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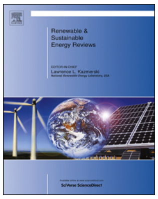

Incorporating bioenergy into sustainable landscape designs ☆

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ABSTRACT

The paper describes an approach to landscape design that focuses on integrating bioenergy production with other components of environmental, social and economic systems. Landscape design as used here refers to a spatially explicit, collaborative plan for management of landscapes and supply chains. Landscape design can involve multiple scales and build on existing practices to reduce costs or enhance services. Appropriately applied to a specific context, landscape design can help people assess trade-offs when making choices about locations, types of feedstock, transport, refining and distribution of bioenergy products and services. The approach includes performance monitoring and reporting along the bioenergy supply chain. Examples of landscape design applied to bioenergy production systems are presented. Barriers to implementation of landscape design include high costs, the need to consider diverse land-management objectives from a wide array of stakeholders, up-front planning requirements, and the complexity and level of effort needed for successful stakeholder involvement. A landscape design process may be stymied by insufficient data or participation. An impetus for coordination is critical, and incentives may be required to engage landowners and the private sector. Hence devising and implementing landscape designs for more sustainable outcomes require clear communication of environmental, social, and economic opportunities and concerns.

Contents

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1. Introduction

1.1. Bioenergy systems

Bioenergy is renewable energy made from materials derived from biological sources. Biomass feedstocks include any organic material that has stored energy from sunlight in the form of chemical energy, such as plants, residues from agriculture or forestry, and the organic component of municipal and industrial wastes. Biomass is the earliest form of energy used by humans and could provide about one fourth of global primary energy, or 138 exajoules (as measured by averaging projected values from five reports [1]). Biomass can be converted to energy-dense liquid fuels or dispatchable power, characteristics that cannot be easily matched by other renewable sources.

Bioenergy supply systems include the production or collection of biomass feedstock, transport of the feedstock to a conversion plant, the conversion of biomass into useable energy, the distribution and use of the energy, and disposal of any wastes. These steps can occur at different spatial scales. For example, a small plot of land may supply a household with fuelwood, or expansive agroforestry systems across multiple continents may supply crude palm oil that is refined in The Netherlands and distributed across Europe. Consequently, bioenergy production systems can have a wide range of complex ecological and socioeconomic effects that often operate over broad spatiotemporal scales [2].

Major bioenergy supply networks are established based largely on economics, policy, and existing industries and infrastructure. Demand and supply of biological commodities combined with long-established production systems determine the location, size and spatial extent of bioenergy supply systems. Supply is largely influenced by the availability of low-cost feedstock that are byproducts of existing industries such as organic wastes, forest industry and agricultural residues, and least-cost industrial commodities produced primarily for other markets (maize, sugarcane, palm and soy). While markets are driven by such factors as population dynamics, economic growth and policy incentives, supply and demand also depend on availability and use of technologies that can transform the chemical energy stored in biomass to a more useable form. Those technologies range from wood fuel stoves for heating and cooking to flex-fuel engines that use liquid biofuels. Since the development of most biomass and energy supply systems depends on the business plan of the project, other aspects of sustainability such as biodiversity, soils, water and air quality, and social well-being may arise as issues after production is underway. Financial analysis often treats such aspects as externalities that may be recognized but are not accounted for when assessing profitability or return on investment (e.g., the economic feasibility of a system).

There is great interest in identifying conditions under which sustainable bioenergy might be produced, and yet good practices are still being developed, implemented, assessed, and revised [3]. However, selection of sustainability performance measures for bioenergy involves human value judgments. The meaning and interpretation of sustainability are context-specific and change across both temporal and spatial scales in response to changing societal needs, economics, and technology. Some parts of the industry recognize business opportunities in producing sustainable products for niche or mandated markets, and some governments are requiring that sustainability criteria be met to participate in certain programs or count towards policy goals, although the measures and means of meeting those requirements are not always clearly specified. The Global Bioenergy Partnership (GBEP) has convened public and private actors to raise awareness and increase understanding of issues related to bioenergy development [4]. More than 60 countries have policies promoting the production and use of biofuels [5], and, in response, a large number of standards to assess and document “sustainability” of bioenergy have been developed (Box 1). Mandates for “sustainable” bioenergy are typically top-down requirements devised by government officials with limited involvement of stakeholders who are affected by the decisions while bottom-up efforts typically aim at involving a broad range of stakeholders. Most regulations include sustainability requirements that vary in scope and specificity. Voluntary certification schemes developed by private organizations offer a mechanism for documenting compliance (Box 1). Certification schemes are relatively recent and hence are supported by new tools and policies [6]. Many voluntary standards include criteria and indicators of sustainability beyond those required by law. Some of the voluntary certification schemes were developed by private organizations to offer a mechanism for documenting compliance with specific legislation, while other schemes include additional criteria and indicators to reflect broader sustainability goals.

1.2. Landscape design

Landscape design is a process for spatially explicit planning involving stakeholders who share concerns. It aims to identify opportunities to manage resources for more sustainable provision of services while taking context, trends, and current conditions into consideration [7]. Hence landscape design combines spatial planning with biomass production systems, supply chain optimization, horizontal and vertical performance analyses, stakeholder processes, education, monitoring, and adaptive management.

The term draws from analysis of interrelatedness between spatial pattern and process, which is the foundation of the field of landscape ecology [8], with roots in both landscape architecture and environmental sciences [9]. Early examples of these ideas are expressed in the parks, country estates, residential communities, and campuses designed by Frederick Olmsted based on his guiding principles for effective organization of space [10]. Olmsted’s principles promote the use of naturally occurring features of a given space with the overall design being concealed to produce a

Box 1–Regulatory standards and certification schemes for documenting progress toward sustainability of bioenergy systems

Current regulatory standards include the U.S. Renewable Fuels Standard, California's Low-Carbon Fuel Standard, the European Renewable Energy Directive (EU RED) for liquid biofuels, and the criteria for sustainable biomass production announced by United Kingdom's Department of Energy and Climate Change (DECC). EU RED and DECC standards have mechanisms that accept specifically endorsed voluntary certification schemes for showing compliance. As of December 2014, the EU RED recognized 19 widely varying schemes for showing compliance with its sustainability requirements [81], while the DECC accepts forest certification systems as part of the evidence. Some certification systems such as the Roundtable on Sustainable Biomaterials (RSB) [82] were developed and modified to address requirements of the RED and similar regulatory frameworks regardless of type and source of biomass. Such schemes may include sustainability criteria relevant for the whole supply chain with special emphasis on methods to calculate greenhouse gas (GHG) emissions.

Certification schemes may be more or less ambitious or focus differently. Some systems are designed for a specific feedstock or product, and other standards address some but not all sustainability criteria demanded by some regulations. For example, forestry standards such as Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI) consider sustainable forest management for production of any forest product regardless of end use [83], but they do not include the GHG emission accounting required by most bioenergy regulations. Developed countries tend to focus on environmental effects such as soil fertility and biodiversity, while developing countries are generally more concerned about social issues such as jobs, access to firewood and working conditions [83]. Some of these dissimilarities in national level standards relate to differences in the objectives of the stakeholders involved in standard setting in each location [34,84]. Context specific priorities are also sometimes expressed in mandatory or voluntary guidelines. For example, in the United Kingdom aesthetics are very important, and there are guidelines requiring that the character of the rural landscape be maintained when planting bioenergy feedstock crops.

harmonized unit focused on purpose rather than ornamentation. However, landscape designs such as Olmsted's do not necessarily result in conditions that optimize all values [11]. Trade-offs are inevitable, and the way people interact with the natural, managed and built environment depends on context and can change over time [12].

Landscape designs provide a means to engage stakeholders and to help identify how to integrate effectively a set of objectives [13–15]. The managers involved might include private entities (e.g., a family or corporate farmer, forester, or rancher), public authorities (e.g., state or federal agency), or a non-governmental organizations (e.g., an environmental group or professional associations). The premise of landscape design is that management approaches consider options that cut across dissimilar economies, disciplines, and territories. That is, combined solutions derived from a landscape approach are "better than the sum of their sector-specific parts" in reaching a common goal [16]. Holmgren notes that in economic terms, a landscape design approach seeks to decrease or remove externalities between the land-based sectors; in planning terms, it considers a more complete set of options by avoiding narrow and fragmented solutions and encouraging upfront engagement of a broader set of stakeholders that represent a wide set of objectives but also common goals [16]. This process requires extensive collaboration between actors who choose to compromise in order to negotiate solutions that are optimal at larger scales.

Elements of landscape design approaches are common when making decisions about public lands where land-use decisions are often the result of extensive stakeholder engagement. For example, after considering over 170,000 comments from fishermen, scientists, conservationists and other stakeholders, the U.S. established the Pacific Remote Islands Marine National Monument. While there is always room for improvement, the approaches that have evolved in the public sector for parks and reserves offer insights into the costs and challenges that confront landscape design involving bioenergy and other services on private land.

2. Landscape design as a means to move toward more sustainable bioenergy systems

2.1. Approaches to landscape design for bioenergy

The opportunity to move toward more sustainable resource management in the production and use of bioenergy needs to consider land tenure and ownership patterns. Modern biomass production is likely to occur on public land in countries such as Canada where 90% of the forest estate is held by the Crown or on privately owned land in countries such as the U.S. Hence information about landowner objectives, constraints and opportunities, and means of communication and learning are all critical factors for successful deployment of the bioeconomy. Landowners are a diverse group, with their major objectives, values, and concerns being derived from individual personal experience [17,18]. Some of the energy production and climate change mitigation potential of bioenergy systems depend on variables beyond the individual landowner, such as gross energy production, the carbon intensity of that production, the total land area involved, prior land use, the type of production system, and the reference energy system [19]. As a result, successful development and implementation of a landscape design process for bioenergy will have to mesh the goal of producing bioenergy sustainably with the needs of the people engaged in all stages of the supply chain. Projects may involve offers to utilize lands that have traditionally been used by local communities, nomadic grazers, or seasonal occupants. In such cases, the guidelines of The Food and Agriculture Organization (FAO) for any activity involving land transactions are consistent with landscape design. The affected individuals, groups, and/or institutions should be consulted, traditional access to land by local communities should be safeguarded, and any affected parties should be appropriately compensated [20].

Landscape design for bioenergy networks provides an opportunity to move toward more sustainable systems for the local or regional context where it is being implemented. It offers a means for those affecting and affected by the ecosystem and social services associated with bioenergy systems to engage in a process of assessing and planning how bioenergy might better fit into current energy production and land-use systems [21,22]. This engagement entails development and implementation of a spatially explicit, collaborative plan for integrated, sustainable management of landscapes and supply chains. The resulting spatial design is intended to provide a practical plan for developing bioenergy opportunities within given constraints while maintaining or improving the capacity of the system to supply environmental, social, and economic goods and services. When applied to bioenergy, the stakeholders include individuals and groups who are engaged in any part of the supply chain (e.g., land owners, industrial producers, transporters, and users of bioenergy and its precursors) as well as those affected positively or negatively by bioenergy development and use.

Designing landscapes for bioenergy is not a new idea. Basic concepts for landscape design have existed since humans began settling around areas of permanent agriculture [23] and were manifest through the ages when forests were maintained near settlements and estates to provide firewood [24,25]. The 1862 U.S. Homestead Act required that property be cultivated and occupied by settlers for five years to qualify for a deed, but small woodlots were permitted and commonly located near the dwelling on homestead claims [26].

There are several tools that can be adapted to various stages in applying landscape design to support more sustainable bioenergy production (Box 2). Landscape design tools have been discussed in the value chain optimization literature [27], in applying the concept of ecological footprints to bioenergy production [28], and in biofuel development considering protection of high-value conservation areas [29]. For example, a landscape design method for modern bioenergy was proposed by Venema and Calamai [30], who present a rural bioenergy planning framework for a region of India that is based on principles of location, allocation and landscape ecology and is optimized for both household and commercial energy demands and flows. Assessment tools are a useful for the landscape design process. For example, the Tool for Sustainability Impact Assessment has been used to evaluate the environmental, social, and economic sustainability impacts of a stepwise increase in extraction rates of three typical Scandinavian Scots pine based bioenergy production chains [31]. As another example, a region-specific optimization model has been developed for western Kentucky that links aspects of the biofuel supply chain such as feedstock source location, upstream and downstream logistics, and thermochemical and biochemical processing [32]. In addition landscape design relies on tools for effective stakeholder engagement and for developing consensus (Box 2).However, few efforts to date combine the landscape and supply chain approach with ways to reach out to stakeholders and engage them in planning sustainable bioenergy systems.

2.2. Spatial scale of landscape design for bioenergy

Landscape design for bioenergy can be applied to various scales of analysis and planning. The broadest possible scale considers the production of all feedstocks and users of bioenergy. However, such a global analysis is more theoretical than practical, and details are lost that are important at lower scales and for individual stakeholders. Broad approaches may offer some utility when they are applied to build consensus on common targets, such as the United Nations Millennium Development Goals. But actual planning and landscape design takes place at a more manageable scale. Ultimately, boundaries are often decided in relation to goals of key stakeholders [33]. With a basic element being stakeholder engagement, landscape design typically focuses on areas where stakeholders from a particular sector have similar or at least complementary values or concerns. For example, one spatial extent for landscape design for bioenergy systems is a “fuelshed” or the area that provides the biomass meeting specifications for a particular part of an energy system.

While the fuelshed boundaries may be limited to a local area, concerns about effects may exceed those boundaries, thus increasing or diminishing the overall benefits or impacts compared to those inside the fuelshed. For example, the people in a community in Uganda were focused on local issues of power reliability, cost, and local land competition, while a larger-scale concern – greenhouse gas (GHG) emissions – was expressed by stakeholders outside of the community [34]. Landscape design principles can be applied at different scales, ranging from a few

Box 2–Tools for landscape design

Several types of tools have been used to support landscape design efforts. Operations research is the discipline within mathematics that brings together analysis and decision making, and multi-criteria analysis is the part of operations research that considers how multiple criteria affect decisions (Figure A). These approaches have been used to facilitate the design and implementation of more sustainable bioenergy production by providing a framework that structures the problem, helps identify the least robust and most uncertain components in the system, and includes stakeholders in the decision process [34]. For example, multi-criteria decision support tools have been used to identify the most suitable energy–wood supply chain to address energy efficiency; nutrient balance, stability, and vitality of the forest stand and soil; supply guarantees, employment rates, and worker safety [85].

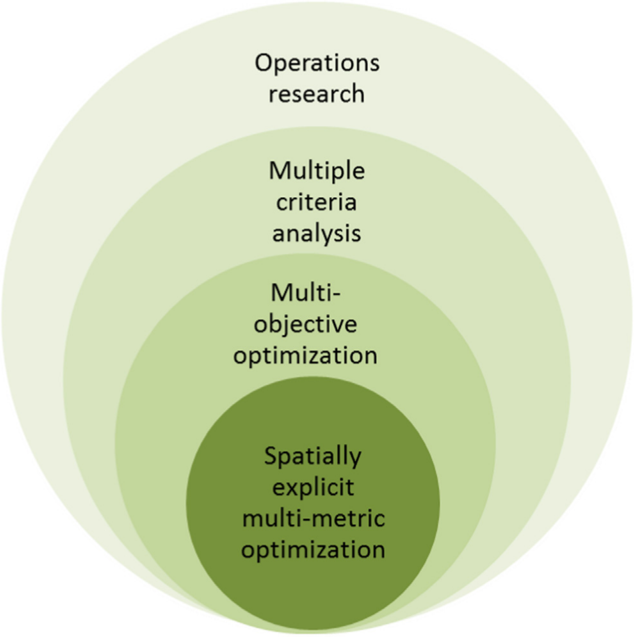
Multi-objective optimization refers to a set of tools within multiple criteria decision making concerned with mathematical optimization problems involving simultaneous optimization of more than one objective function. It allows for consideration of tradeoffs in achieving the objectives. Landscape design has also been used in applying optimization approaches to maximize profit and sometimes to minimize environmental impacts of all or part of the bioenergy supply chain [86]. It has also been used to identify appropriate locations, species, and management approaches for feedstock production [87–89].

Spatial optimization is a method used for determining landscape designs that build from spatial relationships between different land areas in the process of determining the best possible solution to an objective function given context specific constraints. Spatial features are considered by combining mathematical programming with geographic information systems (GIS). Spatial decision support systems have been used to gather information from a wide range of sources, analyze collected data, and present results in a form useful to decision makers [90]. Spatially explicit multi-metric optimization models have been used to determine the scenarios that maximize selected benefits (e.g., profit) and/or minimize a set of environmental impacts under specific conditions [91–95]. However, optimization approaches typically do not include stakeholder engagement.

Another tool is the use of games, such as the Bioenergy Farm Game, that allow users to develop bioenergy supply outcomes that take account of resource stewardship. In the same way that gamers who play SimCity learned about city planning and civics, interested stakeholders could use games to explore the potential effects across space and time that emerge from choices about current resource allocations. There are several carbon footprint and climate calculators, some of which employ game-like platforms that allow users to pull levers and see the effects of different choices related to energy and consumption. Games and simulations that encourage individuals to consider the effects of behavior provide a tool that can advance both learning and stakeholder engagement. Another advantage of such gaming tools is the option to include stakeholder engagement via crowdsourcing — the process of obtaining ideas or content by soliciting contributions from a large group of people, especially an online community.

Stakeholder engagement is a critical part of the landscape design process, and there are a plethora of tools for iterative, systematic and spatially explicit approaches for participation. Some tools for engaging regulators, land owners, and neighbors to identify crops are site specific and consider climate and soil conditions, risks, and the value proposition [96]. Local based partnerships are a useful way to engage diverse players in considering biomass options [97]. Tools that support involvement and sharing of perspectives of participants in visualizing potential impacts enhance the process of scenario development [75]. Spatial considerations are important to impart, and combining geographic information systems (GIS) or game-based tools are an effective way to communicate the complexity of spatial implications. Tools, such as Social Impact Assessment that enable a priori and informed stakeholder consultation and social mapping in the context of particular bioenergy opportunities, are vital for incorporating sustainability into planning [13]. Effective engagement is only part of the process. A major challenge is how to come to some agreement among diverse stakeholders. A Delphi expert elicitation has been used for facilitated negotiation to integrate stakeholder concerns with scientific assessment [98]. A key lesson for use of stakeholder engagement tools is the need to initiate such integration at the beginning of a project in order research to produce scientific results that meet practitioners' needs, specifically in the realm of environmental science and resource management [98].

Figure. A. Hierarchy of optimization tools used in landscape design.



fields or forests that produce bioenergy crops or from which residues are collected, to the entire feedstock supply for an energy production plant, or the entire energy supply system of a town, region or country. Larger scales involve higher costs and complexity.

Questions of the spatial and temporal scale of analysis relate to hierarchy theory as applied to landscape ecology [35]. Once a particular scale is selected, hierarchy theory provides a framework for considering the scales both above and below to help ensure that relevant patterns and processes are taken into account. The consideration of scales that are one-step-above and one-step-below may help identify and improve understanding about relationships not necessarily apparent when focusing on only one selected scale. The dynamics of economic incentives, distribution systems and markets may play a role beyond the selected spatial and temporal extent, while effects on habitat for species of special concern may occur at a scale smaller than that selected.

A challenge in the process is to employ landscape designs that are at the appropriate scale. Top-down approaches can provide a bridge between energy modeling and spatial planning [36]. Tools for top-down planning are useful and informative on a broad scale but often do not match up with local, bottom-up approaches. Strict (top-down) optimization may lead to different results than the outcomes of stakeholder negotiations. On the other hand, bottom-up approaches may fail to address opportunities and concerns at larger scales. Determining the appropriate mix of scales for analysis is necessary to address both local concerns and optimal design for reaching objectives at larger scales.

2.3. *The importance of context for landscape design for bioenergy*

Applying the landscape design approach to bioenergy requires attention to the context surrounding the bioenergy system [37]. Developing landscape designs to integrate bioenergy depends on the biophysical, environmental, societal, and economic conditions at appropriate scales [38]. It may be necessary, for example, to consider climate; topography and orientation; prior and current land ownership and use; objectives of land owners, producers, and other stakeholders; air, water, and soil baseline or desired conditions; site drainage and groundwater recharge; municipal and resource building codes and zoning; human and vehicular access and circulation; property safety and security; construction parameters; energy and resource access; employment and social issues; and the policy, institutional, and market setting. While landscape design can be applicable to all kinds of locations and bioenergy systems, it is not a "one-size-fits-all" application. Rather it is a process for considering context-relevant principles and information that might be selected from a checklist of environmental, social, and economic indicators that may apply to bioenergy systems [39,40]. The selection and importance assigned to each of the indicators may vary depending on the values and perceptions of stakeholders [41,42]. Understanding stakeholders' weighting of these different indicators is necessary to ensure that the most relevant information is collected and assessed.

An example of context-specific landscape design that considers bioenergy is where feedstock can be grown for both bioenergy and remediation of former industrial or polluted sites. In both the U.S. (Box 3) and Europe *Salix* (willow) feedstock crops are grown to reduce pollution from nutrient-rich waste streams such as biosolids and wastewater and also to take advantage of those nutrients to fertilize the biomass crop [21]. These systems produce multiple benefits as they reduce GHG emissions and the costs of waste treatment while increasing crop yields and reducing nutrient input costs.

2.4. *Avoiding adverse impacts of bioenergy systems via landscape design*

Negative impacts of bioenergy can often be avoided, reduced, or mitigated by adhering to three principles of landscape design: conservation of ecosystem and social services, consideration of local context, and monitoring outcomes and adjusting plans to improve performance measures over time (Table 1). Even so, it would be unusual for all goals to be achieved or all ecosystem services to be maintained or enhanced. Any kind of energy production or land use involves trade-offs in costs and benefits that call for precautionary or mitigating measures and adaptive management to provide a mechanism of continuous improvement to address those tradeoffs [43,44].

The first principle is conservation of ecosystem and social services. These services include regulating services and provisioning of food, feed, or fiber as well as preserving biodiversity, and cultural values. Basic knowledge about who benefits from services and their current distribution, as well as the perceived needs and expectations of stakeholders in relation to different services, is important for successfully integrating bioenergy systems into

Box 3–New York landscape design case study of bioenergy being integrated into sustainability goals

Using vegetative cover to address leaching from 240 ha of former industrial land in upstate New York provides an example of landscape design that includes biomass grown to meet goals of protecting human health and the environment while providing biomass for heat or nearby biopower production as well as active stakeholder involvement. The site had been used to store the byproducts of soda ash (Na_2CO_3) production using the Solvay process from 1884 to 1986 [99]. For every tonne of soda ash produced about 10 m^3 of liquid waste was generated containing approximately 0.91 MT of $CaCl_2$ and 0.45 MT of NaCl and minor amounts of other byproducts [99].

This landscape design was achieved via collaboration among a regional network of stakeholders for development of integrated landscapes that combine bioenergy systems with other community interests for shared economic, environmental and social benefits. The main environmental concern at this site is the leaching of chloride into groundwater and nearby surface waters [100]. A variety of mitigation measures have been installed to capture and treat the leachate including several kilometers of French drains around the perimeter of the site. The other part of the remediation effort was to minimize the amount of precipitation moving through the material and carrying salts into the groundwater or nearby surface water. Traditionally a clay or geomembrane cap would be used to minimize percolation, but evapotranspiration (ET) covers are an alternative that have been studied for a number of years [101]. In 2003 a project was initiated to examine the potential of growing an ET cover using shrub willow (genus *Salix*) on this site. The project's goal was to minimize the amount of water percolating into the settling basins thereby reducing the amount of chlorine leaching into and polluting the groundwater and nearby surface waters. A secondary goal was to use the shrub willow to produce woody biomass for a developing renewable energy market in the region and to transform this area into a productive community asset. A series of deliberate, incremental steps, starting with greenhouse screening trials and proceeding to small field trials and finally larger-scale demonstrations, were implemented to select the appropriate willow cultivars and to design an effective ET cover [101,102].

A variety of locally available organic residue streams were evaluated in both greenhouse and field studies to determine what would be the best soil amendments to ensure vigorous growth of shrub willow at the site. Materials assessed included combinations of biosolids from the local wastewater treatment plant, yard waste collected by the local village, biosolids from a local pharmaceutical company, animal manure, and organic residues from a local brewery. During these assessments there were frequent interactions with community leaders who looked for assurance that these soil amendments would not generate unpleasant odors around the site. Over a number of years, a system developed to amend the settled solids with a mixture of residues from the brewery and manure from horse farms in the region. To date, organic amendments have been incorporated into about 40 ha of the settling basins, and it has been planted with the alternative willow cover.

During the development of the willow cover as an alternative cap, there were numerous interactions between the owners of the site, community leaders, the general public, and local and state regulators. This engagement started with tours of the greenhouse screening trials, in which about 40 willow and poplar cultivars were being tested for their ability to thrive under the conditions at the site. As field trials were established, regular tours of the shrub willow plantings on the site were conducted for local officials, middle and high school students, and the general public. Most recently, potential end users of the biomass being produced on the site were engaged in the process to determine their interest in using the material. One of the concerns raised by potential end users was the possibility of contamination of the biomass from the materials at this site. Harvests of material from the site and from nearby agricultural fields are being compared to each other and to new International Organization for Standardization (ISO) standards for graded wood chips. This analysis helps in addressing these concerns and providing outlets for this biomass so it can be used as feedstock to produce renewable heat and power in the region.

existing situations. For example, species of special concern may require habitat conservation plans that include large patches of natural vegetation, connectivity between patches, continuously vegetated riparian corridors, or stepping stones of natural habitats dispersed throughout the matrix [45]. Some invasive species may require special management and control, while some desired ecosystem services may depend on periodic fire. In the case of food provisioning services, this principle implies careful integration of bioenergy to maintain or improve food production. In terms of soil conservation, principles of nutrient management for sustainable production apply [46].

The second principle is that effects of bioenergy production on social and ecosystem services are context-specific and depend on the local or regional environmental, social, economic, and political conditions, and the characteristics of the production system. Special cases may arise if bioenergy-mediated improvements are designed to rehabilitate degraded lands or when areas of high biodiversity value are threatened by expansion of monoculture production. The bioenergy industry could build from established good practices in the local economy related to forestry, agriculture, transport logistics, and refinery establishment and operation. However, some aspects of bioenergy production may be unique. For example, collection of agricultural and forest residues for feedstock must consider how variable amounts of residue interact with heterogeneous soil quality conditions and risk of pests [47]. Residues may provide ecosystem services such as soil conditioning and erosion control under some conditions or, alternatively, may suppress growth, fuel more intense wildfires, or foster outbreaks of pests and diseases.

The third principle requires monitoring outcomes and adjusting plans to continuously improve performance over time (Table 1). Desired outcomes can be prioritized by stakeholders in conjunction with the goals to be achieved through resource management. Data on priority processes and patterns, including resources valued by stakeholders, can be tracked over time so that trends can be understood and problems quickly corrected. Monitoring, analysis, and ongoing interaction with stakeholders are essential to guide improvement in design recommendations and adaptive management [43]. An interesting case involved a wood-fueled facility that opened in the 1990s in northern New York State (Box 3). Because the community expressed concern about deforestation, the facility management arranged visits to harvest sites a few times a year in order to listen to community concerns and allow adjustment of practices. The New York State Renewable Portfolio Standard (RPS) now stipulates a more formal monitoring and reporting process and interaction with stakeholders.

Landscape designs must consider the inevitable trade-offs between environmental resources and social services and energy production and use [48]. For example, a monoculture of an invasive non-native species can sequester carbon and increase yields but could also reduce or eliminate indigenous species and genetic diversity. Hence, establishing steps to avoid, monitor, and/or control the invasive potential is a critical part of management plans.

Table 1
Negative impacts of bioenergy can be avoided or reduced by attention to three principles of landscape design: conservation of ecosystem and social services, consideration of local context, and monitoring outcomes and adjusting plans to improve performance measures over time.

Principles	Examples	Enabling conditions
Conserve ecosystem and social services	• Maintain or enhance provisioning of food, feed, fiber, and water quantity and quality • Protect taxa of special concern • Maintain or enhance social well-being (e.g., safe and well-paid jobs)	• Adequate data and knowledge about services provided • Local capacity • Supporting policies and institutions • Equitable stakeholder engagement
Consider local context	• Assess how bioenergy is influenced by prevailing environmental, social, and economic conditions • Build understanding of how all aspects of the bioenergy supply chain affect local social and ecosystem services • Develop recommendations for practices that consider local characteristics and needs	• Resources or incentives to invest in up-front analysis and planning • Clear rights and responsibilities • Adequate data and knowledge about initial conditions
Monitor outcomes and adjust plans to improve performance over time	• Employ adaptive management • Practice precautionary actions • Evolution of early warning systems to reduce impacts from extreme events (drought, flood, fire, political upheaval, etc.)	• Transparency of monitoring approaches and results • Systems that permit and promote participatory monitoring • Ability to adjust practices, targets and regulations in response to new knowledge

These three principles do not operate independently. Conservation of ecosystem and social services and development of management plans must be done in the context of the particular landscape and bioenergy system. For example, pressures on local land and water resources from urban expansion and industry may suggest that management of bioenergy systems focus on integrating waste reduction, nutrient recycling, water conservation, and cropland rehabilitation to improve overall outcomes [49].

3. Application of a landscape design approach to bioenergy systems

3.1. Early approaches to applying landscape design for bioenergy

Policy decisions reflect products of human values in a specific time and space. Applying landscape design provides an opportunity to interact with stakeholders to come to agreement on values relevant to investment and development decisions. While there are tools for community engagement and consensus building (Box 2), developing agreement on goals and creating commitment among stakeholders is not easily achieved.

There are a few examples of applying landscape design principles to site selection for relatively small bioenergy projects within a much larger region [29,50]. Forman proposed that land-management decisions follow a hierarchy to focus first on water and biodiversity concerns; second on food cultivation, grazing, and wood products; third on sewage and other wastes; and finally on homes and industry [51]. Yet decisions are rarely made in that order, in part because stakeholders' priorities and environmental conditions vary, and because decisions about where to live typically occur first. The majority of modern bioenergy output has emerged from coproducts of traditional agricultural and forestry systems in locations where local population opinions about the landscape and its management have evolved over decades. Understanding historical and current land-use and management and the community's opinions about future land use is an important starting point in considerations on how to apply landscape design for bioenergy.

3.2. The steps of developing and implementing landscape design

One recommendation is that a landscape design approach for bioenergy be applied via six steps: (1) develop design goals in view of the context, (2) identify constraints and opportunities, (3) consider feedstock suitable to the context, (4) evaluate and deploy design, (5) monitor outcomes, and (6) adjust as needed (Fig. 1). These steps should be implemented in view of the principles discussed previously on conservation of services, context specificity, and adaptive management. This approach requires stakeholder engagement at all stages of the process and builds from adaptive management principles in that the initial plan is adjusted as learning occurs. The unique features of landscape design are the scale, spatial considerations, inclusion of diverse stakeholders, and up-front thinking about multiple uses and services over time. McCormick et al. proposed similar steps for planning locations of bioenergy feedstock plantations including (1) screening, (2) assessment and consultation at national or provincial levels, (3) detailed site-level planning, and (4) implementation of responsible land management practices [29]. Sayer et al. evaluate how a landscape perspective reconciles agriculture, conservation, and other land uses [15]. In a similar vein of thought, our approach allows consideration of the entire bioenergy supply system.

Fig. 1. Steps in landscape design.

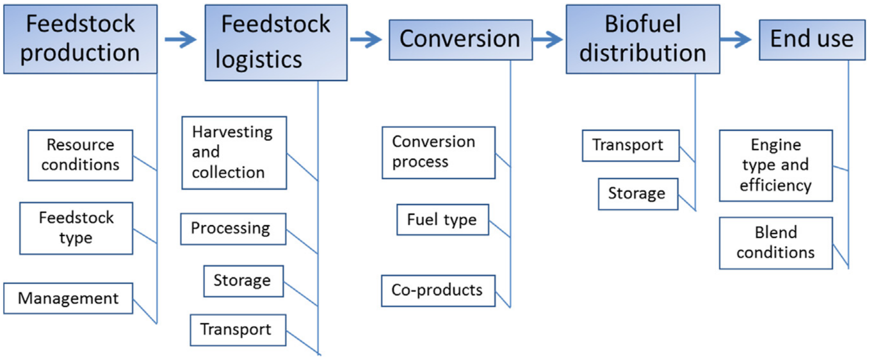


Fig. 2. Major components of the biofuel supply chain (adapted from a figure in Dale et al. [63]). Feedstock options include annual and perennial plants; residues from agriculture, forestry, and related industries; and other organic wastes. The choice and management of feedstock is affected by resource conditions, such as the quality and availability of land and water and is typically selected to maximize yield and, thereby, profit but also affects environmental, social and other economic cost and benefits. Feedstock logistics are specific to the particular context [37]. Conversion technologies include direct combustion, thermochemical conversion, and biological conversion processes and the process implemented may influence feedstock selection. Biofuel distribution varies in both its storage type and amount and transport (e.g., via truck, rail, boat, or pipeline). The end use of biofuels varies by the engine type and efficiency as well as blend conditions of the fuel. Beneficial co-products (e.g., distillers grains, corn oil) and waste by-products (e.g., biorefinery effluent) may be created in some stages of the supply chain. Different actors are important in each stage of the supply chain. For example, land owners are the ones making decisions about engagement in feedstock production, whereas energy users decide about engine/burner types and efficiency based on what is available in the market (which is a response to policy and market conditions).

3.2.1. Establish goals

The first step is determining the goal of the design with input from and, ideally, agreement of the majority of stakeholders (Fig. 1) using an open and participatory process. These goals might include profit, jobs, safety, maintenance or enhancement of environmental services, etc. This step requires specification of the decision variables relevant to the system boundaries, history, and stakeholders' interests. Establishing goals for how bioenergy can be incorporated into existing landscapes requires up-front consideration of sustainable resource allocation and management over space and time while also addressing the environmental and socioeconomic resources along all links of the supply chain (Fig. 2). Establishing a context-specific target for each indicator prioritized by stakeholders provides a way to be explicit about goals. While threshold values for indicators can be established based on scientific analysis, formulating desired targets for each indicator through regulations (e.g., water quality or air emissions) or consensus building processes involves negotiations [52,53]. The trends of the sustainability indicators should be monitored in a manner that permits analysis of linkages between the performance of the bioenergy supply chain with the performance of other affected variables. The effectiveness of indicators and determination of baseline and threshold values should be understood by stakeholders who are encouraged to participate in the process of monitoring and measurement. Science-based methods that are quantifiable and affordable should be applied, the observations consistently documented, and methods of analysis and results openly shared. Otherwise, unrelated problems may be attributed to bioenergy or unintended consequences could result and undermine the process. Identifying thresholds at which non-reversible changes occur is also useful for planning [45].

Landscape design can be applied to distinct bioenergy scenarios, depending on whether one begins with a defined site or a defined demand. In the first case of starting with a spatially defined location, opportunities can be assessed to identify those that best integrate all parts of the bioenergy supply chain with local goals and the other services provided by the region. This approach could provide an estimate of how much bioenergy is supplied under a given set of parameters. In the second case of starting with the bioenergy supply specifications (amount and type of needed energy), the best available options and locations to meet that demand would be assessed, as when a government establishes a policy or an industry specifies a set demand for a specific amount of bioenergy production. Most current landscape-design literature assumes or uses the first approach; while resource assessments such as the U.S. “Billion Ton” studies [54] reflect the second approach.

3.2.2. Ascertain constraints and opportunities

The second step is explicit consideration of constraints and opportunities, including the drivers that support reaching the goal and the forces that oppose the desired change. This step is commonly done through a process similar to a strength-weakness-opportunities-threats or force-field analysis that asks questions such as: What prevents attainment of the goal(s)? What were the primary barriers in the past? How do current trends affect strengths, weaknesses, threats, and opportunities? What changes are expected in future years, and how do those changes affect the analysis? Human, institutional, legal, policy, and financial factors are commonly considered in addition to natural resources and their services. The central theme in this step is considering how goals for bioenergy production could be achieved within the local context while maintaining other provisioning, regulating, and cultural services. Concerns that should be considered include pollution of water, soil, or air and relevant social issues. Consideration of the constraints and opportunities should be done in view of how progress toward more sustainable bioenergy production can be achieved via compliance with local laws and regulations supported by a robust legal system.

A prerequisite for energy security is stable and transparent governance that is both legitimate and accountable [55]. In the absence of reliable institutions and good governance, the principles of landscape design are still applicable, but stakeholders will likely have more urgent constraints and priorities to address than bioenergy. For example, countries or regions that are experiencing ongoing crisis or lack administration of justice are more likely to have high levels of food insecurity, poverty, and deforestation [56,57]. Many institutional and policy issues that are important for sustainability goals cannot be resolved by bioenergy [4]. Social justice, working conditions, gender equity, child labor, fair contracts, and clearly defined and socially accepted land tenure rights cannot be adequately addressed by the bioenergy industry alone. However, careful planning can help avoid unintended negative social impacts of bioenergy system deployment.

3.2.3. Identify optimal options

The third step is up-front and explicit consideration of feedstocks types, locations, and logistics that could be optimal for bioenergy in the specific context being considered. Optimal options seek balance between the economic, social and environmental costs and benefits as expressed in the common goals decided in the first step of the process and given preexisting conditions and constraints. The most obvious feedstock options often include agricultural and forestry residues that are already available or biomass that can be readily grown. Transport of the feedstock, storage, and use of the bioenergy product are all a part of the selection of feedstock and logistic options. Multimetric optimization allows for consideration of several alternative objectives and the tradeoffs entailed (Box 2). The amount, type, location, and scale of waste production can be compared to other scenarios including "business as usual," alternative land uses, and the introduction of alternative energy production systems. In view of the opportunities and constraints identified in step two, feedstocks might be selected that reduce or recycle biological waste materials from other sectors within the region. For example, Muth et al. [58] have developed the "residue removal tool," a downloadable computer application that can help a farmer determine the amount and location of corn stover, if any, that could be removed from places within a field without compromising soil carbon content, productivity or erosion control. This spatially explicit tool focuses on soil carbon and does not attempt to assess potential costs and benefits relevant to many other sustainability indicators.

Box 4–Glossary of terms used in this paper as they apply to bioenergy

Adaptive management: A process for decision making in the presence of uncertainty that allows a decision to be implemented and requires long-term monitoring with clear performance indicators that trigger adjustment of management decisions to account for new information and learning about interactions.

Best management practices (BMPs): Common term and a misnomer since the practices are based on best available science and are continually reviewed and improved. In common use, BMPs are a set of recommendations for how to manage and utilize water and other natural resources based on knowledge and experience about local conditions and operations that specify methods that reduce negative impacts on soils, water, and biodiversity.

Bioenergy: Renewable energy made from materials derived from non-fossil, biological sources.

Bioenergy supply chain: Feedstock production, logistics of accumulating and transporting the feedstock, creation of the energy or fuel, transport and final use of the energy, and decommissioning as appropriate at end of life for equipment or facilities.

Biomass: Any living or recently living organic material that has stored sunlight in the form of chemical energy, including plants, residues from agriculture or forestry, or the organic component of municipal and industrial wastes.

Landscape: A perspective of how phenomena occur in a region that includes both pattern and process.

Landscape design: A spatially explicit, collaborative plan for integrated management of landscape resources and supply chains, developed by an informal or formal group of stakeholders around a set of specified goals.

Lignocellulosic feedstocks: The cellulose, hemicellulose, and lignin components of plant material including municipal wastes; agricultural residues such as corn stover, wheat straw, or sugarcane bagasse; dedicated energy crops such as fast-growing perennial grasses or trees; wood residues from logging operations; and thinnings from forestlands.

Renewable energy: Energy that comes from resources that nature replenishes on a human timescale such as sunlight, wind, rain, tides, waves, and geothermal heat.

Stakeholders: Individuals and groups who are any part of the bioenergy supply chain (e.g., producers, transporters, and users of the product, its precursors, and it coproducts), as well as those affected positively or negatively by the development and use of bioenergy.

Sustainability: A concept that considers development options in terms of meeting current needs while conserving opportunities for future generations to meet their needs. The term is commonly applied to consider the relative sustainability of two or more trajectories or pathways for development where one is compared to other(s) based on sustainability criteria and indicators such as those associated with land, air, water, ecosystems, the biological and human environment, nonrenewable resources, species diversity, and other clearly defined providers of ecosystem services. Sustainability is not a state but rather reflects aspirational goals [103] and is a dynamic of human values, choices and technology. Developing and using effective and cost-efficient measures of sustainability requires (1) a limited set of indicators; (2) collection of data over appropriate spatial and temporal scales; (3) storage and analysis of those data; (4) stakeholder engagement; and (5) communicating and acting upon results [104].

Trade-offs: A situation involving diminishment or loss of one quality in exchange for enhancement of another quality.

3.2.4. *Evaluate and select design options*

The fourth step is to evaluate alternative design solutions in terms of how well they address the goals. Solutions should be defined in terms of spatially and temporally explicit plans that are developed with buy-in from stakeholders. Landscape-design plans include clear descriptions of what will be done, where, when and by whom. Thus, the solutions require clear definitions of rights and responsibilities of various parties. Ensuring support for solutions from a broad coalition of stakeholders who legitimately represent government, the private sector/business community, non-government organizations and land owners will generally increase likelihood of success. Success rates are also improved if the landscape design has enthusiastic local champions who understand the community and the various stakeholder perspectives. The principles and enabling conditions listed in Table 1 can be considered when developing solutions, ensuring that allocation of resources and recommended management practices are appropriate to the context.

3.2.5. *Monitor outcomes*

Any proposed solution must incorporate mechanisms to ensure that outcomes will be monitored over time and analyzed and evaluated to inform future actions. Desired outcomes, assessed needs, stakeholder values, key issues, and budget considerations all influence what information shall or can be monitored, the sampling frequency, and spatial scale. Selecting metrics that effectively indicate the condition of the system is important, because it is not possible to monitor all system characteristics [40]. It is also helpful to include stakeholders directly in monitoring when feasible and to insure that procedures for monitoring and sharing of data and results are transparent and understood by all concerned.

3.2.6. *Adjust decisions*

The sixth step is using the analysis and evaluation of the monitored information to inform management [59]. Design plans and management recommendations should be adjusted over time to ensure that they are supporting movement toward desired outcomes. Indicators or their measurement may also merit

Table 2
Pressures and incentives for landscape design, building on Seuring and Muller [60].

Pressures and incentives for landscape design	Examples
Legal requirements or regulations	• U.S. Renewable Fuel Standard • Renewables portfolio standards of U.S. states • European Commission Directive 2009/28/EC
Spatially and temporally explicit plans can address sustainability+objectives	• Feedstock collection can avoid places and times when species are at risk (e.g., nesting season) • Location of feedstock close to rail or ship access reduces transport costs
Customer demands	• Public demand for employment, safe jobs, and action to address climate change
Response to stakeholders	• Social acceptability
Environmental and social pressure groups	• Environmental nongovernmental groups calling for sustainability
Competitive advantage	• Advertising product as "sustainable"
Reputation loss	• Boycott of product

revision to meet stakeholder needs. Given that local economic factors and other contextual conditions, including stakeholder priorities (desired outcomes), can change over time, this step is sometimes described as "continual improvement" and is key to building learning and resilience into the landscape-design process.

3.3. *Incentives for implementing landscape design*

There are often pressures or incentives outside the industry that enable landscape designs to be more easily or purposefully deployed (see Table 2, which is based on the ideas of Seuring & Muller [60]). Legal demands or regulations and certification standards may require that their sustainability criteria be addressed in a specific manner or that a regional or fuelshed plan be developed with input from stakeholders. For example, the demand from several European Union member states for sustainable bioenergy is pushing industry to document compliance with sustainability criteria along the supply chain [61], although that process generates conflicting policy signals such as the balance between protection of biodiversity and reduction in emissions of GHG by increased use of bioenergy [62]). However spatially or temporally explicit plans are sometimes able to address sustainability concerns in a way that less specific guidelines are unable to do. For example, feedstock planting can be planned to enhance wildlife habitat and the harvest can be scheduled to avoid the location and times of year when nesting occurs for desired species.

Customer expectations, along with environmental and social pressure groups and other stakeholders, can also provide strong incentives for the use of landscape design. Some groups may focus on single issues (e.g., climate change, endangered species, or food security), but most concerns falling within the twelve environmental and socioeconomic categories in Dale et al. [40]. However, individual communities will likely rank these categories in different ways and may have other very site-specific concerns. Experiences from international agreements show that broad initiatives with many signatory countries have a weak enforcement capacity, while the combination of several signatory countries and stronger enforcement are more likely if the agreement is narrowly drawn [63]. Landscape design facilitates an up-front focus on multiple factors and involves stakeholders so that high priority issues can receive the appropriate level of attention and effort.

There could be competitive advantages of using landscape design if it provides a price premium, unique access to markets, ;or reduces production costs. Landscape design aims at guiding choices toward more sustainable provision of services. Sustainability involves conserving options for future generations. The approach has the potential to reduce unforeseen negative outcomes and thus may save money in the long run. Furthermore, involving stakeholders could reduce time and costs associated with addressing public opposition to projects.

Table 3
Obstacles to developing and deploying landscape design, building on Seuring and Muller [60].

- Coordination is complex and requires significant effort
- System is fragmented with disparate interests in different parts of the system
- Up-front planning is required
- Landscape design may raise initial costs
- Communication about system complexity is inadequate
- Data for supply chain may be insufficient
- Assignment and acceptance of roles, cost-share, and responsibilities, some of which may involve long-term commitments

3.4. *Obstacles to implementing landscape design*

In practice, it is a challenge to apply the landscape design approach recommended here especially at large scales where heterogeneity of stakeholders often makes it impossible to agree on common goals and concerns, much less indicator baselines and targets (Table 3). But in most situations the bioenergy system only engages a small portion of the land area in a fuelshed and provides a portion of the energy needs in the region. So while not all stakeholders may agree, the concepts can still be applied to the bioenergy system. Even at smaller scales, stakeholders may not be interested in bioenergy and prefer to steer the process toward other perceived needs related to health, education, or housing that are more challenging to link to bioenergy supply chains. Furthermore, some stakeholder groups may have narrowly defined special interests and be unwilling to compromise. For some indicators, a lack of baseline data and local knowledge may create limitations. The larger the spatial area of analysis, the greater the challenges in convoking stakeholders, reaching agreement on priorities, and completing a landscape design plan. Measuring and defining progress toward sustainability of bioenergy systems are challenging because the systems are complex, the underlying science is still being developed, and it is hard to generalize the inherently context-specific enterprise [64].

Another obstacle to developing and deploying landscape design occurs where the landscape is fragmented in terms of ownership and owners' objectives or local objectives do not match regional, state, national, or international goals. Diverse stakeholders often have disparate interests, which can create barriers if they are not addressed.

Implementation of landscape design requires up-front planning and coordination and may entail higher initial costs or be stymied by insufficient or missing communication in the supply chain (Table 3). However, the proactive investment for synchronization across the supply chain can reduce final costs and increase the likelihood of success for the entire bioenergy system. More bioenergy projects might be implemented successfully if preemptive landscape design processes were employed to identify and address

Table 4
Conditions that facilitate landscape design development, building on Seuring and Muller [60].

- Effective communication throughout the supply chain
- Management systems [e.g., International Organization for Standardization (ISO) 14001]
- Training and education systems in place that are effective at reaching the array of stakeholders
- A clear value proposition. The value proposition may be unique to each stakeholder
- Sharing success stories and lessons learned from “early adopters”

concerns before they became a problem. Without this level of interaction and communication, projects are more likely to founder despite the investment of significant effort and funding [65].

3.5. Conditions that facilitate landscape design for bioenergy systems

The landscape design process is facilitated by good communication across the entire supply chain so that opportunities and constraints are clear from the beginning, and by the use of best management practices (BMPs) for the industry (Table 4 [60]) (Box 4). Recommended best management practices for bioenergy primarily relate to agricultural and forestry activities with reference to water quality, soil quality, or crop production [66–72]. FAO [57,73] discusses good environmental practices and provides examples for agricultural and forest feedstock production pertaining to soil, water, biodiversity, and climate change mitigation, as well as the socioeconomic benefits to income, availability of inputs, and access to energy. BMP development for bioenergy is an active area of research and testing [3].

Training and education about sustainable landscape design approaches is important for both suppliers and employees responsible for feedstock production, supply, and procurement. In general, feedstock buyers are responsible for meeting regulatory and contractual expectations throughout the supply chain. Both the Global Bioenergy Partnership [4] and the United Nations Environment Program [74] focus on education and outreach to a variety of stakeholders. The Center for International Forestry [15] also underscores “continual learning” and “strengthened capacity” as two principles for landscape approaches.

Finally, a clear statement and quantification of the value of landscape design for reaching stakeholders’ goals is necessary to gain acceptance of the process. The bottom line is that a value proposition that addresses stakeholders’ perceived needs (increased profits/market share, decreased costs, improved water quality, more/better employment, etc.) is required to obtain willing participation.

3.6. Landscape design as a means to address trade-offs

A key challenge of landscape design is to enable decision making that addresses multiple objectives. Trade-offs between ecosystem, social, and economic services are important to consider even though it may seem that these services are associated with diverse objectives. Trade-offs also occur within a category, e.g., more jobs versus higher profits, management that favors one species or ecosystem service over another, or improvements in social wellbeing for one group versus another group. Erb et al. [75] refer to the need for “sustainable methods for intensification” of production in order for policies to succeed in optimizing simultaneously for multiple needs: food, energy, biodiversity and other environmental services.

Evaluating tradeoffs is challenging given that modern bioenergy production is relatively new, involves unknowns and uncertainties, and diverse disciplines and stakeholders [59,64]. Examples of multiple objectives being achieved have been noted in situations where urban wastes or residues from agricultural or forestry are used as bioenergy feedstock. In the U.S., 47 million Mg of urban and mill wastes have been projected to be available for bioenergy as well as over 100 million Mg of corn stover (agricultural residue) [76]. Forest mill wastes have become an important feedstock for the rapidly growing wood pellet industry, and two biorefineries in the U.S. are using corn stover as a primary feedstock. By having bioenergy designed to repurpose waste materials, other goals are addressed such as reducing waste management costs, volumes of material sent to landfills, and smoke from open fires used to burn wastes. In the case of intensive maize cultivation, stover removal facilitates no-till soil conservation practices, and the tradeoff to consider is the value of organic material to soil quality or as habitat. Indeed, the hope is that the word “waste” may disappear from common usage as formerly unwanted material is increasingly seen as a valued resource. Waste reduction increases the efficiency of resource use. Improved efficiency generates more services relative to required inputs. The use of waste streams to improve soils and increase biomass feedstock yield is an example of how systems design can provide multiple benefits and increase overall system efficiency. Waste treatment or storage and fertilizer imports (costs and transport) can be reduced while biomass productivity increases. To the degree that resources are renewably produced or reused so that future production is not undermined by current management, system sustainability increases.

Furthermore, multiple goals can better be achieved by designing systems that simultaneously consider sustainable agriculture and forestry, their diversity of ecosystem services, and viable rural livelihoods [64] and by linking energy development to stakeholders' concerns. Energy is essential for food production, processing, transport, and preparation. Both food security and energy security can be addressed by designs that simultaneously consider these goals [77,78]. A key prerequisite is that bioenergy development is not done in a vacuum but rather is part of an integrated strategy aimed at addressing local needs for sustainable energy and food production. Supply chains can be designed to reduce adverse ecological and social impacts, while also minimizing costs and emissions compared to the replaced fossil-fuel energy systems, by implementing new technologies and by providing a means to mitigate economic uncertainties arising from crop failures or volatile prices [79]. For example, price volatility is reduced where there are multiple markets for produced goods.

One goal of identifying and analyzing tradeoffs in landscape design is to benefit from opportunities for synergies that would not be realized without simultaneous consideration of social, environmental, and economic constraints and diverse stakeholders' perspectives. For example, decisions about the landscape and supply chain are made while considering markets. Yet most markets do not quantify the value of clean water, clean air, or other ecosystem and social benefits. The values of social and ecosystem services require explicit recognition and consideration in conjunction with the economic values that otherwise tend to dominate analyses. For example, Haatanen *et al.* [80] engaged stakeholders via a workshop where three scenarios of forest resource use were created based on stakeholders’ preferences and used to explore conflicts and trade-offs of combined biodiversity and bioenergy scenarios.

4. Conclusion

The design and assessment of bioenergy production systems can benefit from using a landscape design approach and systems perspective that recognize spatial heterogeneity and context. Landscape design can be applied to various scales of existing systems to support community goals. Particular situations are characterized by unique products and their distribution, policy background, stakeholder values, location, temporal influences, spatial scale, and baseline conditions. In addition, identification and application of good management practices can improve outcomes. Developing landscape designs takes time and entails upfront planning. Appropriately applied, landscape design can guide spatial choices toward desired bioenergy and related outcomes.

A big challenge is determining how leadership will be provided and responsibility allocated for implementation, evaluation, and revision of landscape-level bioenergy production systems. These determinations will likely result from a confluence of the pressures mentioned in Table 2. Legal, customer, and stakeholder demands, environmental and social pressure groups, and competitive advantages all have a role to play. Some combination of these factors can lead to incentives for developing a "collective concern" and acceptance by the community to apply a landscape design approach to achieve more sustainable provision of energy and other services. Commitments from stakeholders including government, the private sector, non-government organizations and land owners should be explicit throughout the process of goal setting, planning, implementation, monitoring, assessment, adjustment, and learning. Shared ownership of the landscape design process is a key ingredient for success.

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