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Determinants and Tools to Evaluate the Ecological Sustainability of Using Forest Biomass as an Alternative Energy Source

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<http://dx.doi.org/10.5772/intechopen.76005>

Abstract

Forest biomass, the most ancient of fuels, is again in the center of renewable energy production. This chapter provides an introductory view of the main factors that condition the ecological sustainability of this energy source. The basic concepts of ecological sustainability, ecological rotation, and ecological thresholds (among others) are presented. The state of the art on approaches to assess the sustainability of forest biomass production for heat and electricity is discussed, and tools available for decision-makers to evaluate the sustainability of forest biomass production and management are described. This chapter then describes the main advantages and drawbacks of forest certification, growth and yield tables, and ecological models in relationship to their use in sustainable forest management for biomass and energy production.

Keywords: ecological modeling, alternative energy, green energy, district heating, sustainable forest management

1. Introduction: Defining ecological sustainability

Forest biomass is a natural renewable resource with multiple uses, including energy production. In fact, forest biomass is still one of the main sources of energy for heating and cooking in many regions around the world, particularly in developing nations [1]. Indeed, even in many industrialized countries around the world, forest biomass has the potential to substitute an important share of fossil fuels [2–5]. However, biomass is just the result of ecological processes taking place in forests all around the world, in which the energy from the sun is combined with

carbon dioxide from the atmosphere and water and nutrients from the soil to generate chemical energy bounded in the organic molecule product of the photosynthesis. Using forest biomass for sustainable energy production therefore requires understanding the functioning of forest ecosystems [6] and the environmental risks associated [7, 8].

Forests are complex ecological systems composed by many and very diverse elements. Topography, climate, and soil combined with animal, plant, fungi, and microorganism species to generate a unique forest in each site. The way such elements are combined is called ecosystem structure, and it encompasses both biological and nonbiological elements. As gearing parts, the ecological structure allows for the flows of sun energy (captured by plants through photosynthesis) and matter (water, nutrients, and carbon captured by plants through roots and leaves). In turn, such cycles allow animal, plant, fungi, and microorganism species to survive, reproduce, and evolve through time, colonizing new sites as they become available following natural and anthropogenic disturbances. Each of these ecological developments requires physiological processes (photosynthesis, water transport in plants, tissue growth, reproduction, etc.) or ecological processes (organic matter decomposition, seed and larvae dispersal, etc.) to run smoothly to keep the ecosystem working. In these processes, interactions among ecosystem elements (both biological and nonbiological) are determinant to produce the final amount of forest biomass that could be used to generate energy.

For example, when there is enough rain and medium to high temperatures (as in humid subtropical sites or in Mediterranean or dry subtropical areas during the rainy season), tree growth reaches its maximum rates. At the same time, soil microfauna is also in its most active moment, cutting up and processing litter and other soil organic matter in the forest soil. This facilitates the activity of fungi, bacteria, and other microorganisms that carry out the last steps of decomposing organic matter, releasing nutrients that can be used again by trees and plants to keep growing [9]. This complexity allows forest ecosystems to be resilient and recover from changes caused by disturbances.

Disturbances, defined by their intensity and frequency, cause important temporal changes in all ecosystems, causing significant fluctuations in some species populations but also providing new opportunities for species to establish and prosper. This process, called secondary succession, allows forest ecosystems to recover from disturbances by gradual changes in species composition and growing conditions that allow the recovery of the ecological community [10] and the capacity to produce woody biomass [11]. Based on this capacity to recover from change, the concept of sustainable forest management can be defined as the type of forest management that allows the recovery of the forest ecosystem to a situation similar to the one existing before the human intervention. The time needed for such recovery is called ecological rotation (**Figure 1**) [12], which is usually different from the economical or technological rotations, a fact that produces conflicting situations in forest management and planning. In fact, the term “forest biomass sustainability” is still up to discussion, and calls for international definitions and agreements are still common [13, 14].

The biomass obtained from forests should comply with the principles of sustainable forest management that are aimed at safeguarding economic, ecological, and social functions of forests and apply to all forest management activities. Sustainable forest management is the

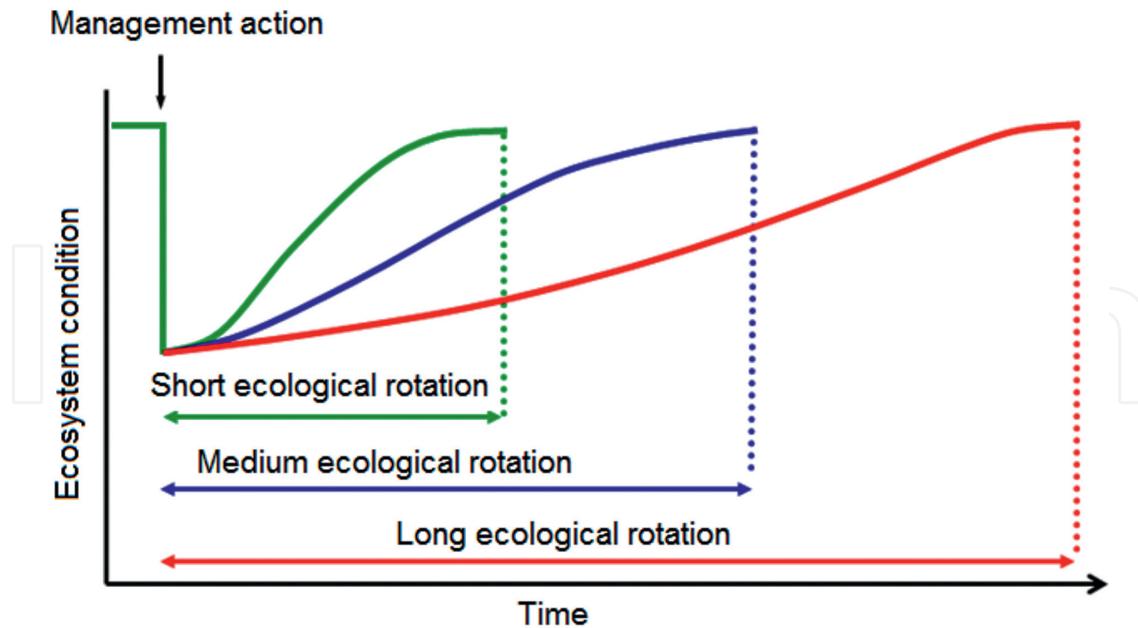


Figure 1. The concept of ecological rotation and its application to three ecosystems under the same management action but with different recovery rates.

practice of managing forests to meet the current needs and desires of society for forest resources, i.e., products, services, and values, without compromising the availability of them for future generations, as mentioned in the Brundtland Report [15]. More recently, new understanding of forests as ecosystems, along with societies' changing views of values derived from forests, has caused forest managers to adopt more comprehensive approaches to sustaining forests [16]. However, to become a useful tool, suitable indicators must be clearly defined and minimum/maximum thresholds for each indicator assigned [17].

Conceptually, forest management actions carried out by humans are not different from other natural disturbances. Both types of disturbances cause a temporal change in the ecosystem condition, which in turn can recover. Hence, from an ecological point of view, forest management actions can be defined by their intensity (how deep is the change in the ecosystem that they cause) and frequency (how often such change is imposed in the ecosystem). With just those two concepts, it is already possible to have a first glimpse of what sustainable forest management means from an ecological point of view (**Figure 2**).

Sustainability is an important concept currently at the forefront of many policy agendas. Sustainable forest management seeks to maintain or enhance ecosystem function and sustainability by emulating natural stand dynamics and disturbance regimes. Recently, interest in applying the ecological threshold concept has increased as a tool for approaching environmental problems, with the principles of sustainable and adaptive management. An ecological threshold is the point at which there is an abrupt change in an ecosystem quality, property, or phenomenon, or where small changes in an environmental driver produce large responses in the ecosystem [18]. The forest systems we deal with—ecological, economic, social, and integrated—are complex and operate by maintaining functional gradients away from equilibrium

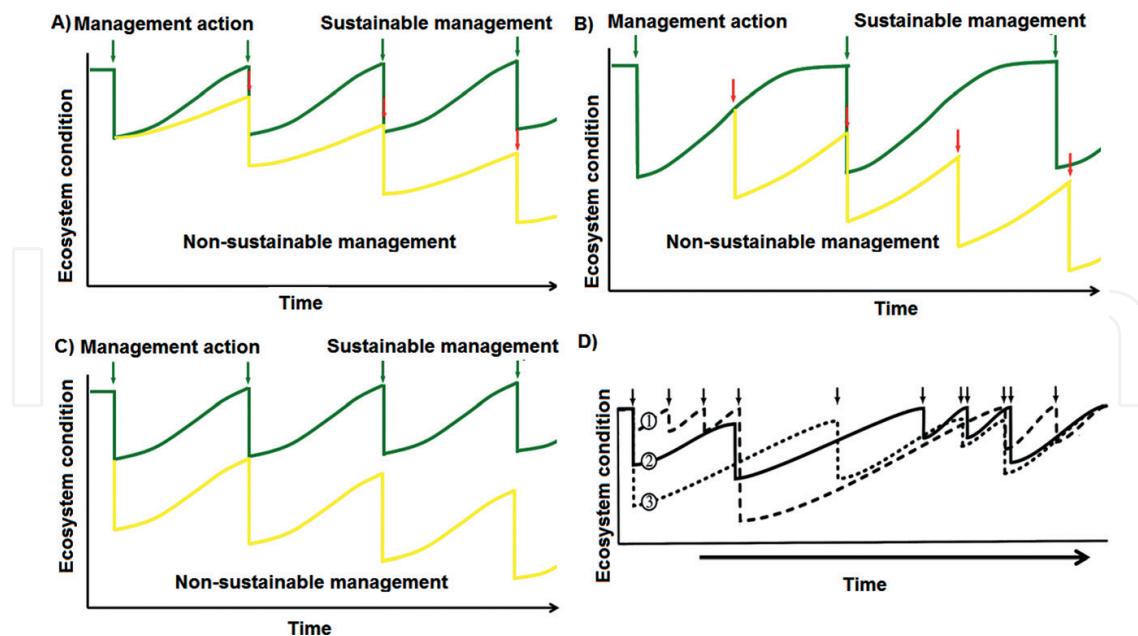


Figure 2. Three parameters can influence the sustainability of forest management: (A) different recovery rates can make a management plan sustainable in one ecosystem but not in another one; (B) human intervention frequency can be too high to allow for ecological recovery; (C) human intervention intensity can be too high to allow for ecological recovery; (D) sustainability should be framed for a given period of time and considered as the maintenance of a dynamic equilibrium of the target ecosystem condition over time.

[19]. Moreover, incorporating threshold concepts into environmental modeling, monitoring and management is a major advance in the ability to deal with ecological changes.

Ecological equilibrium should be then considered as a fluctuating condition that is bounded inside some limits. Therefore, the dynamic and long-term nature of changing ecological conditions in forest ecosystem brings a challenge when assessing if a given management plan to use forest biomass as a sustainable source of energy is sustainable. To support forest management planning and stakeholders' decision-making, several tools have been developed over the last decades, ranging from administrative processes (such as certification schemes) to high-level scientific simulators (empirical, theoretical, and hybrid ecological models).

2. Using forest biomass as an alternative energy source

2.1. State of the art

Forest biomass is a renewable, domestic fuel, which can be used for energy production. Sustainable use of forest biomass does not permanently increase the amount of carbon in the biospheric cycle, in contrast to fossil fuels, as the carbon in forest biomass comes from the atmosphere and not from the lithosphere. However, the difference between carbon sequestration rates by tree growth (commonly a slow process) and carbon releasing rates by biomass burning (a quick

process) means that careful planning must be done to avoid the “carbon debt,” i.e., increasing carbon in the atmosphere [6]. Current concerns regarding climate change and rising energy costs have noticeably increased the interest in the use of renewable and alternative energies. There is an increasing demand for biomass to be used for energy, and the use of forest biomass as an energy resource is growing as a result of increased energy costs and a desire to reduce the greenhouse emissions responsible for climate change. Forest biomass is currently used to generate electricity and heat, combined heat and power, liquid fuels and others.

Some industrialized countries derive a considerable amount of energy from biomass (i.e., Finland, Sweden, USA), but biomass resources are traditionally used in rural areas of developing countries where half the world’s population lives and primary energy supply is provided by these forest resources [1]. Therefore, biomass already contributes a significant part of the world’s energy. Currently, the major use of biomass is in the form of heat in rural and developing countries. Fuels such as firewood, dung, charcoal, peat, harvesting residues, methane, and alcohol are important sources of energy to many people in developing countries [20].

Wood is considered humankind’s very first source of energy. It represents the only domestically available and affordable source of energy for cooking and heating in many households of developing countries [1, 5]. For example, the absolute number of people dependent on biomass fuels in sub-Saharan Africa will increase through 2030, suggesting that policy-makers should pay careful attention to the factors influencing supply, demand, and distribution of forest biomass fuels. This issue is particularly important in regions such as East Africa, where approximately 95% of the population use solid fuels for cooking and heating [1]. Thereby, bioenergy may represent opportunities for domestic industrial development and economic growth. In these countries, traditional biomass is often the dominant domestic fuel, especially in rural areas without access to electricity or other energy sources. There are multiple challenges and opportunities for bioenergy as a potential driver of sustainable development, given enough economic and technological support [21]. However, economic development, agricultural activity, and population pressure remain important drivers of deforestation at developing countries. Recent studies have highlighted trade of agricultural products as a potential driver of deforestation [22], pointing to the need for well-designed plans for reforestation and sustainable forest management.

Wood energy has entered into a phase of high importance and visibility with climate change and energy security concerns. There is a wide variety of biomass sources for bioenergy production: short-rotation woody crops of trees grown specifically for bioenergy, forest residues or woody materials remaining in the forest after harvest (e.g., tops, woody debris, stumps, and other logging residues), nonmerchantable biomass (e.g., small trees and noncommercial species), and waste from the creation or disposal of wood products [23]. The combination of wood biomass resources from forest and plantations will certainly play an important role in the development of energy alternatives [24]. In addition, the development of efficient cookware and modern kitchen installations could increase energetic efficiency in rural and developing areas. Otherwise, development leading to increased population and its associated agricultural activity and energy demands could cause rapid land use change, leading to large net losses in

forest carbon stocks [1]. Such situation could have several unintended consequences. First, higher demand for forest biomass could increase the health burden on women and children due to the time needed to collect fuels and exposure to smoke. Also, goods and services provided by fully stocked tropical high forests could be lost by means of excessive biomass extraction [11]. Such issues could lead to increased climate impacts via carbon emissions from deforestation and forest degradation, and increased particulate and black carbon emissions [1].

On the other hand, use of biomass from residues of forest management aiming to reducing wildfire risks can support climate change mitigation efforts by helping to sequester and store more atmospheric carbon in forest standing biomass and soils [25]. Similar to any other forest management practice, ensuring the sustainability of biomass harvesting for energy requires attention to individual site conditions and consideration of multiple management objectives. Due to this increasing wildfire risks, there are economic as well as environmental reasons to increase the use of woody debris as a source of energy generated from the preventive forest management. Also, an environmental factor to be considered when using woody biomass as a source for heating fuel is the reduction of carbon dioxide emissions [25]. Integrated forest system analysis can provide insights on the overall climate implications of increasing use of bioenergy and biomaterials, which are often seen as a sustainable way to help mitigate climate change by substituting fossil fuels with forest biomass [26].

Global energy supply depends heavily on fossil fuels. Wood-based bioenergy is very competitive, when it is a product of the forest industry and used in highly efficient conversion plants. The competitiveness of forest biomass-based energy production can be further improved by better integration into industrial infrastructures of wood-processing industries, including their feedstock supply systems [27]. Integrated energy systems that supply a package of energy services including electricity, heat, and transport distance reduce the primary energy use and increase the climate benefits of woody biomass [28]. Development of energy conversion technologies and sectoral integration of energy systems could improve the primary energy efficiency of energy systems. Heat and electricity can be coproduced from woody biomass and used interchangeably in several end-use applications. However, the sustainability of all the management options associated with forest biomass should always be assessed.

2.2. Tools for monitoring ecological sustainability

Whether a forest biomass management plan is sustainable or not depends on multiple factors and determinants [29]. Due to this reason, multiple tools have been developed to estimate the sustainability of forest biomass management [30]. Some of them are forest management guidelines [31], administrative tools based on monitoring and indicators (e.g., certification schemes) [32], tools based on experience (empirical models) [33], and other tools based on the best available knowledge (process-based models) [6].

2.2.1. Forest certification: a powerful administrative tool

In forest biomass energy systems, both the management and the biomass product (i.e., chips, pellets, etc.) can be certified. Certification in forestry is a voluntary process in which an

independent organization, recognized by the forest sector in the given country, certifies that forest operations during the management or the manipulation and transformation of the fuel have been done in a sustainable way. This is a process led by the market, in which the producer of forest products tries to get a "green label" that will raise him above the competition. The positive results obtained so far from this approach, together with the compulsory requirement for certified suppliers of many large distribution companies or public institutions, have produced a noticeable number of certification schemes in the last years (**Figure 3**).

The capacity of forest certification schemes to assess and ensure the sustainability of forest management is based on the use of criteria and indicators. A sustainability criterion is a rule, norm, target, or goal that if achieved indicates that management is sustainable. Given the inherent complexity of forest ecosystems, a set of numerous criteria are used, each of them focused on a specific part of the ecosystem [32]. For example, a sustainability criterion could be to keep a given number of dead standing trees (snags) per unit of surface in the forest that can be used as nesting ground for woodpeckers, beetles, or other fauna [34]. Sustainability criteria are usually based on empirical relationships between an ecosystem variable (i.e., number of snags per hectare) and a specific ecological process (i.e., the presence/absence or density of woodpecker birds by area unit, or other type of fauna). Such criteria are defined by the certification organizations and evaluated by the certification auditors during the certification process (**Figure 4**).

The most useful criteria to assess the sustainability of forest management for biomass production are those that can be measured or quantified. Such quantification allows for independent testing whether the sustainability criterion is being met. Such measurable variables are indicators, which can be compared against a threshold defined for a specific criterion [32, 35].

However, in certification processes, not only biological indicators are evaluated but also technical and administrative indicators (for example, creation of documents and files to follow forest management operations, handling of residues or chemicals in the forests, suitability of heavy machinery for different forest soils, etc.). The main advantage of forest biomass certification (in addition to facilitate meeting a given set of sustainability criteria) is that it generates and updates documentation on forest management that can be used for other purposes. In addition, it compares results at local scale (field data or filed documents) to international standards.



Figure 3. Forest certification labels issued by different international certification organizations.

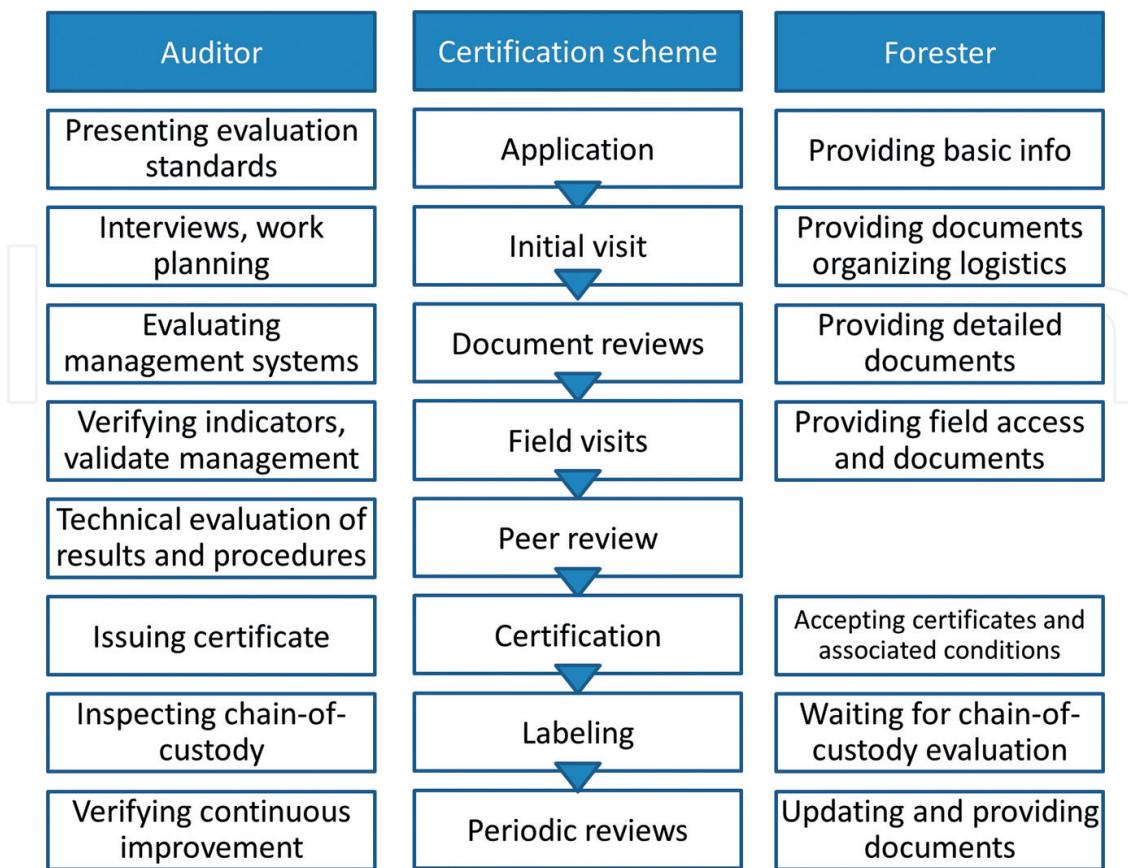


Figure 4. Roles of the three main actors involved in a forest certification process.

Last but not least, forest certification improves the marketability and image of forest producers in the eyes of sustainability-conscious consumers, which can be translated into improved sales in the long term or into being eligible for reaching given customers, such as public institutions that follow programs of buying goods only from sustainable providers. In fact, influencing sustainability of forest biomass production for energy is increasingly being seen as a policy tool that could steer intensive management away from sensitive forests [36]. To do so, technical guidelines for best practices are being developed, in which the precautionary principle is always suggested [31].

Given the increasing importance of the biomass for energy subsector inside the forest sector, certification schemes are being reviewed and adapted for the particular issues inherent to biomass production. Among them, water-related issues (both in terms of quality and availability) are being included. In addition, the overseeing and control of certification schemes must also be ensured, including mechanisms to ensure transparency and verification [37, 38].

However, forest biomass certification has some disadvantages. First, certification schemes assess the sustainability of forest biomass management practices and their ecological impact in a given point of time, but as seen before, sustainability depends on the time frame for which it is assessed. In other words, forest biomass certification studies a “picture” of the forest ecosystem, which may or may not be representative of the “movie” that in fact forest

management is. For example, it could be possible to harvest all aboveground biomass in a forest stand (the so-called whole-tree harvesting) following sustainable indicators of forest management, but what could be sustainable if used once can become unsustainable if repeated over time if the increased nutrient exports in stems, branches, and leaves [39] surpass the inputs of nutrients in the system by deposition, fertilization, or other flows [40]. Other effects of forest biomass removal include changes in acid-base status and influence tree growth and survival [41]. If mineral deficiencies are generated by excessive biomass removal, reductions on forest productivity could last for decades, if not centuries [11, 42].

To address the issue of long-term sustainability evaluation, indicators can be evaluated against sustainability criteria thresholds over a period of time, and then a monitoring plan is created [37]. Controlling, measuring, and monitoring such sustainability indicators are therefore key actions in forest certification schemes. Monitoring plans can therefore detect temporal changes and define the timing when corrective actions should be carried out. For this reason, all certification schemes include periodic revisions of certified producers and owners. Although this is clearly an improvement over assessing sustainability at a unique point of time, it is possible that from an ecological point of view, monitoring plans used in certification are still using time frames too short to correctly assess sustainability of forest management, given the long timescales involved in the development of forest stands. Therefore, certification should ideally be accompanied with other tools to assess the sustainability of forest management in timescales meaningful for long-lived organisms like trees. Some of such tools are ecological models.

2.2.2. Ecological models

Historically, institutions related with forest management have generated large quantities of data and documents as reports, publications, inventories, books, etc. Many of such documents are based on field data from research plots or periodic inventories that those institutions have periodically carried out for many years, if not decades or in some cases even for more than a century [43]. An obvious application of such massive datasets is using their large coverage in time and space encompassing many different forest types (different species, tree ages, stand densities, climates, soils, etc.) to estimate how trees grow along a rotation. In other words: creating tree growth models.

A tree growth model is simply a set of rules, tables, or equations, which allows the estimation of the volume or biomass of a given forest stand at a given time. The most common growth models in forest management are growth and yield tables, which indicate for a site with a given growth potential (site quality) and a combination of tree species, stand density, and stand age, the expected volume to be harvested under different management regimes. These tables are the product of forest stakeholders' historical needs to estimate future forest productivity when planning forest management actions. Design criteria for such tools are simple: they must provide reliable predictions to avoid risks, must be based on data easy to measure in the field and must be able to use, summarize, and reproduce field data. However, as these models basically summarize observed data, their estimations will be valid only if future growing conditions are similar enough to the conditions that existed when field data were collected (**Figure 5**).

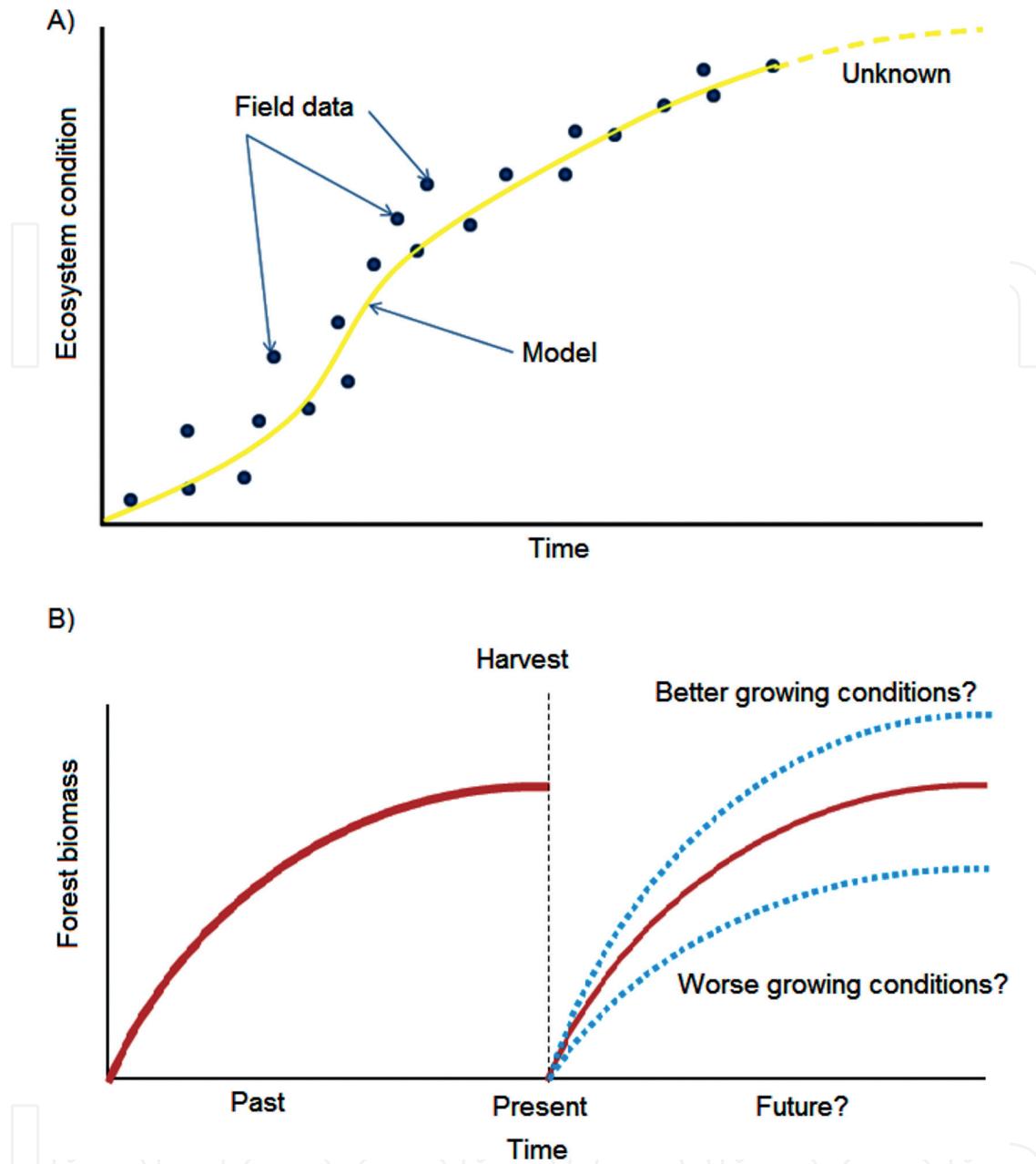


Figure 5. Conceptual development of an empirical model. A) The collection of available data is used to create a continuous equation to estimate growth for the whole range of data availability, but outside such range, tree growth patterns are unknown. B) Empirical models of forest biomass production are valid as predictive tools as long as future growing conditions are similar to the ones occurring when the data used for model creation were collected.

Then, the question to be asked is: will the future be similar to the past? The answer is that likely it won't be. Growing conditions that forest will experience in the future will be different by changes in the biological factors (invasive species, understory competition, farming and grazing abandonment, etc.), as well as in the nonbiological factors (climate change) and human-related factors (management of mixed forests instead of monocultures, continuous cover forestry, new equipment and techniques, land use change, etc.). All those changes combined

will modify growing resources (space, light, water, nutrients) and make them different from the ones that were available for trees when field data were collected. This phenomenon will reduce the utility of traditional growth and yield tables (and in general of any other empirical model based only on observations) to estimate future forest biomass production (**Figure 5**).

Therefore, more complex tools are needed to estimate the sustainability of forest biomass production for energy generation. Such tools already exist (see for example [44, 45]). They are the so-called process-based ecological models. Such models describe ecological processes using mathematical equations that relate tree growth with environmental variables such as rain, temperature, nutrients, etc. Although most of this type models were originally designed as research tools to better understand how ecological processes work at different scales (from individuals to ecosystems, from seconds to centuries), in several noticeable cases, they have reached applicability in forest management operations [44, 46, 47].

The main strong points of such tools are their great flexibility to simulate tree growth under changing conditions, the improvement of ecosystem understanding and their guidance to research. On the other hand, unless there is a deep understanding on the ecological mechanism underlying tree growth, assumptions may need to be made. Particularly, some parameters are difficult to determine in the field without special scientific equipment, which usually is not part of the standard equipment of forest management crews. Finally, additional challenges are ecosystems' emerging properties, in which the addition of what is known about each part of the ecosystem is not the same as the observed ecosystem-level ecological behavior of the system. Such challenges cause that sometimes model estimations of forest biomass are not as reliable as needed for forest management planning.

The reality is that there is not a single model that can do everything, and if there was, it would be so complex and cumbersome to use that it would be useless [33]. Using different methods to estimate sustainability of forest biomass use for energy production ensures that different aspects are taken into account [30]. Hence, it is worth to remember that the aforementioned tools do not exclude each other, and they can be combined in the modern forester's toolkit. Sustainable forest management in the modern world requires the combined use of traditional and new tools, using each of them for specific situations and to solve particular questions, and making them transparent and available for review and harmonization [4]. In fact, empirical and process-based models have already been combined to estimate social, economic, and ecological sustainability of district heating systems fueled with forest biomass [25, 29].

Many models of ecosystem productivity and function exist with varying levels of organization, scope, temporal resolution (from seconds to years), and spatial explicitness (from leaves to global assessments) [33, 48]. Recent reviews of biogeochemical models indicate that accounting for interactions between C and N cycles [49], as well as other nutrients [50], is necessary to predict future tree growth. In addition, not only climate change but chemical changes in atmospheric deposition will also be a major influence on future changes on ecosystem functioning and tree growth [51, 52]. Therefore, to estimate future forest ecosystems responses to global change, an accurate analysis of the importance of nutrient cycling on growth and its natural variability range is becoming paramount. Focusing only on average projections may

not give a complete picture of the variability on nutrient stocks and flows. Variability is intrinsic to ecosystems, and it indicates different possible ecological states. Those alternative ecological states are as realistic as the average condition typically reported, being different just in the probability of such state to happen. Such variability can only be characterized through analysis of historical changes in forest ecosystem condition.

In spite of all these evidences, some state-of-the-art forest models for management and research still assume nutrient availability as a fixed parameter [53], even though models that incorporate site quality change over time have been available for more than 20 years [54]. Therefore, the key to understand the impacts of forest management on sustainable biomass production is the dynamics of belowground processes (e.g., nitrogen mineralization rates, soil respiration rates, and labile carbon forms in soils) [51]. However, empirical models regularly used in forest management do not include such considerations, and attempt to address their lack of complexity by using operational adjustment factors (usually simple multipliers) that account for changes in nutrient availability and climate, but only in a static and linear way, perpetuating their limitations.

On the other hand, over the past two decades, several process-based biochemical and physiological models have been developed for research applications. Several models of forest growth have included soil moisture or rainfall data as a parameter in the calculation of forest production, but few consider the effects of forest management for biomass production on the key processes of nutrient cycling as they interact with temperature, and moisture, under management or natural disturbances. These more complex models have generally been proven impractical in forestry applications due to the quantity of data required for their calibration, and also for failing to represent some part of the ecosystem important in forest management, such as litter decomposition (i.e., PnET-CN, BIOMASS, SORTIE, TASS, FVS/PROGNOSIS), multilayered canopies (i.e., BIOME-BGC, G'DAY, 3-PG, ForCENT, TRIPLEX), or understory (all models mentioned). Similarly, other European models such as PrognAus, SILVA, BWIN, or MOSES are well suited for management applications but they lack an explicit representation of soil nutrient processes, although EFIMOD is an exception. On the other hand, regeneration niche models such as TACA or water circulation models such as GOTILWA+ have been proven very useful for the applications that they were designed for, but they do not include nutrient cycling or nontree organisms. Finally, CENTURY is a proven soil model but it has a simple tree simulator, and therefore, it cannot be considered as a forest research and management tool (see reviews by [44, 46, 47]).

Owing to this lack of adequate and truly ecosystem-level models, decision-support tools that incorporate a greater proportion of the key determinants of tree growth and climate change effects are needed for modern forest biomass production systems. To address such issues, the latest developments in forest modeling move toward incorporating more hybrid approaches to ecological modeling [33, 55, 56], which are a mixture of both causal and empirical elements at the same hierarchical level [57]. To solve some of these issues, new models are being developed to increase the application of truly ecosystem-level simulators that account for stand-level competition for light, nutrients, and water among trees and understory, such as FORECAST-Climate [33, 57] (**Figure 6**).

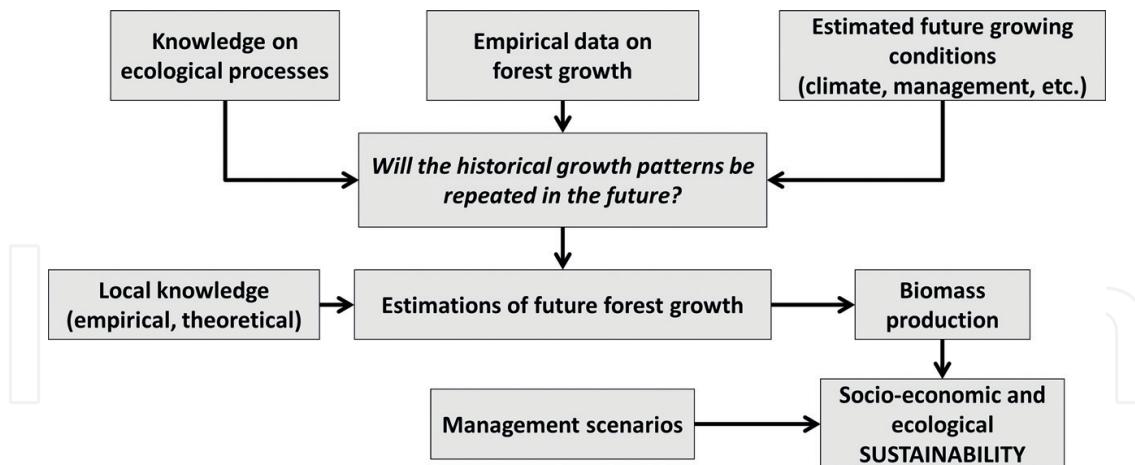


Figure 6. Conceptual development of hybrid empirical-theoretical models of forest biomass production and its use to assess sustainability of forest management practices.

These hybrid models are increasingly popular because they keep the reliability of field data but also add the scientific knowledge on ecological processes. Hybrid simulation models take advantage of the credibility of empirical models and use process simulation to account for changing conditions [57]. The feasibility of using this modeling approach to assess the sustainability of forest management focused on biomass production for bioenergy has been demonstrated for boreal [25, 29], temperate [42], and tropical forests [11, 58]. Such tools can therefore be used to explore the ecological consequences of both intensive forest management but also subsistence biomass harvesting in developing countries for cooking and heating [1]. The limitation for applying ecological models to developing countries is mostly the availability of data to accurately represent the soil, tree, and understory species in the region of interest.

In fact, hybrid models are still not widely used in forest management, as managers favor simpler experience-based empirical models such as growth and yield tables or inventory-based models. As a result, most hybrid models have been applied only as research tools. The reasons are several, but mainly, inventories of tree growth have been a good proxy for future growth as far as the conditions for tree growth remained stable. However, if changes in the forest composition, nutritional status, or climate produce a deviation from the recorded pattern (a situation dominant in European forests since the 1960s) [59], empirical models cannot predict these deviations as they lack the representation of ecological processes involved in tree growth. Therefore, using science-based models that allow for testing new management options such as ash recycling, slash and stump removal, or carbon balances and life cycle analysis should therefore be incorporated in sustainability certification schemes [60].

However, for such ecosystem-level process-based models to be valid management and research tools, they need to incorporate realistic interactions between ecological factors and be evaluated against independent data [33]. Model evaluation should be carried out by comparing model estimations with long-term observations, because even though models can show good agreement with short time series of empirical data, when projecting long-term forest dynamics, their estimations could be very sensitive to model architecture. Unfortunately, this is also a point where the lack of reliable long-term empirical data for model evaluation makes difficult the use of

ecosystem-level models in developing countries. In conclusion, understanding how forests have changed during the forest's life span will allow evaluating the efficiency of current and future forest management practices to produce biomass for energy use: a crucial step to successfully adapt forest management to an uncertain future of climate change and atmospheric pollution [61].

3. Conclusions

As a take-home message, it should be remembered that sustainability of forest biomass management depends on the ecological variable being assessed and the time frame for which the assessment is carried out. As forest ecosystems are complex systems, multivariable sustainability analysis should be done, taken into account variables not only directly related to forest biomass (such as volume growth, tree productivity, etc.) but also other ecological parameters such as soil organic matter, biodiversity of plant, fungal and animal communities, levels of coarse and fine woody debris, etc. [7]. A good starting point to reach sustainable forest biomass management is the use of certification schemes, and particularly, the ones specifically designed for biomass and biofuels as energy sources. In addition, it is important to face the reality that managing complex ecological systems such as forests will always have some uncertainty associated [62]. Such uncertainty should not be considered a limitation, but a challenge that can be overcome by using an appropriate suite of ecological models (from empirical to theoretical, and particularly hybrid) that incorporate the latest scientific knowledge on past, present, and future relationships among ecological, geoclimatic, and human processes. Such tools already exist, and should be used and adapted to ensure the transition from fossil-based to renewable-based energy systems.

Acknowledgements

We thank our project partners from FOR_{RX} Consulting Inc. (Canada) and the Asociación de Propietarios Forestales de Navarra-FORESNA (Spain) for their collaboration at different stages of this research. This research was funded by a Government of Navarre's (Spain) research action (ref. PI037 InFORest, which also funded David Candel-Pérez), and a project funded by the Spanish Ministry of Economy and competitiveness (ref. AGL2016-76463-P TIMENUTRIENT). Yueh-Hsin Lo was funded through a Marie Skłodowska-Curie Action (ref. MSCA-IF-2014-EF-656810-DENDRONUTRIENT). The FP7 post-grant Open Access publishing funds pilot funded the publication of this manuscript.

Conflict of interest

The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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