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Chapter 7

Impacts of Bio-Based Energy Generation Fuels on Water and Soil Resources

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Abstract

The use of bio-based fuels for energy generation can have positive or negative impacts on water and resources. To best understand these impacts, the effects of bioenergy systems on water and soil resources should be assessed as part of an integrated analysis considering environmental, social and economic dimensions. Bioenergy production systems that are strategically integrated in the landscape to address soil and water problems should be promoted where their establishment does not cause other negative impacts that outweigh these benefits. While standardized metrics, such as footprints and water- and nutrient-use efficiencies are convenient and intuitive, these factors can be insufficient to achieving sustainable production and environmental security at relevant spatial and temporal scales. Comprehensive ecosystem impact analysis should be conducted to ensure that sustainability standards like water quality, water supply, and soil integrity are consistent with other agricultural and silvicultural sustainability goals at the local, regional, and global level.

Keywords: bioenergy, water quality, water supply, soil integrity, sustainability

1. Introduction

Water and soil are intimately linked ecosystem resources that provide the basic chemical requirements for plant life on earth (**Figure 1**) [1, 2]. The use of plant resources, for bioenergy or any other human purpose, must be viewed in the context of total ecosystem services and through the lens of long-term sustainability. In the current world, nearly one-third of the planet's land surface is dedicated to agriculture. This same land base accounts for nearly three quarters of the global freshwater use [3]. Because of this connectivity, bioenergy systems development poses

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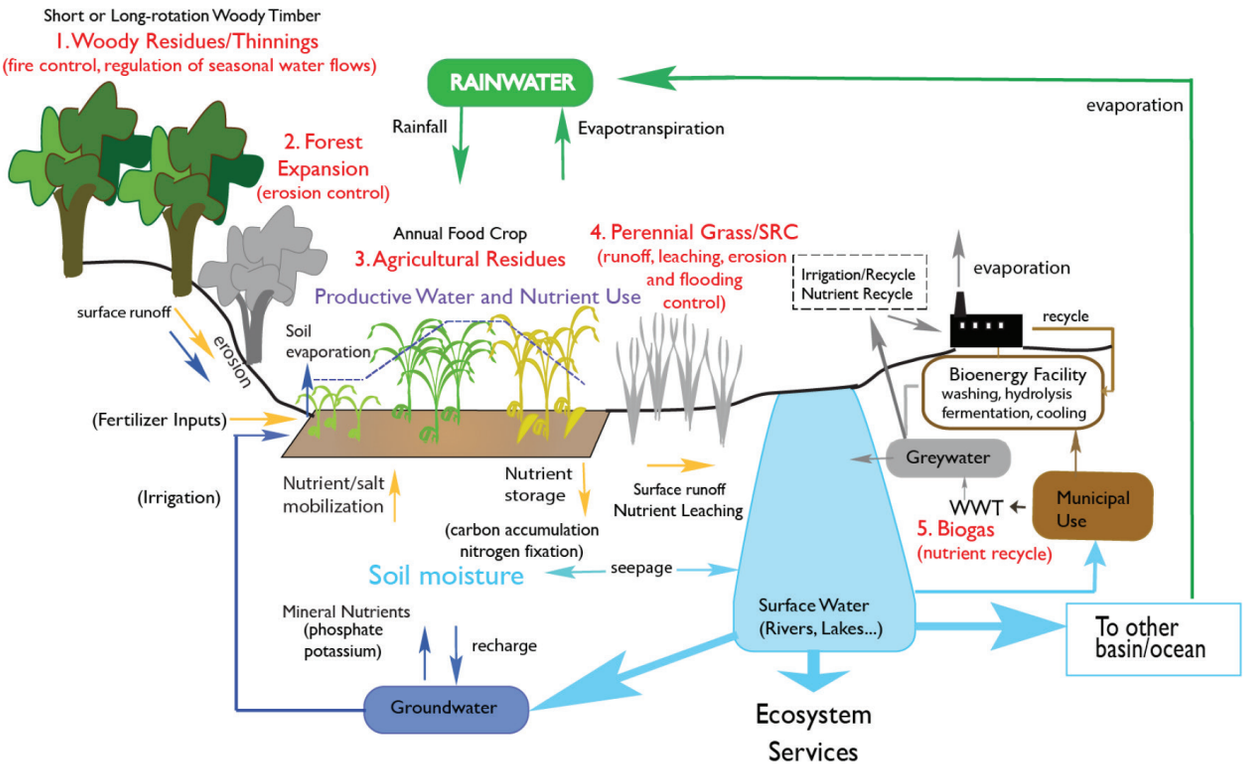


Figure 1. Linkages between bioenergy systems, soils, and water in an agroforestry landscape (From [2]).

significant challenges from the perspective of soil and water quality. At the same time, bioenergy systems present new opportunities to improve land and water sustainability and productivity, as well as addressing soil and water impacts produced by current land use.

1.1. Background

In the search to develop renewable energy, woody and agricultural crops are being considered as an important source of low environmental impact feedstocks for electrical generation and biofuels production [4–7]. In countries like the USA, the bioenergy feedstock potential is dominated by agriculture (73%) [8]. In others like Finland, the largest feedstock source comes from forest resources. Forest bioenergy operational activities encompass activities of a continuing and cyclical nature such as stand establishment, mid-rotation silviculture, harvesting, product transportation, wood storage, energy production, ash recycling, and then back to stand establishment [8]. All of these have the potential to produce disturbance that might affect site quality and water resources, but the frequency for any given site is low [9–12]. Agricultural production of feedstocks involves annual activities that have a much higher potential to affect soils and water resources. Since the rotational cycle for forestry is much less frequent, the potential for disturbance to water and soil resources is greatly reduced.

The way forward relative to assessing the soil and water impacts of bioenergy systems and the sustainability of biomass production rests with three approaches that could be used individually but are more likely to be employed in some combination [12]. These approaches are: (1) Utilizing characteristics that can be quantified in Life Cycle Assessment (LCA) studies by

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software, remote sensing, or other accounting methods (e.g. greenhouse gas balances, energy balance, etc.) [13]; (2) Measuring and monitoring ecosystem characteristics that can be evaluated in a more or less qualitative way (e.g. maintaining soil organic carbon) that might provide insights on potential productivity and sustainability, and (3) Employing other proactive management characteristics such as Best Management Practices (BMPs) that are aimed at preventing environmental degradation.

1.2. Life cycle assessment

Life Cycle Assessment has been used to estimate the environmental impacts of biomass energy uses. Typically they examine greenhouse gas (GHG) emissions, CO_2 emissions, energy balance, and some indirect effects. A review of published LCAs, revealed that more than half of the studies were from North America and Europe, and that most are found in papers published in scientific journals [9–11]. Increased numbers of South Asia, Africa, and South America can be found. About 50% of the studies limited the LCA to GHG and energy balances without considering contributions of bioenergy programs to other impact categories such as soils and water. The published studies concluded that there are a number of problems in currently used LCA approaches that make it impossible to quantify environmental impacts from bioenergy programs. Some of the key indirect effects issues strongly depend on local operations, vegetation, soil, and climate conditions that tend to make accurate assessment of environmental effects very problematic.

Although politicians and upper level managers claim that methods exist for assessing environmental impacts on soil and water, the scientific foundation for estimating indirect effects of bioenergy programs is constrained by the lack of adequate validation research, accurate assessment methods, and the relative infancy of the LCA process. It was clearly pointed out that determination of environmental outcomes of bioenergy production is complex and can lead to a wide range of results [11, 12]. This review clearly stated that the inclusion of indirect environmental effects in LCA represents the next research challenge and not the immediate incorporation into the assessment methodology.

1.3. Sustainability and productivity

The second approach for assessing soil and water impacts of bioenergy systems, and the sustainability of biomass production, is dependent on soil quality monitoring. This approach was developed as a means of evaluating the effects of forestry and agricultural management practices on soil functions that might affect site productivity [13, 14]. A number of soil physical, biological and chemical parameters, which have linkages to soil productivity have been proposed as forming a minimum monitoring set. The way forward relative to assessing soils impacts and the sustainability of biomass production systems rests with proactive proper soil management and not reactive monitoring for screening the condition, quality, and health of soils relative to sustaining productivity [15–17]. Evaluation of soil condition thus would lead to a time-trend analysis that can in turn be used to assess the sustainability of land management practices and bioenergy programs. Even though sustainability is the stewardship goal of land management, more specific definitions of its goals and attributes is often complex and open to considerable

interpretation [18, 19]. Many scientists have attempted to answer the "what," "what level," "for whom," "biological or economic," and "how long" questions of sustainability. However, there is no absolute definition of sustainability, and that it must be viewed within the context of the human conceptual framework, societal decisions on the state of ecosystem to be sustained, and the temporal and spatial scales over which sustainability is to be judged [18]. In short, this approach is loaded with considerable uncertainty and lack of consensus.

2. Water impacts of modern bioenergy programs

Reporting of water impacts on ecosystems caused by the implementation of bioenergy systems is both variable and incomplete (**Figure 1**). While some assessments include only active human uses such as irrigation and water used in biofuel conversion processes, others include hydrologic processes such as evapotranspiration, infiltration, runoff, and baseflows, which are natural ecosystem processes influenced by human activity (**Figure 2**) [2]. Water limitations may reduce the opportunities to use bioenergy in some ecosystems. However, there are many situations where bioenergy may advance both socioeconomic and sustainable landscape objectives [9, 12]. The objective of good bioenergy management is to keep water flow on the right side of the diagram in **Figure 2**.

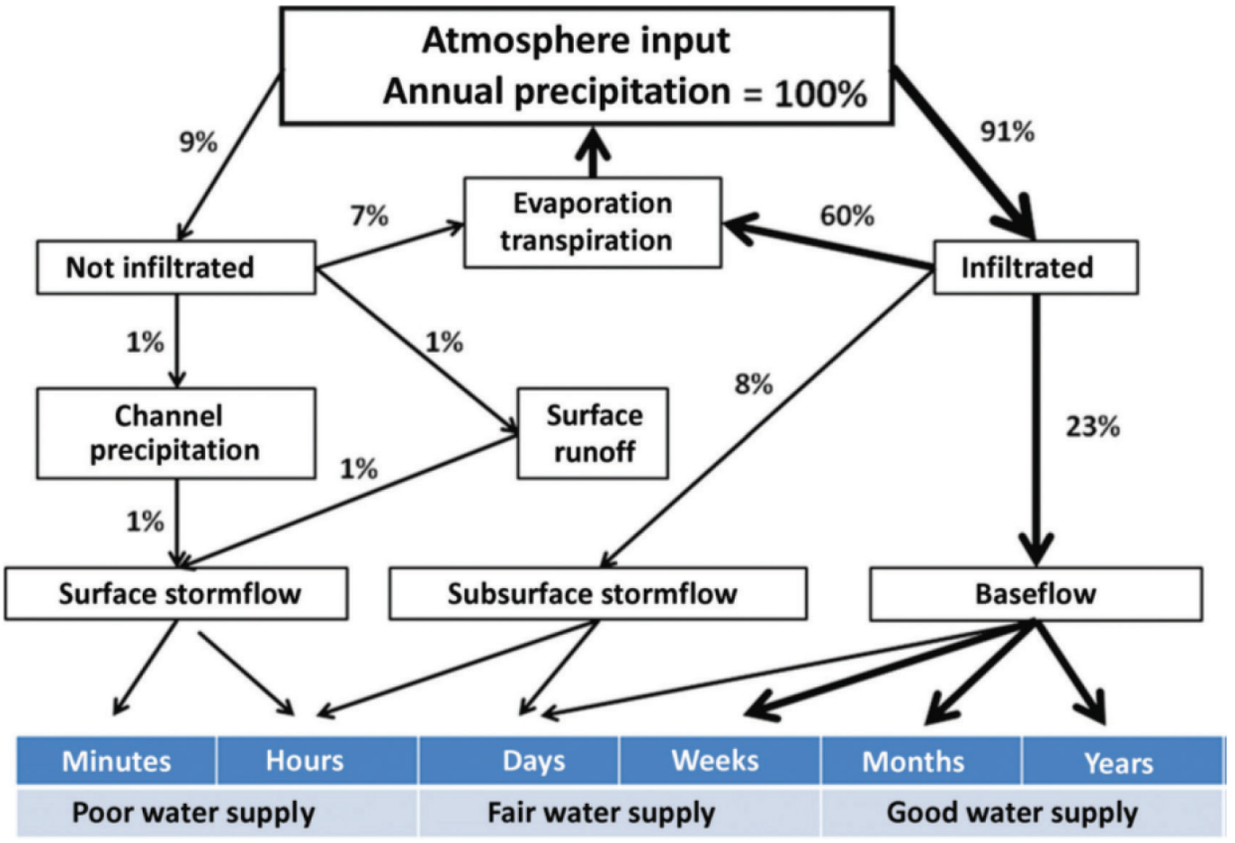


Figure 2. Hydrologic processes governing the water cycle and the distribution between desired good water supply, fair water supply, and poor water supply in ecosystems (From [12]).

2.1. Annual agricultural crops

The cultivation of conventional annual crops as bioenergy feedstocks affects soil and water resources similar to crop cultivation for food and livestock feed. Water withdrawals and the effects of agrochemicals must be carefully managed to avoid human health impacts, water quality degradation, and damage to ecosystems [20]. As in other agricultural and forestry activities, the adoption of BMPs is crucial to minimizing the risk of water quality impacts and promoting sustainable resource use. Assessing BMPs and their effectiveness further requires defining appropriate water quality expectations, determining what site conditions limit BMP effectiveness, and identifying the specific watershed characteristics and appropriate spatial and temporal scales for assessment [21].

2.2. Perennial and semi-perennial crops

Extensive root systems, long-term soil cover and protection, and reduced need for tillage and weed suppression, give semi-perennial crops excellent choices for bioenergy feedstocks. Crops such as sugarcane, perennial grasses like switchgrass, *Miscanthus* spp. and elephant grass, and trees grown in short rotations tend to have lower water quality impacts than conventional crops [22–24]. While many perennial crops considered for bioenergy have relatively high water use efficiency, their total water requirements can also be relatively large. Such crops are ideally suited to areas with high water availability and flows where water quality can be easily managed [25]. For example, one analysis indicated that that *Miscanthus* spp. could replace 50% of corn acreage in most areas of the Midwest US without adversely affecting the hydrologic cycle. In drier regions, *Miscanthus* spp. should be limited to 25% of the area [26]. Additionally, it has been suggested that the use of perennial grasses may increase seasonal evapotranspiration (ET) compared to grains due to the access of these grasses to moisture deeper in soil profiles [27].

2.3. Forest woody biomass

Forests provide important regulation of both water quality and seasonally available water quantity in most large watersheds. Forest bioenergy systems are judged compatible with maintaining high-quality water supplies in forested catchments. This general statement is true as long as BMPs that are designed for environment and resource protection, and include nutrient management principles, are followed [28–30]. While short term water impacts, including increased sediment, nitrates, phosphates, and cations can occur, there is no evidence of long term adverse impacts in forest catchments subject to normal management operations [12]. However, more research is needed to guide BMPs concerning special activities in forest management (e.g. stump extraction, weed control, and forest fertilization [29, 31]. Quantitative water flows in forest stands are affected if stands are subject to operations involving significant basal area reductions. But since a forest estate typically is a mosaic of stands of different ages, where only a small share of all stands are harvested in a particular year, water flow regimes on the larger landscape level typically are not affected significantly by stand level operations. Exceptions occur where forests are replaced with other land covers or more intensively managed tree crops.

2.4. Organic residues

Secondary and tertiary waste biomass (e.g. municipal wood waste, food processing waste, manures, and wastewater with high organic content) has the potential to improve water quality in communities by reducing landfill deposits, and leachates. However, utilization of this resource remains inefficient. Even with zero landfill policies and a Waste Framework Directive, the EU-28 countries recovered energy from only 7% of its non-recyclable municipal waste in 2011 [32]. Currently, use of primary waste biomass (e.g. harvest residues, forest thinnings, and slash) for energy is limited because of the economics of transporting these residues. Increased use of wood residues can improve land and water productivity but requires that site-specific conditions (e.g., soil, climate topography, etc.) and competing uses (e.g., animal feed and bedding) are considered.

2.5. Algae

The water impacts of algal propagation vary widely by technology and environmental conditions, with water use ranging from minimal up to 3,650 L L^{-1} of biodiesel or advanced biofuel produced [33]. Freshwater is needed to replace water losses from open ponds, even when halophilic organisms are used. While the volumes in photobioreactors are relatively small, cooling requirements, usually met by freshwater, are large. Water impacts of conversion technologies result from competition from often scarce freshwater supplies.

2.6. Electrical generation impacts

In general, water impacts of biomass powered electricity generation remain similar to fossil fuel pathways, with large water withdrawals but low consumptive use ranging from 0–1800 L MWh^{-1} [34]. Cooling water, which may contain some salts, is returned at higher temperature to the source stream or basin, with variable ecological impact. Water requirements for biofuel processing continue to improve. Use per tonne of feedstock has decreased dramatically for both corn and sugarcane ethanol. For instance, the consumptive water use of ethanol-sugar mills in Southeast Brazil has decreased from 15 m^3 Mg^{-1} of sugarcane bagasse prior to 2008 to <3 m^3 Mg^{-1} in 2008 [35]. However, in water stressed regions new or expanded facilities may still not be approved due to the associated water demand [35]. While, untreated effluent can create water quality problems, process water offers an opportunity to recover and recycle nutrients. Biofuel facilities with zero liquid discharge have been operating in the U.S. since 2006 and continue to expand worldwide. Technological improvements in water recovery and recycling have progressed to the point that some facilities are able to use municipal wastewater and some have achieved closed loop recycling of process water.

3. Soil impacts of modern bioenergy programs

Soils are a critically important, basically non-renewable ecosystem resource, that provide the physical, biological, chemical, and hydrologic foundation for agricultural and forest bioenergy feedstocks production [36–38]. Soils are able to redevelop after being degraded but the

	Soil Texture	Soil Organic Matter	Mineral Nutrient Availability	Water Holding Capacity	Erosion
Water Runoff	M	S	S	S	W
Precipitation Interception					W
Water Supply Availability	S	S		S	
Soil Moisture	S	S	W	S	
Evaporative Losses	M	S	W	W	
Surface Water Turbidity		S	S		S
Eutrophication		S	S		S
Groundwater Recharge	S	S		S	

Key: S = soil effect on water W = water effect on soil M = mutual effect

Black = direct physical effect, Green = effect mediated through the crop specific attributes such as root or canopy structure, Blue = effect is both physical and plant -mediated

Table 1. Interdependencies of water and soil resources (adapted from [2]).

time period might be several centuries or millenia, depending on climate and vegetation. Because of this long time factor, soils are considered to be non-renewable. They are heterogeneous and highly diverse components of ecosystems that form over long time periods under the influence of parent mineral material, climate, landscape position and biological activity.

As the base of bioenergy production systems, soils constitute a major factor that interacts with water to determine the type and amount of plant biomass production (**Table 1**, [2]). They provide the physical anchor which tie plants to the earth, supply water and mineral nutrients for plant growth, decompose and recycle organic material and residues and mediate hydrological processes [39–41]. Bioenergy feedstock systems are part of agricultural and forest management systems that provide multiple ecosystem products and services [42]. These include plant biomass, water flow, water quality control, biodiversity, cultural heritage, and carbon storage. Soils are important factors in each of these services. Therefore, it is critical that in the process of managing soils for bioenergy production, soils must be managed to sustainably provide a wide range of ecosystem services important to human communities. Maintaining the quality of soils will ultimately ensure maintenance of water quality.

4. Best management practices

The focus on renewable energy sources has raised concerns about environmental effects. In particular, the increase in the use of woody biomass, agricultural crops, agricultural residues and processing wastes residues as feedstocks for bioenergy production has intensified questions about potential impacts on water quality and soil sustainability. Intensification of

forestry and agriculture raises concerns about cumulative effects on water quality and soil integrity [43]. Best Management Practices have been developed and implemented since the early 1970s to ensure that land management for wood fiber and agricultural crop production can be carried out with minimum impact on the environment [44]. Although BMPs were originally designed to minimize water quality impacts, they can be used ensure soil sustainability and biodiversity. The use of BMPs is widespread in developed countries and some developing nations. It varies from mandatory to voluntary depending on the degree of legislative support. For example, in many countries, BMPs are already incorporated in "Codes of Practice" that guide forest managers and farmers through the complete bioenergy life cycle. Best Management Practices have been developed and implemented in many agricultural countries to deal with water quality problems [44]. The use and implementation of BMPs is not a static process, but one that is dependent on a continual cycle of application, assessment and monitoring, refinement, and application. Although some countries have "national standards," the complex matrix of forest and agricultural ecosystems, climates, soils and topography, crop establishment and tending systems, and harvesting systems requires on-going evaluation and refinement to achieve BMPs to best fit local management and environmental conditions.

The rationale for BMP usage is multifaceted. Some of the reasons include: (1) State and National environmental regulations, (2) Agency regulations and goals, (3) Private land management objectives, (4) Land manager desires to seek certification for marketing purposes, (5) Corporate/individual commitment to sustainability goals, (6) Recognition of the productivity benefits of BMPs, (7) Desires to integrate multiple ecosystem services into land management, (8) Cultural and religious legacy, (9) Personal conservation heritage, and (10) Local needs to incorporate effective and successful examples of good natural resources management [2]. Research and development activities play a key part in the refinement and communication of improved BMPs. These projects are also crucial in validating the effectiveness of BMPs. This is especially important where local conditions or operational standards are unique. Best Management Practices function to ensure that forest and agricultural bioenergy programs can be a sustainable part of land management and renewable energy production. There are thousands of BMPs that have been published. Some are common to multiple forest management and farming systems. Others are unique to local environments and management practices and thus not pertinent everywhere.

5. Conclusions

Water and soil are so closely linked that the assessment of positive and negative effects of bioenergy production on water and soils should be part of any integrated analysis considering the environmental, social, and economic dimensions of bioenergy production. Water footprints and other measures have little informative value unless combined with data about resource availability and measures of competing uses at similar spatial and temporal scales. Assessment of the relative positive or negative soil and water effects of bioenergy systems depends largely on whether changes in management of land, water and other resources for bioenergy development alters the state and quality of soil and water [44].

Forest and agricultural bioenergy systems that utilize accepted BMPs should be capable of maintaining soil quality and high-quality water. Excessive removal of plant material from the field or forest may jeopardize soil and water quality. Extended or intensified cultivation of plant annual crops for bioenergy feedstock will produce the same impacts as when the objective of crop cultivation is for food. Cultivation of perennial grasses and woody plants commonly causes less impact on water and soil resources. These production systems can, through well-chosen siting, design, management and system integration help mitigate potential soil and water problems associated with current or past land use. Ultimately, careful land management through the implementation of BMPs will improve soil and water use efficiency.

Advances in water recovery and recycling have the potential to reduce water requirements for conversion processes as well as contribute to the reduction of manufacturing effluents. Feedstock production and conversion stages can, in some cases, be integrated to use resources more effectively and support good land and water management.

The quantity and timing of water withdrawals should be carefully considered in context of water needs, watershed vulnerability, and resilience to disturbance of hydrological cycles. Water scarcity may limit some conventional bioenergy systems in some regions. However, other bioenergy cropping systems may be able to take advantage of currently non-conventional water sources.

Matching bioenergy feedstocks, management practices, and conversion technologies to local conditions and constraints is essential for development of sustainable bioenergy systems. Successful implementation requires investments in the development of suitable plant varieties and conversion systems, systems integration to use resources effectively, and implementation of BMPs in forestry and agriculture.

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