestry (Mead and Pimentel 2006; Marshall and Brockway 2020). Specific indicators such as the ratio of energy return to energy invested (EROI) (Zavitkovski 1979; Klopatek and Risser 1981; Herendeen and Brown 1987; Sundberg and Silversides 1988; Mead and Pimentel 2006; Balimunsi et al. 2012; Buonocore et al. 2014), net energy (NE) (Zavitkovski 1979; Klopatek and Risser 1981; Herendeen and Brown 1987; Mead and Pimentel 2006), and input-side indicators such as gross energy requirements (GER) (Enger 1983; Wells 1984; Berg and Lindholm 2005; Lindholm and Berg 2005; González-García et al. 2014; Kouchaki-Penchah et al. 2023) have been applied to forestry systems. The EROI of forestry systems ranges from 10:1 to over 800:1 depending on the tree species, management type, system boundaries, and rotation period assessed (Klopatek and Risser 1981;

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Herendeen and Brown 1987; Mead and Pimentel 2006). In all cases, EROI values remain positive, highlighting the positive energy returns of forestry to society.

Despite the favorable returns, conventional energy analyses of forestry systems are incomplete (Dunlap and Schramski 2024). In these analyses, the forestry system is a subsystem of the human industrial economy (i.e., the *technosphere*) (Fig. 1a). Under these system boundaries, only the merchantable biomass valued to humans is considered and the rest of the forest stand is not included within the systems scope. As a result, conventional energy analyses capture only the industrial efficiency of forestry operations with respect to human society. In actuality, forestry systems are industrial–natural systems existing within a forest ecosystem that accumulates biomass through natural processes of ecosystem growth and development (Fig. 1b). Thus, while conventional energy analysis has commonly been applied to forestry systems, this approach does not consider changes in natural capital stocks such as biomass. More comprehensive forestry energy analyses should include boundaries that capture forest biomass dynamics along with conventional industrial energy metrics.

There have been limited efforts to incorporate changes in natural capital stocks alongside conventional industrial energy metrics in agroecosystems (Hercher-Pasteur et al. 2020). Bulatkin (2012) and Fan et al. (2018) conducted emergy analyses of agricultural systems, including changes in soil organic carbon stores, while Golberg (2015) argued for incorporating impacted species biomass levels in the exergy efficiency of bioenergy systems. In all cases, magnitudes of the change in natural capital stocks were substantial portions of the overall energy budget, underscoring their importance. However, a drawback of these studies involves using emergy and exergy-based indicators, which, compared to conventional energy indicators, demand additional modeling efforts and have been criticized for their complexity in conveying results to non-technical audiences.

Several indicators have been developed to measure the human energy impact on agroecosystems. The human appropriation of net primary production (HANPP) quantifies the appropriation of the biosphere's capacity to produce biomass, and is defined as the difference between the NPP that would prevail absent human interference and the remaining NPP in the ecosystem (Haberl 1997; Krausmann et al. 2013). Galán et al. (2016) expanded the scope of EROI to include additional indicators that capture the human and ecological dimensions of agroecosystems. This includes $NPP_{act}EROI$ which expresses energy return as the ratio of the biomass produced by the agroecosystem to the external inputs invested and internal biomass reused within the system (Galán et al. 2016; Guzmán et al. 2018). While these indicators capture aspects of the annual flow of photosynthetic primary production appropriated for human uses, a literature gap still remains for studies which directly capture changes in biomass stocks alongside conventional industrial energy metrics in intensively managed forests.

In addition to describing the industrial efficiency of forestry systems, energy is also a state variable that conveys information about an ecosystems thermodynamic state (Odum 1983). Ecosystems are open, dissipative thermodynamic systems, degrading energy and material gradients while striving toward states of maximum stored energy in the form of biomass (Odum 1969; Fath et al. 2004; Chen 2007). These accumulated energy stores in the form of

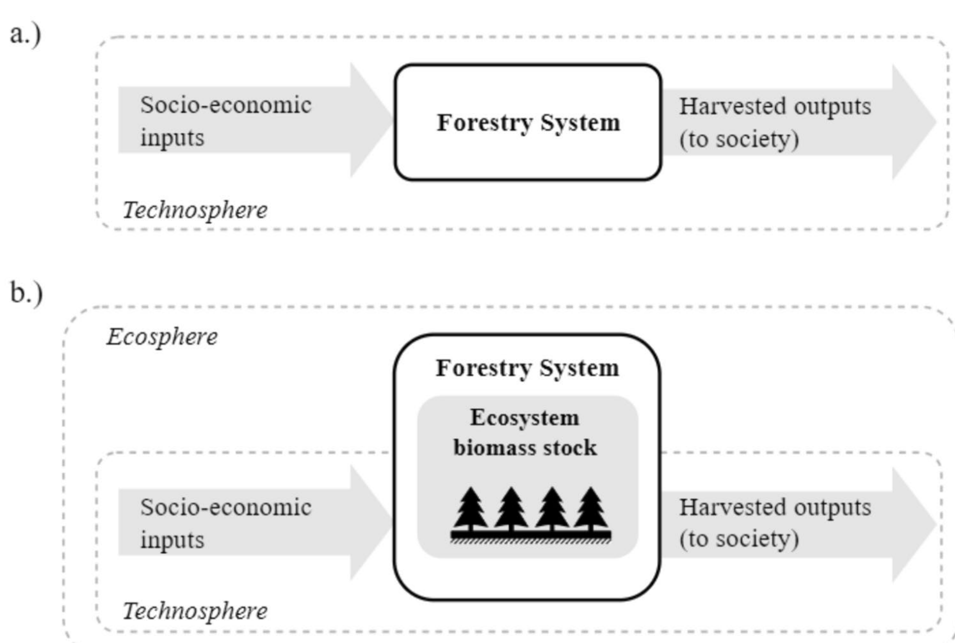

Fig. 1 Contrasting system boundaries of forestry energy analysis approaches including, **a** conventional boundaries where the forestry system is a sector of the technosphere, and **b** extended boundaries where the forestry system is an industrial–natural system consisting of a forest ecosystem that accumulates biomass stocks

biomass quantify the systems distance from thermodynamic equilibrium (a state devoid of stored potential energy or biomass) and define a specific thermodynamic state operating away from equilibrium. However, intensive land management disrupts the ecosystems ability to accumulate and store biomass, as managed forests typically store less biomass than the natural system they have replaced (Doka et al. 2002; Erb et al. 2018; Erb and Gingrich 2022). This results in a gap between potential and existing biomass stocks (Fig. 2) as a direct consequence of intensive management.

This gap represents the '*foregone*' quantity of stored energy in the form of biomass relative to a reference scenario where a natural ecosystem, absent human land-use activity, would exist. Globally, the gap between existing and potential biomass is substantial with anthropogenic activity estimated to have reduced terrestrial biomass by ~50% with most of the losses occurring in forests (Smil 2012; Schramski et al. 2015; Erb et al. 2018; Erb and Gingrich 2022). In other words, global forests would store double the quantity of energy, in the form of biomass, in the absence of human land-use activities. Intensive forest land management thus maintains the ecosystem at lower energy states closer to thermodynamic equilibrium.

In this context, energy is a system-level indicator able to capture and express information about the industrial and ecological dimensions of forestry systems. Yet, few studies have assessed both aspects together in the context of intensive forest management. Addressing this shortcoming, the purpose of this study is to develop an energy analysis model of managed forestry systems which assesses impacts to ecosystem biomass stocks directly alongside conventional energy analysis metrics. Including ecological aspects in conventional energy analyses contributes not just to our understanding of the resultant ecosystem impacts of differing types of forest management, but also adds context to our most fundamental energetic relationship with managed ecosystems and can help inform the design of sustainable forest management practices.

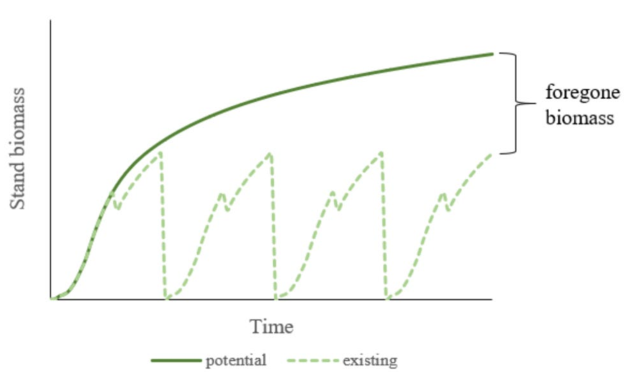

Fig. 2 Conceptual diagram of foregone biomass as an indicator of the impact of intensive management on stand-level forest biomass over time. Foregone biomass is the difference between potential (solid green line) and existing (light green dashed line) biomass at any time

Materials and Methods

An energy analysis is performed on one hectare (ha) of a managed forest stand under four different management scenarios (Sect. 2.1) in the southeastern United States. To do this, a dynamic energy accounting framework (Fig. 3) compares (1) the direct and indirect technical energy inputs invested in the stand by different forestry operations (Sect. 2.2), (2) the total biomass harvested from the stand (Sect. 2.3), and (3) the foregone biomass stocks relative to different baseline reference scenarios over time (Sects. 2.5 and 2.6). To this end, the system boundaries expand on conventional forestry energy analyses and include the existing and potential biomass that would exist in the absence of intensive land occupation (Fig. 1b). To enable direct comparisons of energy metrics over time, all metrics represent the cumulative technical energy invested and harvested, as well as the cumulative change in biomass stocks over a 100-year period. Accordingly, all metrics are expressed in units of GJ/ha.

Forest Management Scenarios

Compared with management types in other regions of the US or Europe, managed pine forestry practices in the southeastern US are often more intensive and require large quantities of external inputs, making them ideal case studies for a forestry energy analysis. Four different forest management scenarios are selected to represent commonly implemented pine management practices in the southeastern US. Forest management data were collected from literature sources specific to southeastern pine forestry (Table S1). Management scenarios vary in intensity with differing combinations of fertilizer and herbicide treatments, thinning intensities and applications, planting densities, and rotation lengths, and include less intensive saw timber (ST) and conventional (C) managements contrasted with more intensive heavy thinning (HT) and short rotation (SR) managements. The silvicultural characteristics of each forest management scenario can be found in detail in Table S5.

The ST management scenario defined here, consists of a 35-year rotation to prioritize timber production, with an intermediate thinning at year 15 (Mills et al. 2013). The C management represents a commonly applied approach that yields a mix of pulpwood and timber on a 25-year rotation with a thinning at year 15 (DOE 2011). Conversely, the HT scenario involves an increased planting density with an additional thinning at years 10 and 15 on a 25-year rotation to produce a large quantity of pulpwood (Scott and

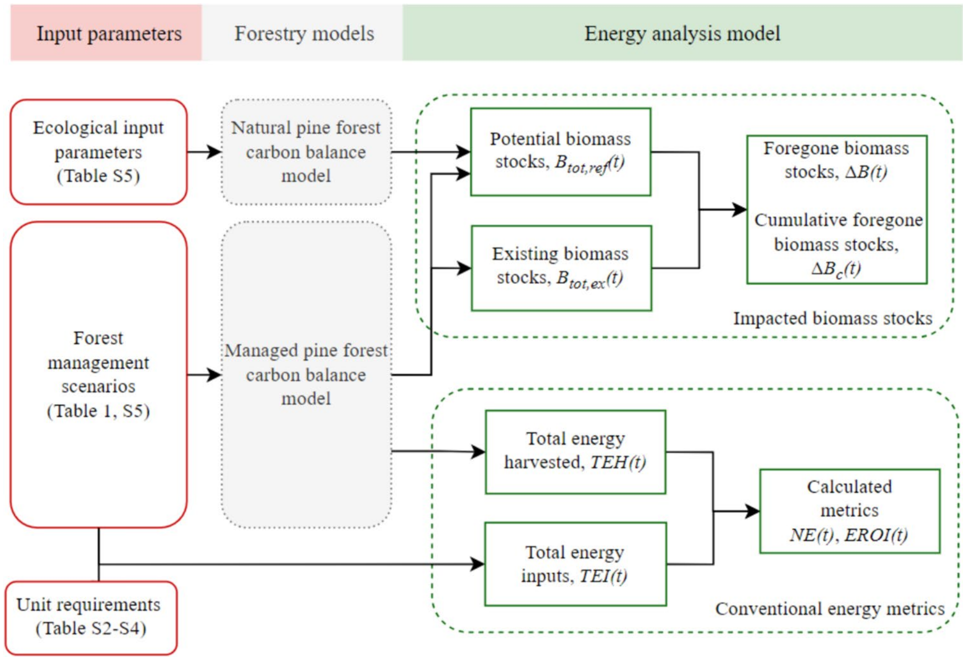

Fig. 3 Process flow of the energy analysis model of forest management. Red boxes denote inputs and background data, grey boxes depict forest carbon balance models for calculating stand biomass stocks and harvests, and green boxes show all conventional and impacted biomass metrics

Tiarks 2008). Finally, the SR scenario consists of a high planting density on a short 16-year rotation with heavy fertilizer application to achieve fast biomass accumulation and high yields (Lu et al. 2015).

For each scenario, management activities are grouped into four main forestry operations, including site preparation, stand management, thinning, and logging with each operation supported by respective fuel and material inputs. A full breakdown of all fuel and material requirements for each forestry operation can be found in Table S2. Site preparation includes initial groundwork to prepare the site for planting and re-establishment as well as initial fertilizer and herbicide treatments. Stand management includes any additional fertilizer and herbicide treatments in years following site preparation. Thinning involves the intermediate removal, typically 30 or 50%, of the stand while logging involves the final clear felling and removal of tree biomass. The respective timeline of each forestry operation for each management scenario is displayed in Table 1.

Energy Inputs

Following procedures from previous agroecosystem energy analyses, technical energy inputs include the direct and indirect fuel and materials supporting the system (Schramski et al. 2011, 2013; Pimentel 2019). Direct inputs include the energy content of diesel fuel to drive machinery for site preparation, management, and logging activities. Indirect inputs include the embodied energy required to produce and deliver all fuels and materials such as diesel fuel, lubricating oils, nitrogen and phosphorus fertilizers, and herbicides. Human labor is excluded as an energy input based on (1) being a negligible term in previous literature studies (Herendeen and Brown 1987; Mead and Pimentel 2006) and (2) that most of the work in intensive forestry is performed by machinery (Wells 1984; Sundberg and Silversides 1988). Infrastructural supporting activities such as forest road building and maintenance are not activities invested directly to support the forest stand, do not cross the system boundaries of the stand, and are thus excluded from the analysis.

Table 1 Timeline of forestry operations for each management scenarios

Year	0	1	4	6	8	10	15	16	25	35
Saw timber (ST)	SP						TH	SM		L
Conventional (C)	SP		SM		SM		TH		L	
Heavy thinning (HT)	SP	SM	SM			SM & TH	SM & TH		L	
Short rotation (SR)	SP	SM	SM	SM				L		

Forestry operations include site preparation (SP), stand management (SM), thinning (TH), and logging (L). Further details of the fuel and material requirements for each operation can be found in the Supplementary Information

Several assumptions are made regarding unit input requirements. First, fuel and material requirements for the initial groundwork and site preparations are assumed to be the same for all managements. Herbicide requirements are assumed constant while the number of herbicide applications varies by management. For logging operations, diesel and lubricant requirements are assumed constant across managements, however, similarly depend on the volume of harvested biomass at the time of final clear felling. Fuel and material requirements for thinning were not found in the literature and thus are assumed to be proportional to logging requirements as a function of thinning intensity, i.e., requirements for thinning 30% of the stand are assumed to be 30% of those required for logging.

All required unit inputs are converted to unit energy intensity values by multiplying each respective input of each management type with a specific energy conversion value (Tables S2, S3, S4). Then, for each forestry operation k, the sum of all unit energy intensity values n, determines the total energy input E_{tot} (GJ/ha) invested in the stand at time t,

$$E_{\text{tot}}(t) = \sum_{k} \sum_{n} E_{in,k,n}(t) \tag{1}$$

The total energy invested in the stand TEI (GJ/ha) over a given time period t is calculated as the sum of the total energy inputs over a given time period,

$$\text{TEI}(t) = \sum_{t} E_{\text{tot}}(t) \tag{2}$$

TEI is the cumulative total of all direct and indirect energy inputs invested in the forest over a given period and thus represents the total technical energy inputs supporting the system.

Energy Outputs

System outputs include the merchantable biomass harvested during thinning and clear felling at the rotation age of the stand. This consists of the stemwood and bark harvested from live pine trees. Logging residues were not included as harvested outputs. Instead, residues were burnt at the time of harvest, as is common practice in intensive forestry, and a small fraction fluxes to the dead wood pool. To convert biomass into energy units, an average energy content value of 17.5 MJ/kg (or 35 GJ/tonne C) is applied (Smil 2007). For each management scenario, the total energy harvested TEH (GJ/ha) is then the sum of all biomass harvests E_{har} (GJ/ha) from the stand over a given period t,

$$\text{TEH}(t) = \sum_{t} E_{\text{har}}(t) \tag{3}$$

Thus, TEH represents the accumulated quantity of biomass harvested by humans from the system, in energy terms, over a given period.

Conventional Energy Analysis Metrics

For each management scenario, net energy NE (GJ/ha) represents the cumulative net quantity of energy obtained through harvests after inputs are accounted for and EROI represents the energetic efficiency with which those outputs are obtained,

$$\text{NE}(t) = \text{TEH}(t) - \text{TEI}(t) \tag{4}$$

$$\text{EROI}(t) = \frac{\text{TEH}(t)}{\text{TEI}(t)} \tag{5}$$

In a forestry context, NE is a proxy for harvests yet is more descriptive as a system-level indicator as it accounts for the net quantity of energy harvested after inputs invested to obtain those harvests are accounted for. Similarly, EROI is a system-level indicator of the energetic efficiency of a biomass production system (Schramski et al. 2011, 2013). EROI quantifies the quantity of energy obtained per unit of energy invested into the system and thus accounts for the capacity of the system to provide valued outputs despite external investments (Hall et al. 2009). Taken together, both indicators capture differing aspects of the system-level performance of forestry systems, aspects which are absent when considering only the gross quantity of harvests (i.e., yields) or inputs invested into a forestry system, as is often the case in forestry studies.

To account for differences in rotation lengths of each management, energy metrics are assessed in three different ways including on a per-rotation basis, normalized over a consistent time-horizon, and a fixed 100-year period, for all managements. Energy metrics are normalized over a consistent time-horizon as follows,

$$\text{normalized metric} = \frac{\text{energy metric} * \text{LCM}}{\text{rotation length}} \tag{6}$$

where LCM is the least common multiple of the different rotation lengths (equal to 2800 years for 16, 25, and 35-year rotations). Considering different temporal approaches to analyzing energy metrics ensures fair comparisons across different types of management and ensures that conclusions drawn regarding trends in energetic performance do not vary significantly under diverse types of analysis.

Modeling Forest Biomass Stocks

A carbon balance model of planted loblolly pines (*Pinus taeda*), from the University of Florida's Carbon Resources Science Center V1.32, is used to simulate stand-level biomass stocks under different forest management scenarios (Gonzalez-Benecke et al. 2011). Input parameters to initialize the models for each management scenario are detailed in Table S5. A key strength of the model is that it allows for the simulation and partitioning of biomass stocks beyond tree biomass and also includes understory, dead wood, and forest floor biomass, which comprise ~ 20% of total stand biomass (Fig. 4). The total biomass stock in the forest at a given time is the sum of the biomass of all individual compartments in the stand and is reported as either tonnes/ha or tonnes C/ha. Where necessary, biomass stocks are converted to carbon mass units assuming an average carbon content of ~ 50% of biomass. As the stand consists of multiple biomass stocks with large variability in composition including water content, an average energy content value of 17.5 MJ/kg (or 35 GJ/tonne C) is applied to convert all biomass stocks to energy units (Smil 2007).

Foregone Biomass

To calculate foregone biomass, the total existing stand biomass is compared to potential biomass under a reference or baseline scenario. Potential biomass represents the natural unmanaged biomass that would have existed on the land if it had not been intensively managed. Foregone biomass $\Delta B(t)$ (GJ/ha) at time t is then,

$$\Delta B(t) = B_{\mathrm{tot,ref}}(t) - B_{\mathrm{tot,ex}}(t) \tag{7}$$

where $B_{\mathrm{tot,ref}}(t)$ is the total potential biomass stock under a reference scenario and $B_{\mathrm{tot,ex}}(t)$ is the total existing biomass stock in the managed stand. $\Delta B(t)$ is calculated with respect to two reference scenarios including a *no-harvest* scenario for each management, where harvest is assumed not to have occurred, and a *natural regeneration* scenario where the land is allowed to return toward a natural state which would exist in the absence of land-use activity. The longleaf pine (*Pinus palustris*) ecosystem was chosen as the natural reference ecosystem for the natural regeneration scenario that would exist in the hypothetical absence of intensive forest management. This ecosystem once dominated most of the southeastern coastal plains in the United States, but now occupies less than 5% of its original range (Outcalt 2000). A carbon balance model was used to simulate biomass dynamics of the longleaf pine reference ecosystem (Fig. S1) (Baldwin 1983; Lauer and Kush 2011). All biomass stocks under the managed and reference scenarios are started from an initial planting with stocks of 0 at time $t = 0$. Further details of the inputs to parameterize the reference model can be found in the supplementary information (Table S5).

Cumulative foregone biomass $\Delta B_c(t)$ at any time t is calculated for each management scenario,

$$\Delta B_c(t) = \sum_t \Delta B(t) \tag{8}$$

At any time, t, cumulative foregone biomass represents the total change in the forest's accumulated energy store that would have existed up to that point in time if the stand was either unharvested or not intensively managed. Thus, $\Delta B_c(t)$ is similarly calculated with respect to both no-harvest and a natural regeneration reference scenario. This magnitude quantifies the impact on the ecosystem's energy state

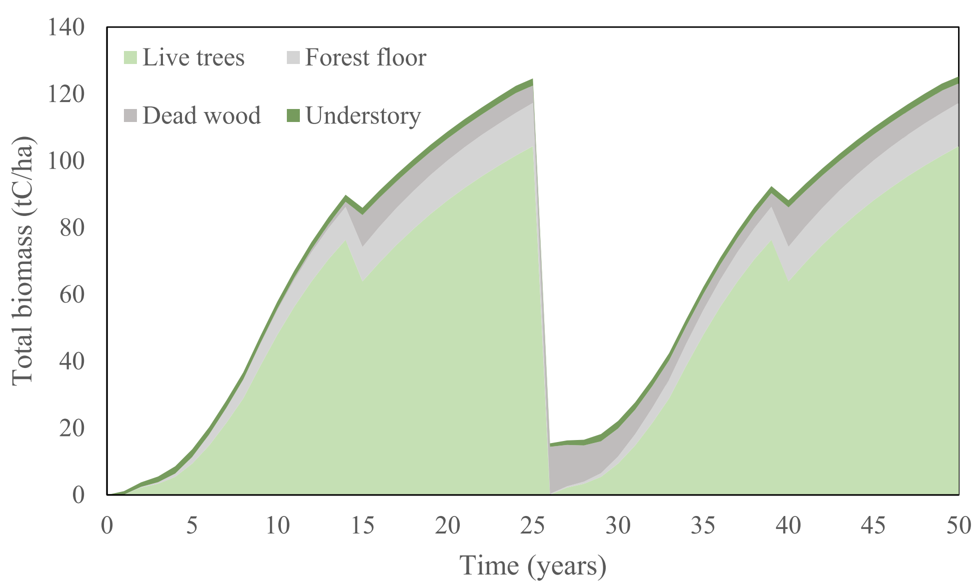

Fig. 4 Example showing the composition of total existing stand biomass ($B_{\mathrm{tot,ex}}$) over time in a managed forest for two harvest periods. The depicted scenario is for the conventional (C) forest management over two 25-year rotations. Total stand biomass consists of live pine trees, forest floor, dead wood, and understory compartments

resulting from intensive land occupation and management over time.

Sensitivity Analysis

The quantity of ΔB_c is dependent upon the modeled potential biomass stocks of the baseline reference scenario. To provide validation for this quantity, a sensitivity analysis was performed for differing levels of biomass stocks under the natural regeneration reference scenario. Biomass stocks of the longleaf pine ecosystem depend on site index (SI) which is a measure of site productivity and can range from 16 to 29 m (Lauer and Kush 2011; Gonzalez-Benecke et al. 2015; Samuelson et al. 2017). Thus, SI was varied between 16 and 29 m for the reference scenario and ΔB_c is recalculated for each management scenario to test the sensitivity of foregone biomass stocks to different SI values.

Results

Energy Analysis of Forestry Operations Assessed Over Different Time-Horizons

On a per-rotation basis, total energy inputs (TEI) to forest management are largest under more intensive heavy thinning (HT) and short rotation (SR) scenarios followed closely by less intensive saw timber (ST) and conventional (C) managements, respectively (Table 2a). In contrast, total harvests (TEH) are largest under the least intensive ST followed by HT, and lowest under SR and C management, respectively. These relationships are attributed to the longer rotation period of ST resulting in more biomass harvested at the rotation age, and the additional harvests obtained through the additional stand thinning under HT management (Table S6). As a result, the net energy (*NE*) obtained follows the same trend and is largest under the least intensive ST followed by the more intensive HT management scenario. The ratio of energy outputs to inputs (EROI) is largest under the least intensive ST and C managements and declines with increasing management intensity. Regardless of the NE obtained, lower-intensity management regimes are more energetically efficient at obtaining their outputs (i.e., have higher EROI) in comparison with the more intensive alternatives.

If energy metrics are normalized over a consistent time-horizon (i.e., 80 successive rotations for ST, 112 for C and HT, and 175 for SR management over 2800 years) previous input and output comparisons between management scenarios differ significantly (Table 2b). TEI, TEH, and NE values are lowest under low-intensity ST management and increase with increasing management intensity. These are due to the greater quantity of harvests that occur under more intensive management scenarios when assessed over a consistent time-horizon. Both the magnitude and trend in EROI, however, do not differ from the previous comparisons on a per-rotation basis and still decline with increasing management intensity (i.e., decline with declining rotation length). Similar to when analyzed on a per-rotation basis, lower-intensity forest managements are more energetically efficient at obtaining their outputs (i.e., have higher EROI) than more intensive management.

Over 100 years, comparisons between energy metrics are consistent with normalized metrics although they differ in magnitude. TEI, TEH, and NE increase with increasing management intensity and are the largest under more

Table 2 Conventional forestry energy analysis metrics assessed over different time-horizons

	TEI (GJ/ha) (1)	TEH (GJ/ha) (2)	Net energy (GJ/ha) (3) = (2)–(1)	EROI (~) (2)/(1)	No. of rotations
a. Per harvest rotation					
Saw timber (ST)	57	3443	3385	60	1
Conventional (C)	51	2681	2630	52	1
Heavy thinning (HT)	71	3406	3335	48	1
Short rotation (SR)	58	2540	2482	44	1
b. Normalized over a consistent time-horizon					
Saw timber (ST)	4592	275,403	270,811	60	80
Conventional (C)	5749	300,266	294,517	52	112
Heavy thinning (HT)	7934	381,498	373,563	48	112
Short rotation (SR)	10,131	444,442	434,311	44	175
c. Over 100 years					
Saw timber (ST)	137	7104	6967	52	2
Conventional (C)	205	10,724	10,518	52	4
Heavy thinning (HT)	283	13,625	13,342	48	4
Short rotation (SR)	365	15,238	14,873	42	6

intensive HT and SR management (Table 2c) due to the greater number of harvests and greater outputs achieved over 100 years compared with their less intensive counterparts (Table S7). While trends in EROI remain consistent with previous analyses and decline with increasing management intensity, the magnitudes differ slightly for ST and SR. This is due to the truncation of their rotation cycles (i.e., which are not multiples of 100) when assessed over 100 years, thus leading to slightly lower EROI values compared with previous analyses.

Irrespective of how energy metrics are analyzed, EROI values are always largest under the least intensive (ST and C) management scenarios, indicating that lower-intensity forest management is more energetically efficient at obtaining their harvested outputs than more intensive ones.

Foregone Biomass—Impacts to the Ecosystem's Stored Energy Potential

The dynamics of foregone biomass (ΔB) depend on the reference scenario with which they are compared (Fig. 5). Before the initial harvest, ΔB is negative under the natural regeneration reference due to lower biomass accumulated compared with fast initial growth in the managed stands. However, successive harvests quickly overcome these improvements. In contrast, ΔB is always positive under no-harvest references, as biomass continues to accumulate despite harvests. Although magnitudes of ΔB do not vary significantly between the two scenarios after 100 years, ΔB under natural regeneration outpaces ΔB under no-harvest scenarios due to its continued biomass accumulation as the ecosystem develops while biomass approaches a steady-state in the no-harvest scenarios.

Impacts to the ecosystem's total energy storage, measured as cumulative foregone biomass (ΔB_c), while larger

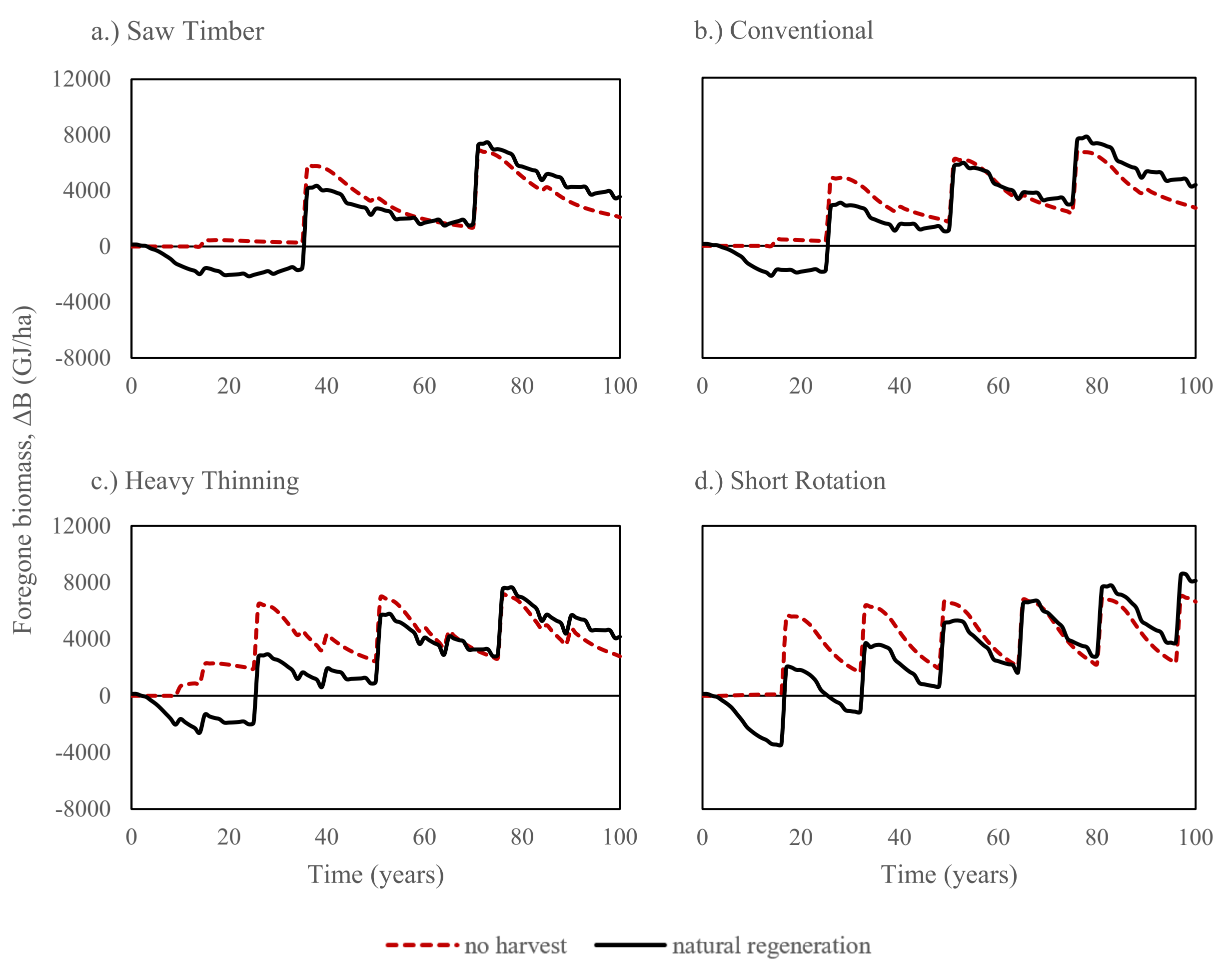

Fig. 5 Foregone biomass (ΔB) in GJ/ha (10^9 J/ha) under different forest management scenarios. Foregone biomass is evaluated under two different reference scenarios: a no-harvest (dashed red line) and a natural regeneration scenario (solid black line)

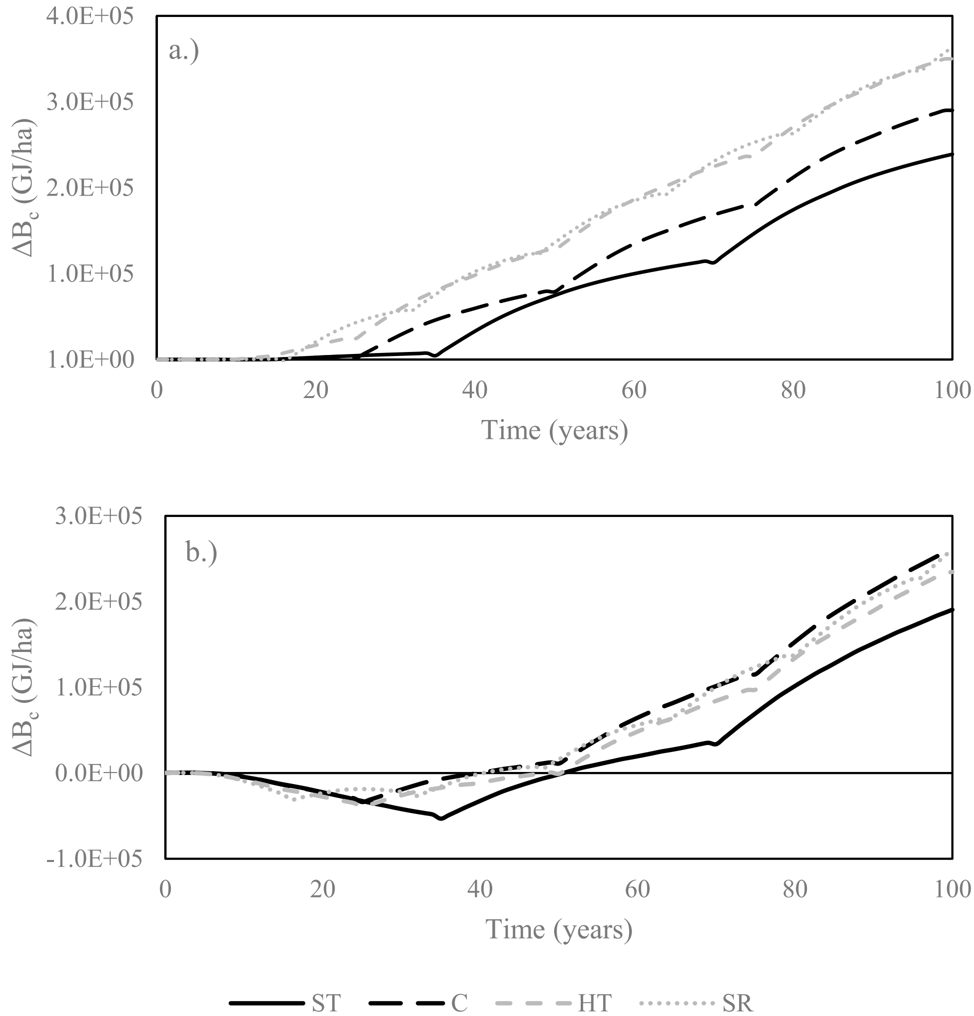

Fig. 6 Cumulative foregone biomass (ΔB_c) in GJ/ha (10^9 J/ha) for various forest management scenarios assessed under two reference scenarios including, **a** no-harvest and **b** natural regeneration scenarios. Management scenario abbreviations are: saw timber (ST, solid black line), conventional (C, dashed black line), heavy thinning (HT, dashed grey line), and short rotation (SR, dotted grey line)

in magnitude than ΔB, follows a similar trend over time (Fig. 6). Under no-harvest reference scenarios, ΔB_c increases with increasing management intensity and is comparable in magnitude for more intensive HT and SR managements. In comparison to no-harvest scenarios, ΔB_c under natural regeneration scenarios display lower magnitudes due to the initial improvements in ΔB before harvest. Under a natural regeneration reference, ΔB_c is lowest under least intensive ST management, increasing with increasing management intensity, but displaying less variability between managements than the no-harvest references. Interestingly, for natural regeneration, ΔB_c for the less intensive C management scenario is comparable in magnitude to the most intensive SR management. This is attributed to the lower quantity of biomass stocks under the C management compared to the natural regeneration reference. Additional details of the individual compositions of ΔB and ΔB_c over 100-years, broken down by each biomass compartment, can be found in the Supplementary Information (Tables S8 and S9).

Table 3 Comparison of net energy (NE) and cumulative foregone biomass (ΔB_c) in GJ/ha over 100 years for differing management scenarios

	NE	ΔB_c	
		No-harvest	Natural regeneration
Saw timber (ST)	6,967	238,932	190,558
Conventional (C)	10,518	290,085	258,817
Heavy thinning (HT)	13,342	350,034	234,652
Short rotation (SR)	14,873	363,600	261,149

Comparing the Energetics of Forestry Operations and Ecosystem Impacts

While trends in NE and ΔB_c between management scenarios depend on the time-horizon and reference scenario over which they are analyzed, comparing their magnitudes over a consistent timespan can reveal insight into the energy dynamics between the human/industrial and ecological dimensions of forestry operations. Regardless of the reference scenario or the type of management, impacts to forest biomass stocks ΔB_c are 1–2 orders of magnitude larger than NE from forestry operations over 100 years (Table 3). These results signify a strong energy imbalance, as the quantity of NE obtained from the ecosystem through intensive management also leads to substantial reductions in the ecosystem's accumulated energy stores. In essence, reductions in ecosystem energy storage resulting from intensive management greatly exceed the magnitudes of the technical energies invested and harvested by humans from the system.

Sensitivity Analysis Results

A sensitivity analysis assessed the variability in ΔB_c under the natural regeneration reference scenario for different SI values. SI was varied from 16 to 29 m and resulting values of ΔB_c were recalculated for each management scenario. For all management scenarios, variation in SI varies ΔB_c from a minimum of − 50% to a maximum of + 127% compared to an SI of 20 m applied in the main study (Fig. S2). This variability holds regardless of whether ΔB_c is calculated over 100 years or on a per-rotation basis. While the relative changes in ΔB_c are high under large SI values, such variability is not enough to alter the magnitudes of ΔB_c more than an order of magnitude in either direction (Fig. S3). Thus, variation in site productivity alone is not enough to alter the conclusions drawn between comparisons of *NE* and ΔB_c. Regardless of SI, the NE of forestry operations remains 1–2 orders of magnitude smaller than ΔB_c across all management scenarios.

Discussion

Conventional energy analyses of forestry systems are incomplete, as they account only for the technical energy inputs and biomass harvested from the system (Zavitkovski 1979; Herendeen and Brown 1987; Sundberg and Silversides 1988; Mead and Pimentel 2006; Balimunsi et al. 2012; Buonocore et al. 2014). In these analyses, the forest system is treated as another sector of the economy (Hercher-Pasteur et al. 2020). However, forestry operations take place within a forest ecosystem which, through natural ecological processes, accumulates and strives toward states of maximal energy storage over time. Therefore, a more complete energy model should include forest biomass and their resultant impacts under differing types of intensive management. Our approach differs from previous approaches by extending the system boundaries to encompass the whole forest ecosystem. Doing so allows for direct comparisons of the resulting reductions in potential biomass stocks (i.e., foregone biomass) alongside conventional energy metrics, highlighting the coupled energy interactions between the industrial and ecological dimensions of managed forests.

Despite its applications, the model is not without limitations. Foregone biomass is calculated as the difference between potential and existing biomass and therefore depends on the biomass of the modeled reference scenario. While variability in biomass of the natural reference ecosystem was accounted for with no impact on overall conclusions, this may not be the case for all forests or management types. In cases of afforestation, or where the managed forest replaces an ecosystem with lower biomass stocks, such as grassland or degraded land, biomass stocks are likely to be improved when compared to the natural baseline reference, resulting in negative impact values. As the purpose of the study was to capture impacts to biomass in typical intensive southeastern forestry scenarios, such cases were not considered but should be explored in future research. The developed model applies to cases where intensive management occupies land where the historical baseline would include a mature ecosystem, as is the case throughout much of the southeastern and northeastern United States (Rathbun 1993; Hanberry et al. 2018).

A shortcoming of this study involved the focus on managed pine forests in the southeastern United States. Compared to management practices in other regions, southeastern pine forestry is often far more intensive, frequently involving site preparation, fertilization, and herbicide applications (Jokela et al. 2010). Although the greater use of external inputs makes these practices ideal case studies for energy analysis, future research should broaden the scope to include other types of forestry, such as managed pine or hardwood forests in other geographical areas. Additionally, the spatial scope of this research took place at the stand scale, as the stand represents the primary spatial unit in forest management. Since biomass stocks at the landscape scale are simply the sum of those at the stand scale, extension of the model to the landscape scale is an important next step. However, differing land uses and forest age distributions across the landscape will require additional consideration and modeling efforts that were beyond the scope of this study.

When analyzed over 100 years, results revealed tradeoffs between management intensity, industrial energetics, and ecosystem impacts. In general, intensive management produces greater net energy returns through more frequent harvests, but this comes at the expense of greater biomass losses over time. While less intensive managements reduce biomass losses, they also achieve higher EROI values in comparison with more intensive regimes, regardless of how they were analyzed. This is a significant finding as it illustrates that less intensive managements are more energetically efficient at obtaining their harvests per unit of input invested compared to their more intensive counterparts. These findings agree with previous assessments indicating an increase in energy ratio with increasing rotation ages (i.e., for less intensive management) (Herendeen and Brown 1987). However, earlier studies compared energy performances across different forest types (i.e., pine vs oak) (Klopatek and Risser 1981; Herendeen and Brown 1987), while this study compared the energetic performance of differing management scenarios within the same forest and under different study scopes. Considered together, our results further support the hypothesis that less intensive forest managements exhibit greater energetic efficiency, whether considering various forest types, different management scenarios within the same forest, and regardless of the time-horizon over which energy metrics are analyzed.

This energy model has applications in forest management and decision-making which involve increasingly diverse objectives, requiring managers to balance conflicting goals such as sustainability, yields, and economic efficiency (Chaudhary et al. 2016). The use of an extended energy framework in forestry systems offers valuable insights for decision-makers by facilitating direct comparisons between magnitudes of the human/industrial and ecological dimensions of different management regimes. An energy model captures and expresses, in consistent units, the human inputs and outputs supporting and harvested from the stand, the existing energy stored as biomass in the stand, and the resultant impacts to the energy storage potential of the stand as an outcome of intensive management. In this way, the usefulness of energy models extends beyond traditional forest yield, carbon, and ecological models which are often assessed disparately and across multiple disciplines. Furthermore, quantifying impacts to the forest's energy state as the distance from potential energy stores establishes a benchmark for restoration potential which goes beyond considering only carbon stocks but also recognizes the foundational role of energy in maintaining ecosystems away from thermodynamic equilibrium (Odum 1983; Jorgensen and Svirezhev 2004).

Conclusion

Quantifying and understanding ecosystem impact together with the industrial efficiency of forestry operations requires an extended framework and indicators that can capture both the human/industrial and ecological energy dimensions of managed forests. Such a framework extends beyond the traditional perception of intensively managed forests as merely industrial production systems producing human-valued outputs while requiring external energy and material inputs.

Results showed improved energy efficiency under less intensive management approaches, while also highlighting substantial disparities between the human-extracted net energy and ecosystem impacts resulting from intensive management. Quantifying such imbalances is crucial, as permanent reductions in ecosystem biomass can lead to an irreversible return to thermodynamic equilibrium. Natural ecosystems required significant timespans, over millions of years, to accumulate substantial energy stores in the form of biomass. While human activities such as deforestation directly destroy biomass, intensive management, and land occupation permanently reduce and alter the ecosystem's ability to store biomass, as intensively managed ecosystems typically store less biomass than their natural counterparts (Smil 2012; Poorter et al. 2016; Erb et al. 2018; Lewis et al. 2019).

Despite these stark thermodynamic realities, the global state of forests is deteriorating, with natural forests experiencing ongoing losses of biomass and forest cover while the area of intensively managed forests expands by ~ 1% per year (FAO 2020; UNEP 2020). Although some degree of intensive management will likely always be necessary to meet biomass demands, this extended energy framework provides context to our most fundamental interactions with managed ecosystems and is essential for further understanding of the coupled energy interactions between the industrial forest management operations required to sustain and extract biomass for society and their resultant impacts to the ecosystem's overall energy state.

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Data Availability The data repository for this study can be found in the publicly available figshare repository linked below. Data in this repository includes (1) outputs of the conventional energy analysis models (https://doi.org/10.6084/m9.figshare.26169526) and (2) foregone biomass indicators (https://doi.org/10.6084/m9.figshare.25569936.v1), for each forest management scenario.

Declarations

Conflict of interest The authors declare no competing interests.

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