

Soils and Water

Göran Berndes^{*a†}, Heather Youngs^{†b‡}, Maria Victoria Ramos Ballester^c,
Heitor Cantarella^d, Annette L. Cowie^e, Graham Jewitt^f,
Luiz Antonio Martinelli^g, and Dan Neary^h

^{*}Lead Authors

Responsible SAC and Associate Editor: Reynaldo L. Victoria

Contact: [†]goran.berndes@chalmers.se; [‡]hlyoungs@berkeley.edu

^a*Chalmers University of Technology, Sweden;*

^b*University of California Berkeley, USA;*

^c*Universidade de São Paulo, Brazil;*

^d*Agronomic Institute of Campinas, Brazil;*

^e*University of New England, Australia;*

^f*University of KwaZulu-Natal, South Africa;*

^g*Universidade de São Paulo, Brazil;*

^h*USDA Forest Service, USA*



Highlights

- Bioenergy systems can have positive impacts on water and soil resources when feedstocks and conversion technologies are matched to local conditions and planning includes holistic landscape-level assessment.
- Landscape-level optimization of bioenergy, especially perennial and woody systems, can reduce soil erosion, improve water quality, allow nutrient recycling, and promote carbon sequestration in soils.
- Like other agricultural, silvicultural and industrial systems, bioenergy can cause negative impacts, which should be minimized through appropriate planning and use of Best Management Practices.
- Policies addressing environmental impacts of bioenergy should be informed by assessments specific for the location, rather than relying on average/generic data and broad brush footprint and efficiency metrics.

Summary

Bioenergy production can have positive or negative impacts on soil and water. 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 (Figure 18.1). While standardized metrics, such as footprints and water- and nutrient-use efficiencies are convenient and intuitive, they can be insufficient to achieving sustainable production and environmental security at relevant spatial and temporal scales. Rather, comprehensive ecosystem impact analysis should be conducted. Sustainability standards and certification schemes should use metrics that are consistent with other agricultural and silvicultural activities and sustainability goals at the local, regional, and global level.

Matching bioenergy feedstocks, management practices, and conversion technologies to local conditions and constraints is possible and essential. Bioenergy crops offer

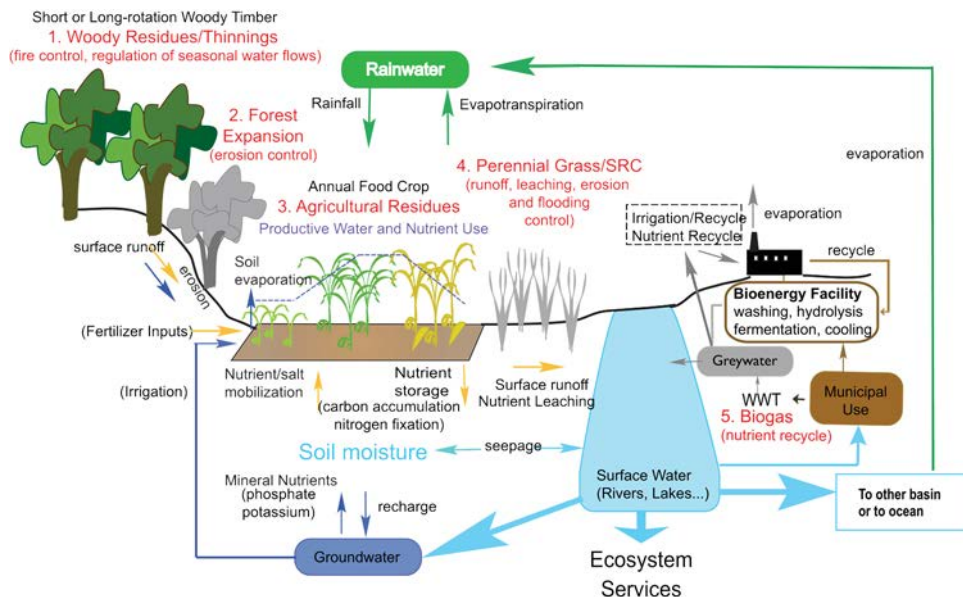


Figure 18.1. Bioenergy, Soils and Water – There are many opportunities to implement or improve bioenergy production to address long-term sustainable use of water and soil resources. For example, in cases where erosion and water/nutrient flows are excessive, such as sloping land (2) and riparian zones (4), woody and perennial bioenergy crops may provide relief. In lands already under productive forest (1), agricultural (3), or urban use (5), the use of harvest residues may be appropriate. As in all land use, inputs such as fertilizers and irrigation should be used judiciously. The inter-related impacts of bioenergy systems on water and soil must be examined in an integrated assessment with consideration of other human activities and ecosystem service requirements.

good opportunities for nutrient recycling, and in some cases, can increase soil organic matter, which improves soil quality and may also mitigate carbon dioxide (CO_2) emissions. However, excessive removal of plant material from the field or forest may jeopardize soil and water quality, causing economic and environmental losses. The need to retain some portion of crop or forest residues is site-specific and regional data are important to guide practices. Higher output in crop and forest production, enabled by active management and the use of inputs such as fertilizers and irrigation, can spare land and enable more efficient resource allocation. However, possible negative impacts on water availability and water and soil quality should be assessed and minimized. If there is a risk for serious impacts on local livelihoods and food security and environmental flows, irrigation of energy crops may need to be avoided, even in instances where it represents the most productive use of available water in terms of output or income per unit water. Caution, periodic evaluation, and appropriate water pricing and allocation systems can help avoid unwanted effects in water-stressed regions. In most cases, bioenergy solutions can be found that contribute to energy and climate security and which are compatible with local and regional constraints. As

in other agricultural activities, the adoption of Best Management Practices (BMPs) is important in bioenergy feedstock production because it tends to minimize risks of excessive input use.

18.1 Introduction

Bioenergy systems can affect the state of water and soils in both positive and negative ways. The outcome depends on: (i) the nature of the feedstock production systems; (ii) their location in the landscape; (iii) what types of land cover/use are replaced; (iv) the location of the biomass conversion facilities; (v) whether - and if so how - the biomass conversion facilities integrate with other societal activities, such as waste management, industrial activities, energy supplies other than bioenergy, and the land using sectors, and (vi) the quantity and quality of local water supplies.

This chapter describes the soil and water consequences of bioenergy systems and discusses how novel and emerging bioenergy systems may present challenges as well as opportunities concerning soil and water. Soil and water effects depend critically on how previous management has influenced the state of soil and water and whether bioenergy implementation induces *changes* in management of land and water resources (and in management of energy and material flows in general). For this reason, special attention is paid to how an expanding bioenergy sector - that changes in character over time due to evolving governance and innovation - may affect the state of soils and water. There has been a surge in research studying environmental impacts since the previous SCOPE reports (de Fraiture and Berndes 2009). New knowledge - which has moved beyond speculation to hard data - is highlighted, but general quantitative impact factors such as efficiencies and footprints are not specified in the discussion since these numbers may provide a false sense of surety regarding impacts and they often bear little relevance to impacts within any particular region or implementation strategy (Berndes 2002; Efroymson et al. 2013; Jewitt and Kunz 2011) (see section 18.1.2).

18.1.1 Interconnectivity of Water and Soil

Water and soil are inextricably linked (Table 18.1, Figure 18.2), providing the basic chemical requirements for plant life on earth (Neary et al. 2009). The use of such 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 a world where close to one-third of the Earth's land surface is used for agriculture production - which is also responsible for about 70% of global freshwater use (Aquastat 2012) - bioenergy development might present considerable challenges, from the perspective of soil and water quantity as well as quality. At the same time, bioenergy systems present new opportunities to improve land and water productivity and help address soil and water impacts of current land use.

Table 18.1. Interdependencies of water and soil resources.

	Soil Tilth	Soil Organic Matter	Mineral Nutrient Availability	Water Holding Capacity	Erosion
Water Runoff	▲	●	●	●	■
Precipitation Interception					■
Downstream Water Availability	●	●		●	
Soil moisture	●	●	■	●	
Evaporative Losses	▲	●	■	■	
Surface Water Turbidity		●	●		●
Eutrophication		●	●		●
Groundwater Recharge	●	●		●	

Key: ● Soil effect on water ■ water effect on soil ▲ 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

18.1.2 Metrics

The use of metrics that concern only one or a few aspects (e.g., footprints, water and nutrient use efficiency (Box 18.1) in lieu of comprehensive ecosystem impact analysis has become common in discussions about bioenergy. However, such metrics, while convenient and intuitive, should not be used in isolation since they can be misleading and irrelevant to assessing sustainability of production and environmental security (Yeh et al. 2011). For example, a system can have ten-times the water use efficiency (WUE) as another system while using twice the water. Even so, neither the absolute water use nor the WUE is sufficient to decide if either system is appropriate for a given site. Rather, a full understanding of the land cover-soil-atmosphere feedbacks on the hydrologic cycle in the context of all human uses and ecosystem functions, as well as the consequences for other resources including information about social and economic costs and benefits at that site is required. Assessing these effects among resource users requires agreement on metrics, methodology, and ethical values, including social, economic, and environmental sustainability criteria and acceptable limits to change in resource availability and quality, which requires transparency and stakeholder input as well as an appropriate baseline against which any impacts can be assessed (Chapter 19, this volume). Also, allocation of water impacts in multiproduct landscapes such as the production of both food/feed and energy needs to be standardized (Chapter 13, this volume).

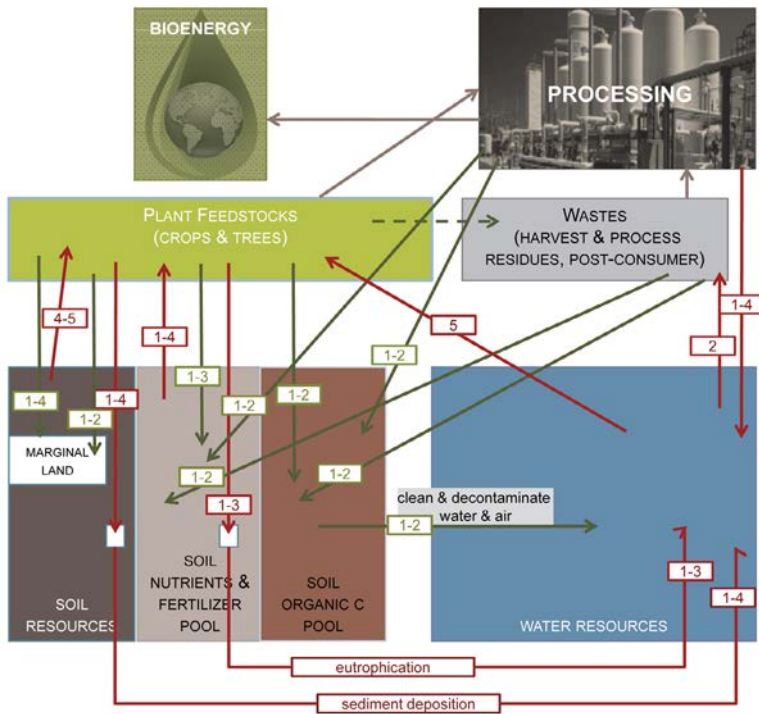


Figure 18.2. Water and Soil Impact Matrix – Diagram of the complex soil-water-feedstock interactions for bioenergy production. Red arrows indicate resources expenditure for feedstock production or negative impact. Green arrows represent mitigating activities or positive impact. Boxed numbers are the estimated size of the impact in a 1-5 scale and illustrate the possible range of impact. Proper management of bioenergy production should focus on increasing the beneficial and reducing the negative impacts so that the balance is positive. **Resource expenditures:** soil, water, and nutrients are needed for cultivation of bioenergy biomass; water is also spent for feedstock processing. **Negative impacts:** contamination/eutrophication from waste disposal; erosion, sediment deposition and nutrient leaching that affect soil and water quality from land cover change and field cultivation and maintenance. **Positive impacts:** Carbon and nutrient recycling and soil protection from perennials, plant residues, and wastes (both from feedstock and processing) returned to or maintained in the field; organic matter improvement to soil quality and provision of environmental services such as water and air cleaning and decontamination.

The water intensities (or water footprints) of biofuels reported in the literature vary by orders of magnitude (Figure 18.3). Though widely adopted, the methodology for such reporting is not standardized, not validated by measurement, and marginally useful for determining ecosystem impact. Some footprints include rainwater inputs, theoretical transpiration losses from plant growth, and in some cases theoretical use of irrigation water. Some include additional water volume as a proxy for water quality impacts. Water use is not consistently allocated when multiple products arise from a particular feedstock.

However, the recently completed ISO water footprint standard (ISO 14046) is intended to improve consistency in quantifying water footprints.

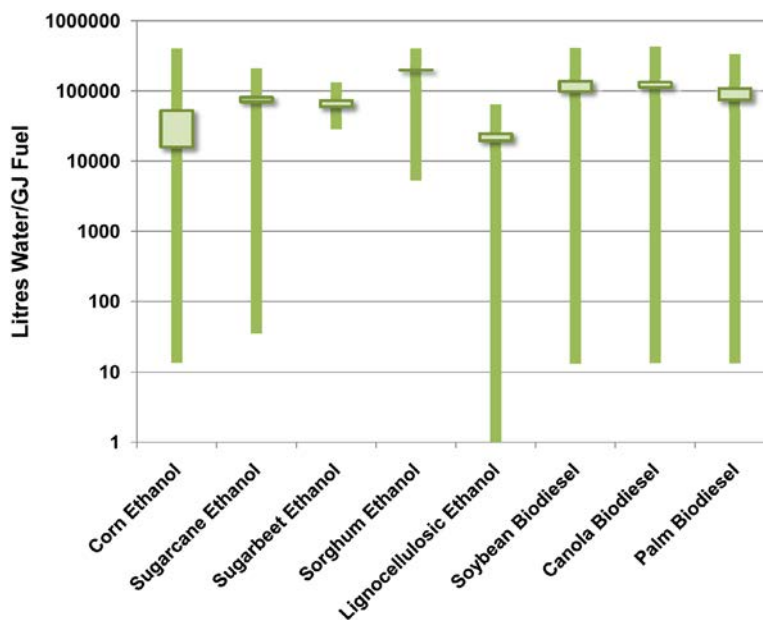


Figure 18.3. Water intensity indicators are not sufficient to guide decisions but must be complemented with other metrics and evaluation frameworks. (Solid bars indicate the range of values reported in literature. Boxes represent the difference in the median and mean values. The range for lignocellulosic ethanol includes thermochemical and biological conversion pathways.) Sources: Gerbens-Leenes et al. 2009; Fingerman et al. 2010; 2011; US National Research Council 2008; Bhardwaj et al. 2010; deFraiture et al. 2008; Scown et al. 2011; Schornagel et al. 2012; Wu et al. 2009; Kaenchan and Gheewala 2013; Gerbens-Leenes et al. 2008; Dominguez-Faus, et al. 2009; Rio Carrillo and Frei 2009; Gerbens-Leenes and Hoekstra 2012; Chiu and Wu 2012.

Box 18.1. Definitions of Terms (Sources: Hoekstra et al. 2011; Baligar et al. 2001; Baldock and Nicoll 2008; Neary 2013)

Best Management Practices (BMPs): These activities constitute a system of recommended actions. In bioenergy production these can relate to resource stewardship, biomass cultivation and harvest, and waste disposal. 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) Desire to integrate multiple ecosystem services into resource management, (8) Cultural and religious legacy, (9) Personal conservation heritage, and (10) Desires to emulate successful examples of good natural resources management.

Nutrient Use: The mass of nutrient amendment (fertilizer added) or the amount required for optimal yield. Thus, the use is dependent on the concentration of available nutrients in the soil, which is highly variable. The nutrients most commonly limiting plant growth are nitrogen, phosphorous, potassium and sulfur.

Nutrient Use Efficiency (NUE): Similar to WUE, the term NUE is a commonly used abbreviation for yield per unit nutrient input. In agriculture this is usually related to the input of fertilizer, whereas in scientific literature the NUE is often expressed as fresh weight or product yield per content of nutrient in the plant. NUE depends on the ability to efficiently take up the nutrient from the soil, but also on transport, storage, mobilization, usage within the plant, and even on the environment. Improvement of NUE is an essential pre-requisite for expansion of crop production into marginal lands with low nutrient availability.

Soil Organic Matter/Soil Organic Carbon (SOM/SOC): Soil organic matter (SOM) is plant and animal material humified or in the process of decay. This material contains many elements including soil organic carbon (SOC). Deposition and lifetime of SOM and SOC varies by climate, plant type, by soil and water conditions, microbial population, and management activities including fertilization, tilling, drainage, etc.

Water Footprint: An indicator of freshwater use that looks at both direct and indirect water use and can include groundwater, surface water, rainwater, and traded water embedded in products (virtual water) as well as proxies for water quality and other ecological impacts. Footprints are usually expressed in the same units as efficiencies. How footprints are calculated is highly variable.

»

» **Water Use:** The volume of water required by an activity such as growing a feedstock or converting that feedstock to a useful energy carrier. Water use is discussed in terms of water withdrawal (the volume of freshwater abstraction from surface or groundwater) and water consumption (the volume of freshwater used and then evaporated, transpired, incorporated into a product, or moved to another watershed).

Water Use Efficiency (WUE): The volume of water used in relation to a specified parameter, commonly water use per unit of product or, water use per unit gross/net revenue. For bioenergy this is typically liters of water per liters of biofuel produced or liters of water per MWh electricity, etc. WUE can be improved through management by eliminating excess water applications and minimizing water losses or through plant selection, taking advantage of varying physiological adaptations that maximize growth and minimize water loss. Improvements of the biomass conversion process can improve the WUE by reducing process water requirements and/or improving the biomass conversion efficiency.

18.1.3 The Need for Local and Regional Integrated Assessments

Integrated impact assessment frameworks are evolving to recognize the interconnectivity of water, soil, and biodiversity into a systematic view with integrated metrics (Donnelly et al. 2010; Fernando et al. 2010; Hooper 2003). Such frameworks allow replacement of disjointed field- or facility-based productivity analysis with decision-making at the landscape level, which is required for long-term sustainability. Improved data collection and modeling capability now allow high resolution of local impacts and assessment of the differing sensitivities and tolerance of individual regional niches to human activities such as biomass cultivation and removal and the various processes of energy generation. However, the requirements to conduct and implement such assessments still present technical and sociopolitical challenges. Integrated assessments require fairly detailed landscape-level baseline data and an adequate understanding of the mechanistic linkages among regional environmental processes and regional activities including other human and non-human use.

18.2 Water Impacts of Modern Bioenergy

Reporting of water requirements for bioenergy is widely variable (Figure 18.3). While some estimates include only active human use such as irrigation water and water

used in biofuel conversion processes, others include rain-fed evapotranspiration, which is a natural ecosystem process that is influenced by human land use. While, water limitations may reduce bioenergy opportunities in some regions, there are many opportunities for bioenergy to advance both socioeconomic objectives and sustainable landscape planning (Figure 18.1).

18.2.1 Water Impacts Current and Novel feedstocks (see also Chapter 10, this volume)

18.2.1.1 Annual Bioenergy Crops

The cultivation of conventional annual crops as bioenergy feedstocks affects soil and water resources in the same way as when such crops are cultivated for food and feed. Water withdrawals and the effects of fertilizers, pesticides and other chemicals applied to croplands on surface and ground water must be carefully managed to avoid human health impacts and damage to ecosystems (Sutton et al. 2012). Worldwide, 20% of agricultural cropland is equipped with irrigation (FAOstat 2010), of which bioenergy crops represent less than 1%. As in other agricultural and forestry activities, the adoption of BMPs is crucial to minimizing the risk of water impacts and promoting sustainable resource use in the cultivation of bioenergy crops (see Box 18.1 and Section 18.5). Assessing BMPs and their effectiveness further requires defining appropriate water quality expectations, determining what site conditions limit BMP effectiveness, and determining specific watershed metrics and appropriate spatial and temporal scales for assessment (Ice 2011).

18.2.1.2 Perennial and Semi-Perennial Crops

Because of their extensive root systems, long-term soil cover and protection, and reduced need for tillage and weed suppression, semi-perennial crops such as sugarcane, perennial grasses such as switchgrass, *Miscanthus* and elephant grass (Morais et al. 2009; Dale et al. 2011) (Chapter 10, this volume), and trees grown in rotations ranging from just a few years up to several decades (both coppice and single-stem plantations) tend to have lower water quality impacts than conventional crops (Dimitriou et al. 2011). While many perennial crops considered for bioenergy have relatively high WUE, their total water requirements can also be relatively large. Such crops are ideally suited to areas with high water availability, with caution to preserve ecological water flows (Parish et al. 2012). For example, Van Looke et al. (2010) report that *Miscanthus* could replace 50% of corn acreage in most areas of the Midwest US without affecting the hydrologic cycle, but that in drier regions *Miscanthus* should be limited to 25% of the area. Additionally, it has been suggested that the use of perennial grasses may increase seasonal evapotranspiration (ET) compared to maize due to the access of these grasses to deeper soil moisture (Hickman et al. 2010). This increase in ET would lead to higher humidity, lower surface temperature, higher precipitation and cloud cover with lower solar radiation. In turn, soil moisture would increase, affecting soil metabolism and finally carbon sequestration. The

same trend was observed for sugarcane in parts of the Central Brazil savannas (Loarie et al. 2011) and Southeast Brazil (Cabral et al. 2012).

18.2.1.3 Forest Biomass in Long Rotation

Forest biomass for bioenergy is typically obtained from a forest estate managed for multiple purposes, including production of pulp and saw logs, and provision of other ecosystem services such as water purification and regulation of water flows in watersheds. Forest bioenergy systems are judged compatible with maintaining high-quality water supplies in forested catchments, as long as BMPs that are designed for environment and resource protection and include nutrient management principles are followed (Mead and Smith 2012; Neary 2013; Shepard 2006). 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 (Neary and Koestner 2012). However, more research is needed to guide BMPs concerning stump extraction and forest fertilization (de Jong et al. 2014). Quantitative water flows in a specific forest stand are naturally affected if the stand is subject to operations involving significant felling and biomass extraction. 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 as discussed in section 18.4.

18.2.1.4 Organic Waste and Residues

Energy recovery from secondary and tertiary waste biomass (e.g. municipal waste, food processing waste, manures, and wastewater with high organic content) has the potential to improve water quality in communities all over the world by reducing landfill leachate and providing incentives to avoid direct discharge of waste into water bodies. However, utilization of this resource remains inefficient. For example, even with zero landfill policies and a Waste Framework Directive, the EU-28 countries recovered energy from only about 6% of its non-recyclable municipal waste in 2010 (EuroStat 2014). Currently, use of primary waste biomass (e.g. harvest residues, forest thinnings and slash) for energy is limited. By increasing the use of these materials, bioenergy output can increase without requiring more land and water. However, site-specific conditions (e.g., soil, climate topography) and competing uses (e.g., animal feed and bedding) need to be considered (see section 18.4.2.1).

18.2.1.5 Algae

The water impacts of algal propagation vary widely by technology and environmental conditions, with water use ranging from 3 to 3,650 L L⁻¹ of biodiesel or advanced biofuel produced (Wigmosta et al. 2011; US NRC 2012). 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. Algae do provide an opportunity to recover nutrients from wastewater for lipid-based biofuel production, which may be advantageous in some locations (Pittman et al. 2011).

18.2.2 Water Impacts of Conversion Technologies (see also Chapter 12, this volume)

In general, water impacts of biomass electricity remain similar to fossil fuel pathways, with large water withdrawals but low consumptive use ranging from 0-1800 L MWh⁻¹ (Fthenakis and Kim 2011). Cooling water, which may contain some salts, is returned at higher temperature to the basin, with variable ecological impact. Water requirements for biofuel processing continue to improve. Water use per metric ton of feedstock has decreased dramatically for both corn and sugarcane ethanol. For instance, the water use of ethanol-sugar mills in Southeast Brazil decreased from 15 m³ per metric ton of sugarcane prior to 2008 to approximately 1-3 m³ per metric ton in 2008 (Martinelli et al. 2013). However, in water stressed regions new or expanded facilities may still not be approved due to the associated water demand (Martinelli et al. 2013). While, untreated effluent can cause eutrophication and acidification of waterways, process water offers an opportunity to recover and recycle nutrients (see section 18.5.3.1). Biofuel facilities with zero liquid discharge, such as Pacific Ethanol in Madera, California, have been operating in the U.S. since 2006 and continue to expand worldwide. The most recent example is the BioChemtex/Beta Renewables lignocellulosic ethanol plant in Crescentino, Italy. 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 recycle (Figure 18.4).



Figure 18.4. The Tharaldson Ethanol plant in North Dakota uses municipal wastewater and returns about 25% of the volume at drinking water quality to the city of Fargo (www.tharaldsonethanol.com).

18.3 Soil Impacts of Modern Bioenergy

18.3.1 Soil Impacts of Current and Novel Feedstocks

The soil organic carbon (SOC) pool to 1 m depth holds more carbon than the atmosphere and the biotic pool combined (Lal 2008). The changes in soil carbon at any site reflect the balance between organic matter inputs, and mineralization rate. Considering the large size of the SOC pool, fluctuations in this balance over large areas can have a significant impact on atmospheric CO₂. Land conversion to agriculture often leads to SOC losses, especially when annual crops are cultivated (Nafziger and Dunker 2011; Perrin et al. 2014). Mechanization of agriculture has accelerated SOC losses in croplands, whereas development of carbon-sequestering practices over the past decades may have limited SOC loss from arable soils (Eglin et al. 2010).

Bioenergy systems vary widely in their potential to affect soil properties including soil tilth, SOM including SOC, soil water holding capacity, risk of erosion, and mineral nutrient content (Figure 18.1). The outcome will, to a significant degree, be determined by the existing and previous land use where the bioenergy systems become established. Matching appropriate feedstocks and management practices to soil requirements offers many opportunities to improve soil conditions and avoid negative impacts (See also Chapters 9 and 10, this volume). Biomass production for bioenergy should apply management practices that minimize negative impact on soils and - where possible - promotes positive outcomes (Cowie et al. 2006). Box 18.2 summarizes key points relating bioenergy feedstock production and soil carbon discussed in this chapter (See also chapters 5 and 9, this volume).

Box 18.2. Bioenergy feedstock and soil carbon

General trend of soil carbon stock

Decrease

Replace forest and other natural ecosystems with crops

Replace perennial or semi perennial crops with annual crops

Crop and forest residues removed or burned

Intense soil mechanical disturbance (i.e. plowing, sub soiling, uprooting forest stumps, etc.)

Biomass production systems or managements that increase soil erosion

Increase

Grow perennial or semi perennial crops on degraded land including degraded pastureland

Return plant residues and organic wastes to soil (organic fertilization)

Preserve plant residues by avoiding burning

No till or minimum till

Amending soil with biochar (economic feasibility to be established)

18.3.1.1 Annual Bioenergy Crops

Annual crops provide farmers with flexibility in land use decisions and immediate income. However, annual systems can be demanding of soil resources. SOM is a fundamental soil quality indicator and affects ecosystem services such as nutrient retention, degradation of pollutants, water infiltration and cleaning, invertebrate biodiversity, etc. (Lal 2009a; Lal et al. 2007). In annual crops used for bioenergy such as maize and rapeseed, frequent cultivation and removal of biomass can lead to low SOM, nutrient loss, and poor soil physical characteristics not to mention emission of greenhouse gases (Blanco-Canqui and Lal, 2009). In addition, nutrient depletion caused by inadequate fertilization and residue removal can jeopardize long-term productivity of soils (Snyder et al. 2009). Use of BMPs (section 18.3.2) can obviate these negative effects.

18.3.1.2 Perennial and Semi-Perennial Crops

Perennial and semi-perennial systems (i.e. crops with multi-year rotations) offer several benefits to soil. In parts of the USA, soil loss could be reduced by 60% if switchgrass is grown for bioenergy instead of corn (Khanal et al. 2013). While some nutrient loss can occur during the establishment phase, bioenergy crops including sugarcane (Galdos et al. 2009) and *Miscanthus* (Anderson-Teixeira et al. 2013) have been shown to accumulate SOM/SOC in many soil types under BMPs (Figure 18.5). In general, perennial systems have lower nutrient requirements than annual crops. Crops that undergo seasonal senescence such as *Miscanthus* can relocate nutrients to root structures and soil, reducing loss during harvest of above-ground material (Cadoux et al. 2012). Like grasses, short rotation woody crops such as willow and poplar can improve SOC when compared to tilled annual crops (Dimitriou et al. 2011). The ability of some perennial feedstocks to tolerate higher levels of metals and salts may present soil remediation opportunities (see section 18.3.3).

18.3.1.3 Forest Biomass in Long Rotation

Long-rotation forests offer clear benefits to biodiversity and soils. The large and permanent root systems of trees can take up nutrients deep in the soil profile, thus reducing leaching losses and accumulating carbon (Maquere et al. 2008; Woodbury et al. 2007). Forestry operations for fiber and bioenergy can affect SOC and cycling of nutrients such as nitrogen through soil movement and alterations in flow routes. Forest harvesting and the subsequent site preparation for forest regeneration (including soil scarification, trashline burning and road construction) are major disturbances. Logging machinery may cause soil compaction and the removal of nutrients at harvest can be negative from a nutrition and acidification perspective, but can result in reduced N loading of ecosystems in areas subject to high N loading via atmospheric deposition (de Jong et al. 2014). Nutrient losses can be compensated by fertilization and ash recirculation (Saarsalmi et al. 2012). Also the use of herbicides and other chemicals associated with intra-rotation silvicultural operations can have transient impacts on water quality and other ecosystem parameters (Neary et al. 1993, Neary 2002).

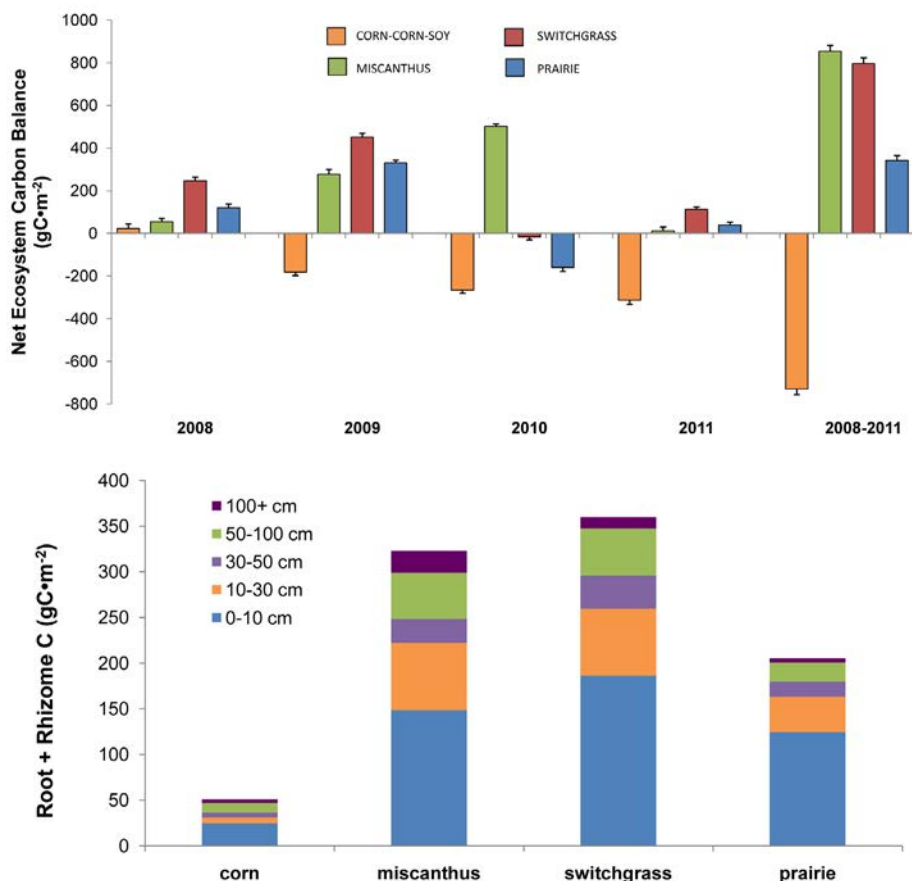


Figure 18.5. Perennial bioenergy crops can accumulate soil carbon – Primarily mediated through changes in below-ground plant matter (bottom), surface litter, and soil respiration, perennial systems tend to have higher net ecosystem carbon balance (top) compared to annually tilled crops such as corn and soy. Soil organic matter losses are reduced in no-till annual systems. Source: Anderson-Teixeira et al. 2013.

18.3.1.4 Waste Biomass

The use of waste biomass for energy affects soils primarily through diversion of the biomass from its normal disposal route. The use of municipal waste for energy allows for destruction of toxic organic compounds and recovery of toxic metals such as cadmium, arsenic, and lead that can contaminate soils. In addition, some nutrients required for biomass production are recoverable (see section 18.5.3.2). Agricultural residues normally left in the field contribute to nutrient cycling, erosion prevention, and turnover of soil organic matter. If these residues are increasingly removed from fields and used for energy, this can cause soil impacts (see section 18.4.2.1). The extraction of branches and tops from silvicultural operations and from

final felling implies additional carbon and nutrient export with possible consequences for soil status and tree growth (Helmisaari et al. 2011). However, growth reduction can be a temporary consequence of reduced N availability (Egnell 2011) and can be compensated for through earlier stand establishment, better conditions for site preparation and planting operations, and fertilization. Research and practical experience gained so far indicate that stump extraction can reduce the cost of site preparation for replanting (Saarinen 2006) and reduce damage from insects and root rot fungus (Berch et al. 2012; Cleary et al. 2013; Zabowski et al. 2008). While stump removal may not affect forest productivity in the short term, it can lead to negative effects including reduced forest SOC and nutrient stocks, increased soil erosion and soil compaction (De Jong et al. 2014; Persson 2013; Walmsley and Godbold, 2010).

18.3.2 Phytoremediation and Recovery of Marginal Soils

Bioenergy feedstock systems can be designed, sited and managed to provide specific environmental services, such as when plantations are established as vegetation filters for the treatment of nutrient-bearing water (e.g. pre-treated wastewater from households and runoff from farmlands (Börjesson and Berndes 2006; Dimitriou et al. 2011) (Figure 18.6). Studies with sugarcane indicate some benefit from irrigation with sewage effluent, although evaluations are still needed to assess long-term impact (Leal et al. 2010; Leal et al. 2011). Some species, such as willow, that accumulate heavy metals can remove cadmium and zinc from cropland soils (see, e.g., Berndes et al. 2004; Dimitriou et al. 2011), while others, such as *Spartina*, can be grown on arsenic contaminated soils (Mateos-Naranjo et al. 2012). The use of such marginal lands provides an important economic potential. For example, saline soils could support as much as 50 EJ of biomass for energy (Wicke et al. 2011).

18.4 Anticipating Changes Associated with Expansion of Bioenergy Production

18.4.1 Effects of Land Cover Change

Perhaps the most controversial aspect of bioenergy expansion involves the potential for changes in vegetative land cover or land use change (Lapola et al. 2010) (Chapters 5 and 9, this volume). The trend through much of human development has been to convert forests and perennial landscapes to annual cropping systems (Chapters 4 and 9, this volume), which has often caused negative impacts on water and soil resources. Changing annual systems back to perennial systems and forests affects water and soil resources, usually - but not always - in a positive way. For example, downstream water availability may decrease; see Figure 18.7 and further discussion below.



Figure 18.6. Willow to the rescue - combining bioenergy with waste treatment.

Willow is commercially grown in Sweden to produce wood chips for heat and power production. Willow coppice plantations with drip or sprinkler irrigation systems have been established adjacent to a range of wastewater treatment plants to facilitate alternative wastewater treatment and recirculation of N and P. Different types of nutrient-rich wastewaters, such as municipal wastewater, landfill leachate and log-yard runoff, have been treated in such willow vegetation filters. Willow producers benefit from increased yields and reduced fertilizer cost thanks to the irrigation water input. The Enköping municipal wastewater plant, shown in the photo below, installed 75 ha of willows used as vegetation filters to treat municipal wastewater. The wastewater is stored in lined ponds during the cold season. Between May and September, the stored water is mixed with conventionally treated wastewater and used to irrigate the adjacent willow plantation using drip pipes laid in double rows so that harvesting will not be obstructed. The willow plantation receives about 250 mm yr⁻¹ of irrigation water containing some 200 kg ha⁻¹ nitrogen and 10 kg ha⁻¹ phosphorous. Monitored low nitrogen losses indicate that the system is capable of capturing the added nitrogen at improved costs over conventional N treatment. The wood chips are used in the local district heating plant, which in turn recycles boiler ash back to the willow plantation. Source: Börjesson and Berndes (2006) Photo credit: Per Aronsson, Swedish University of Agricultural Sciences, Sweden.

18.4.1.1 Effects of Land Cover Change on Water

Land cover change can cause changes in the partitioning of precipitation between runoff, drainage, evaporation and plant transpiration (Figure 18.8). Gordon et al. (2005) found that deforestation is as large a driving force of changes in the hydrological cycle as irrigation. Studies have also found that afforestation with tree plantations can decrease streamflow and regulate seasonal water release (See section 18.6). King et al. (2013) combined projections of the global distribution of relative water availability in the coming decades, obtained from 16 global circulation models, with data on the water-use efficiency of tree- and grass-based bioenergy systems and found that relative water availability will be one of the most important climatic changes to consider in the design of bioenergy systems. For example, an analysis of 504 annual catchment observations revealed that afforestation

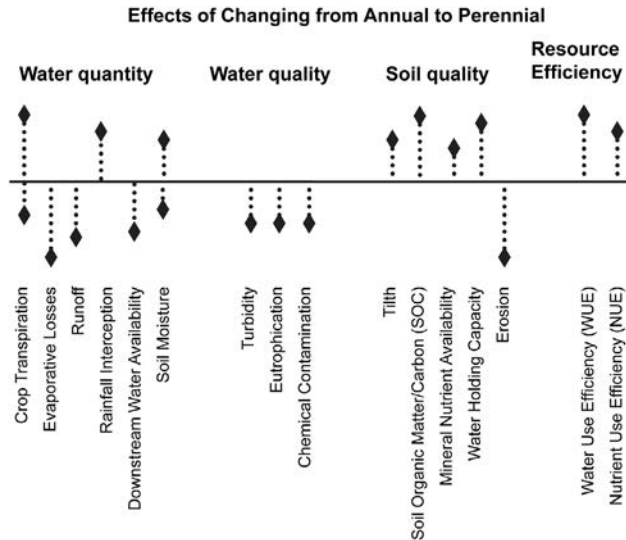


Figure 18.7. Land cover change affects soils and water in a multitude of ways. For example, changing from an annual to a perennial crop has a range of effects that depend on which plants are being changed and how management changes.

commonly resulted in reduced streamflow. Averaged over all plantation ages, afforestation of grasslands, shrublands or croplands reduced streamflow by almost 40%. For 10- to 20-year-old plantations, average losses were about 50% of streamflow (Jackson et al. 2005). Similarly, Zomer et al. (2006) report that large areas deemed suitable for afforestation - especially grasslands and land used for subsistence agriculture in drier areas, notably semi-arid tropics - would exhibit increased ET and/or decreased runoff, if planted with trees. A third example, Vanloocke et al. (2010) evaluated scenarios of miscanthus production on the simulated Midwest US hydrologic cycle and found that on an annual basis miscanthus uses more water than the ecosystems it will likely replace.

Bioenergy implementation involving irrigation can bring further changes in field-level water availability, ET rates and downstream water flows. The direction and size of the changes depends on location, prior land cover and use, and on what specific changes are made (Sterling et al. 2013). For example, replacing natural vegetation (forest or savannah) with pasture or annual crops, including sugarcane, in Brazil decreases local ET (Cabral et al. 2012). In contrast, annual ET of sugarcane is higher than pasture and other annual crops (Figure 18.9). Thus, sugarcane expansion into existing crop and pasture land increases ET in rain-fed areas (Cabral et al. 2012; da Silva et al. 2013), which may have a local cooling effect (Loarie et al. 2011) but can also reduce downstream water availability. Sugarcane ET is similar to the annual ET found in savannah regions, where most expansion is occurring in Brazil.

ET increases and reduced runoff can cause or intensify water shortages in some regions but can have positive effects in other regions. For instance, earlier conversion

of native vegetation to agriculture land in parts of Australia resulted in rising water tables due to reduced ET. As a consequence, salt moved into the surface soils and reduced their suitability for agriculture (Anderies 2005). Tree plantations can, in such situations, intercept water that moves through the soils and in this way help reduce groundwater recharge and soil salinization (Bartle et al. 2007, Harper et al. 2013; Pannell et al. 2004). Afforestation can also have other positive impacts on water flows;

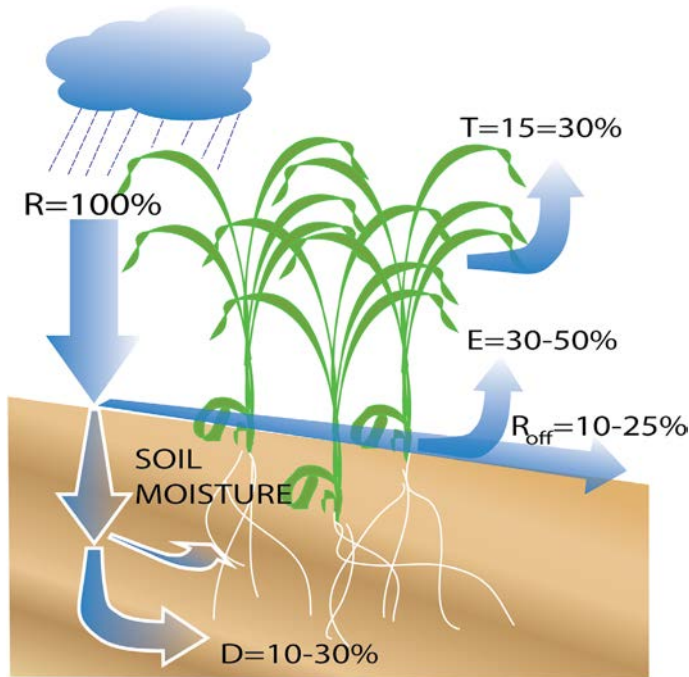


Figure 18.8. More biomass can be cultivated without using more water.

Rainfall (R) is partitioned by vegetative land cover. The water that is lost from the field due to runoff (R_{off}) and drainage (D) is potentially available further downstream, unless it is lost as evaporation (E) elsewhere in the landscape. Transpiration (T) by the cultivated plants represents the productive use of water. The percentages shown correspond to conditions in the semi-arid tropics in Sub-Saharan Africa (Rockström et al. 1999). E is often larger than T during the early part of the growing season for annual crops and may comprise 30-60 percent of seasonal ET, sometimes even more. Sparsely cropped farming systems in regions characterized by high evaporative demand can have very large water losses through E. If E losses can be reduced and a larger part of the rainfall can be channeled to plant T, productivity and biomass production can increase without necessarily increasing the pressure on freshwater resources. However, if total ET increases this can have consequences for both groundwater recharge and available surface water. The ET can increase both as a consequence of measures to enhance the yields of presently cultivated crops, or as a consequence of changes in land use such as when high-yielding biomass plantations are established on lands with sparse vegetation, e.g., degraded pastures. However, ET increases can in some situations be beneficial (Section 18.4.1.1). Source: Berndes (2008).

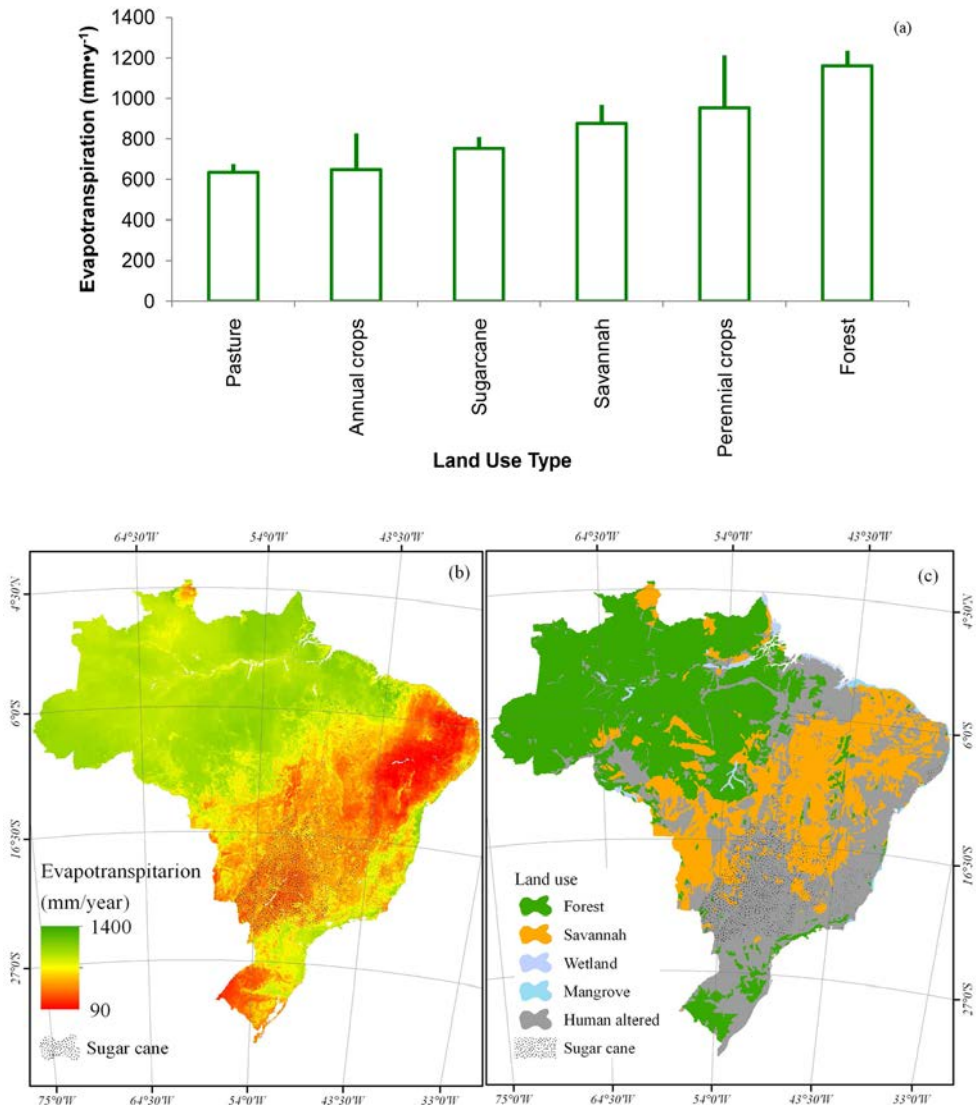


Figure 18.9. Landcover effects on evapotranspiration in Brazil. (a) Total ET (mm·year⁻¹) of monthly values for 2012 (b) for main land use types in Brazil (c), derived from a GIS integrated analysis of a 1 km time series of monthly MODIS ET product using land use (EMBRAPA Satellite Monitoring 2012; IBGE 2012) and vegetation maps (MMA 2005) to integrate over space. MODIS ET data were obtained from the Global Evapotranspiration Project - MOD16- (Mu et al. 2007; <http://www.ntsg.umd.edu/project/mod16>). The MOD16 algorithm is based on the logic of the Penman-Monteith equation which uses daily meteorological reanalysis data and 8-day remotely sensed vegetation property dynamics from MODIS as inputs.

in humid areas and steep slopes, tree cover can decrease runoff, erosion, and even floods, by increasing infiltration of rainfall and its retention in the soil. For example, Garg et al. (2011) modeled the hydrologic consequences of planting *Jatropha* on wastelands in India and found several desirable effects: more precipitation was channeled to productive plant transpiration and groundwater recharge and less was lost as soil evaporation. Also, soil erosion was reduced and downstream water conditions were improved resulting from that more stable runoff.

18.4.1.2 Effects of Land Cover Change on Soils

Changing vegetation types and management practices can alter soil physical and chemical properties, which can impact soil microbial systems, nutrient availability, SOM, and water holding capacity and, consequentially, plant growth. Understanding impacts on changes in SOM, especially SOC, are important if bioenergy is to contribute to low-carbon energy solutions to addressing climate change. Shifting from annual tilled crops to soil-covering perennial plants on sloping land with erodible soils can reduce flooding (Zuazo and Pleguezuelo 2008), soil erosion and degradation (Khanal et al. 2013; Maetens et al. 2012) and increase SOC (Anderson-Teixeira et al. 2013; Mello et al. 2014; Watanabe and Ortega 2014) (See also Chapters 10 and 16, this volume). However, the outcome of other land uses changes is site- and use-specific and dependent on physical and historical factors, as well as the time frame for evaluation. For example, replacement of tropical peatland forest with oil palm incurs a carbon debt ranging from 54 to 115 Mg CO₂eq ha⁻¹ yr⁻¹, varying by site and also by the accounting time frame (Page et al. 2011). In contrast, SOC under oil palm may equal or exceed native forests over time in some locations (Frazão et al. 2013).

18.4.2 Effects of Changes in Residue Management and Irrigation Use and Practice

18.4.2.1 Effects of Changes in Residue Management

It is likely that socioeconomic pressures on resources for bioenergy will drive a shift to multifunctional landscapes. In many scenarios increased bioenergy demand will trigger new approaches to residue management. Most plant residues presently left on the field from corn and other cereal grains may become economically viable feedstocks for heat and power, biomethane, or cellulosic biofuel production (Tyndall et al. 2011; Muth et al. 2013).

For example, the usual practice of burning sugarcane to facilitate harvest is being replaced in many countries by mechanical harvest thus preserving the straw in the field. The amounts of plant material that remains after stem harvest are huge – on the range of 8 to 20 Mg ha⁻¹ of dry material (Leal et al. 2013). The benefits of straw for nutrient cycling, soil conservation, yield increase, and carbon sequestration in soil are well documented (Carvalho et al. 2013; Figueiredo and La Scala Jr. 2011; Galdos et

al. 2009; Robertson and Thorburn 2007). Soil nutrients removed with the plant material can be replenished with synthetic fertilizers, but maintenance of SOM depends on regular supply of plant residues (Trivelin et al. 2013; Lal 2009b). The tradeoff between more bioenergy per unit land area and the need to maintain soil quality is the subject of intense debate (Cantarella et al. 2013; Franco et al. 2013; Gollany et al. 2011; Hassuani et al. 2005; Karlen et al. 2011; Lal, 2009b; Tarkalson et al. 2011). In many systems some or all of the residues must be left behind (English et al. 2013; Blanco-Canqui and Lal 2009; Huggins et al. 2011). For example, while palm residues have been proposed for expanded bioenergy production (see Chapter 16, this volume), the importance of these residues in nutrient recycling may limit that activity (Moradi et al. 2012; Bakar et al. 2011). With site-specific information, collecting plant residue can be sustainable in many situations (Hassuani et al. 2005; Muth et al. 2013). The threshold limits for residue removal depend on soil type, slope and climate.

In silvicultural activities, studies report wide ranges concerning how much forest residues can be extracted without causing negative impacts (e.g., Dymond et al. 2010; Gronowska et al. 2009; Lamers et al. 2013). This reflects varying biotic and abiotic conditions over landscapes and considerations of more aspects than soil and water effects, e.g., biodiversity. In addition, differences in forest industry infrastructure associated with forest resources and varying economic realities will cause extraction rates to vary over space and time.

18.4.2.2 Effects of Changes in Irrigation Use and Practice

The growth of bioenergy feedstocks is an economic activity that occurs in the context of agricultural and silvicultural production, which in some areas includes irrigation. There is no inherent need for bioenergy feedstocks to use irrigation. However, the availability of water in many regions will limit bioenergy potential. For example, one modeling study found that the global biomass potential varied from 130 to 270 EJ yr⁻¹ in 2050, depending on land availability and extent of irrigation (Beringer et al. 2011).

Unsustainable use of water can occur in any agricultural or silvicultural endeavor, but societal preferences and technological changes also shape the land use and intensification outcomes. Economic modeling (Popp et al. 2011) supports the intuitive hypothesis that, under climate change, bioenergy could increase irrigation in some regions. Although past evidence may indicate that these effects could be less than anticipated (Figure 18.10). Supplementary irrigation in rain fed areas can significantly increase biomass yield (Rockström et al. 2010) with little additional water use. There is large scope for improving WUE in both rain-fed and irrigated production (Figure 18.8) and water not suitable for food production can be used in bioenergy feedstock production (Figure 18.6). Use of drought-tolerant plants, plants adapted to regional seasonal water constraints, and proper management of water transfers and groundwater recharge can mitigate water stress impacts. Water withdrawals for irrigation (both quantity and timing) should be carefully considered in context of watershed needs, vulnerability, and resiliency, regardless of whether the irrigation supports food, biomaterials or bioenergy feedstock production.

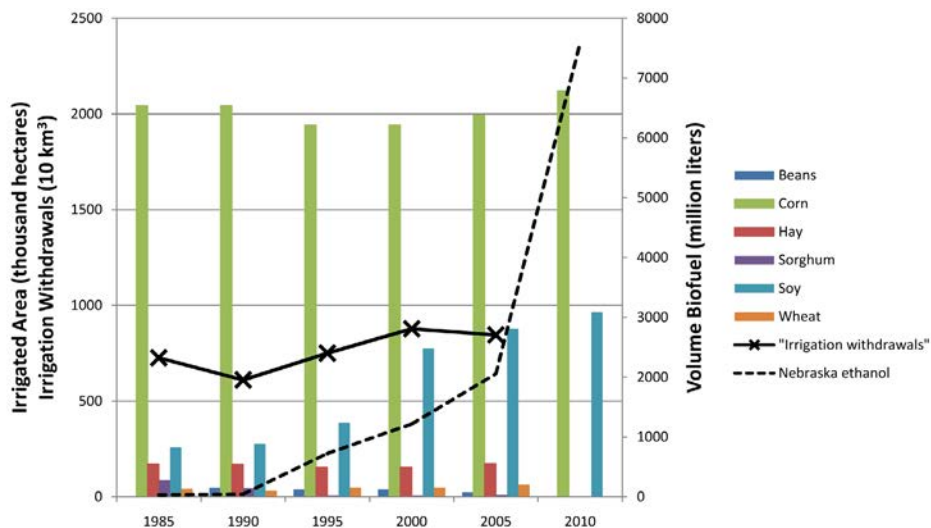


Figure 18.10. Will bioenergy drive increased water use?

The answer is most likely yes, but perhaps not as much as is feared, and this will vary by location. The state of Nebraska in the US Midwest has the highest share of irrigated land (15% of the US total) and is the second largest ethanol producing state. With construction of 25 biorefineries, corn ethanol production in the state skyrocketed from 32,176 m³ yr⁻¹ (8.5 million gal yr⁻¹) in 1985 to 8.328 million m³ (2.25 billion gal yr⁻¹) in 2012. Although the total area of irrigated land has increased in the past five years, irrigated corn has fluctuated around 20.242 million ha (50 million acres) since 1979 and the percentage of corn land that is irrigated has decreased. The trend in water withdrawals is less clear. Overall water withdrawals increased from 9 billion m³ in 1985 to 10.4 billion m³ in 2005 (water withdrawals peaked at 11.5 billion m³ in 1980). While some interpret the data below as fluctuating around 10 billion m³, others contend that water use did increase, reversing a previous downward trend. A confounding factor is that this period coincided with a near tripling of irrigated soy acreage for food and feed production (Nebraska has no biodiesel production). More refined data are required to assess the true impact of corn ethanol expansion. Data from USDA 2013; RFA 2012; AFDC 2012.

18.5 Minimizing Impact of Bioenergy Production

18.5.1 Selecting Appropriate Bioenergy Systems for Ecosystems

The promotion of bioenergy offers considerable opportunities for the agriculture and forestry sectors, which can find new markets for their products, diversify land use, and also make economic use of biomass flows previously considered to be waste (Chapters

11 and 13, this volume). For instance, several major wood producing countries are seeking alternative markets as the demand for pulpwood has declined. In agriculture, perennial grasses and woody plants can be grown in sensitive locations where cultivation of conventional food crops causes soil, water and other impacts (Chapters 9 and 10, this volume). Strategic placement of such plants can reduce eutrophication (Dosskey et al. 2008), and improve soil structure, which in turn increases water infiltration, permeability, and water-holding capacity (Table 18.1).

Perennial biomass crops (Chapter 10, this volume) can also make better use of rain falling outside the growing season for conventional food/feed crops, and some plants can use water not suitable for conventional crop production, such as saline water and pre-treated municipal wastewater. Hardy and drought tolerant plants with traits suitable as bioenergy feedstock are considered for cultivation in areas where conventional food and feed crops are difficult to cultivate. While over-optimistic expectations about “wonder crops” have caused a number of projects to fail, there is still scope for optimizing the use of land with varying suitability based on cultivating a wider set of plants. Successful implementation requires both investments in the development of suitable plant varieties and implementation of BMPs in forestry and agriculture (Chapter 10, this volume). Development of integrated systems for optimal use of soil and water resources requires consideration of local/regional socio-technical structures as well as ecosystem properties.

18.5.2 Landscape-Level Planning and Mixed Systems

Landscape-level planning is an important tool for balancing social and economic resource use with environmental objectives including conservation of water and soil resources (Dale et al. 2011; Harper et al. 2013; Frank et al. 2014) and biodiversity (Bourke et al. 2013; Dale et al. 2010; Dwivedi et al. 2011; Foster et al. 2011). Mixed plant systems such as crop-pasture rotation or crop-pasture-forest integration are options for small farmers to combine the production of food and plants for bioenergy (Herrero et al. 2010) (Chapters 3 and 4, this volume). Mixed systems help to overcome problems of economic returns of long cycle crops, price fluctuations and allow the combination of production of food, bioenergy and plants for other purposes (Chapter 6, this volume). Management of bioenergy production systems can be adjusted to achieve substantially greater social and environmental benefits, in terms of soil impacts and greenhouse gas balance, such as through crop selection, timing of harvest, residue management practices (Dale et al. 2013; Davis et al. 2013; Herrero et al. 2010; Pereira et al. 2012; Vilela et al. 2011; Smith et al. 2013) (Chapter 5, this volume).

18.5.3 Evolution in Best Management Practices

Appropriate agronomic practices such as minimum tillage or no-till can overcome many soil effects of biomass removal by maintaining soil cover and decreasing mechanical soil disturbance (Govaerts et al. 2009). In some systems such as sugarcane, no-till can result in increased SOC, higher water storage, decreased losses of soil, water and agrochemicals,

decreased fertilizer need because of better soil conservation, and lower fuel consumption by field operations (Boddey et al. 2010; de Moraes Sá et al. 2013). No-till with mulch preservation is especially important in tropical regions. In other systems, such as no-till in continuous corn in temperate regions, some biomass removal may be necessary to provide sufficient soil warmth for germination (Gentry et al. 2013). Presently, in Brazil over 30 M ha are managed under no-till as part of a sustained effort to improve agricultural practice in the past decades (Bernoux et al. 2006; Pereira et al. 2012). While no-till is less important in perennial or semi-perennial crops than annual crops, increased SOC has been reported when soil plowing is skipped and sugarcane is planted with no-till (Bordonal et al. 2012; Galdos et al. 2010; Segnini et al. 2013). In forest systems, applying BMPs may mean setting limits on the amounts, timing, and methods of biomass extraction and nutrient management in forests (Helmisaari and Kaarakka 2013; Lamers et al. 2013). For instance, extraction of branches, tops and stumps needs to be adapted to local soil and watershed conditions to limit impacts. In all systems, optimized nutrient management is essential to long-term sustainable soil health. Of course, BMPs must be tailored to the local site in the context of a landscape perspective (Figure 18.11) (see also section 18.5.2.1).

18.5.4 Using Wastes in Bioenergy Systems to Improve Water and Soil Quality, Close the Nutrient Cycle, and Recover Energy

18.5.4.1 Fertirrigation

Fertirrigation using wastewater (Chapters 12 and 14, this volume) can provide soil moisture and nutrients for biomass growth, while simultaneously providing a solution to wastewater disposal. One example of such practice is the use of vinasse (Figure 18.12), a by-product of ethanol fermentation, with a high biological oxygen demand ($175,000 \text{ mg L}^{-1}$), containing around $3\text{--}6 \text{ g L}^{-1}$ of organic carbon and 2 g L^{-1} potassium as well as other nutrients (Mutton et al. 2010). About 10 to 13 L of vinasse are produced for each L of ethanol, around 300 billion L yr^{-1} from sugarcane in Brazil alone. If vinasse accidentally reaches water bodies, it can be a pollutant, creating algal blooms and anoxic zones (Martinelli et al. 2013). Similarly, if applied in excessive amounts to agricultural soils it can increase salinity and cause nutrient leaching, with potential to affect ground water quality (Magalhães et al. 2012). However, vinasse can also act as a fertilizer, recycling potassium and other nutrients, and adding organic matter to the soil. In Brazil, practically all vinasse is returned to the fields, reducing the need of synthetic fertilizers in sugarcane (Cantarella and Rossetto 2012). Current legislation in São Paulo State regulates the disposition of vinasse to the soil in order to avoid soil salinization and nutrient overload (Magalhães et al. 2012) (See also chapter 5, this volume). Direct discharges of vinasse to water bodies are not allowed in Brazil (Magalhães et al. 2012), although accidental discharges have occurred and can affect water quality in areas where sugar mills are located (Martinelli et al. 2013).

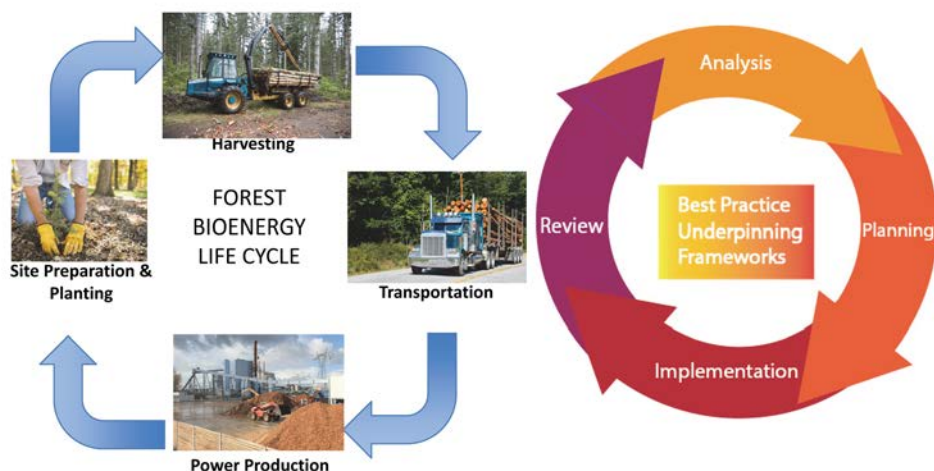


Figure 18.11. The use of BMPs enables forest feedstock production for bioenergy programs as a sustainable part of land management and renewable energy production. The development and application of BMPs to the life cycle of bioenergy is not a static process, but one that relies on a continual cycle of analysis, planning, implementation and monitoring, and review (Neary and Koestner 2012). Although some countries have “national standards”, the complex matrix of forest ecosystems, climates, soils and topography, crop establishment and tending systems, and harvesting systems requires on-going assessment, monitoring, and refinement to craft BMPs to best suit local conditions. The use of BMPs is widespread in developed countries and it varies from mandatory to voluntary (Neary et al. 2011). For example, in many countries, BMPs are already incorporated in “Codes of Forest Practice” that guide forest managers through the complete bioenergy life cycle. BMPs have been developed and implemented in many agricultural countries to deal with water quality problems. Research and development studies play a key part in the refinement and communication of improved BMPs and are also crucial in validating the effectiveness of BMPs. This is especially important where local environmental conditions or operational standards are unique.

The recycling of vinasse and other industrial residues is generally managed using appropriate pipelines, channels and roads that cross several fields, an infrastructure investment that is facilitated by the vertically integrated structure of the sugar/ethanol industry in Brazil. Depending on the feedstock-industrial structure of specific ethanol industries in different countries, the recycling of vinasse may be more difficult or costly. Alternative options include anaerobic digestion to yield methane, concentrating vinasse to facilitate long-distance transport for disposal, and reduction in vinasse production. For instance, in Brazil it was demonstrated that by increasing the alcohol content of the sugarcane extract during the fermentation process, the volume of vinasse could be decreased by 50% (Martinelli et al. 2013). Biomethane production and vinasse concentration are not currently common in the sugarcane industry.

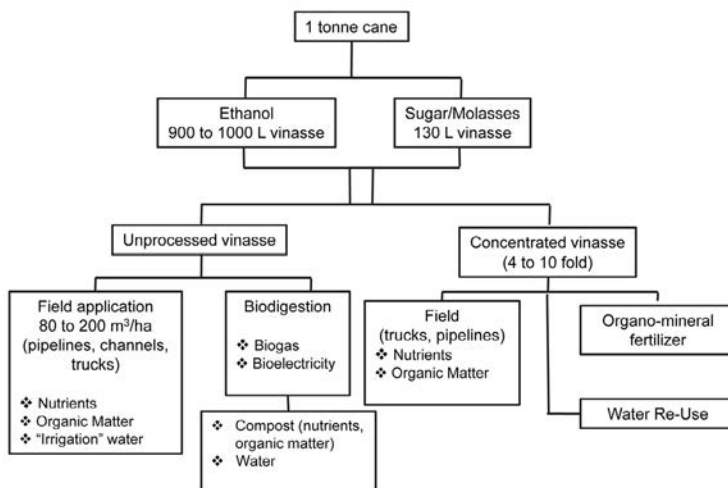


Figure 18.12. Possible modes of nutrient recovery from vinasse in Brazil.

Presently, most ethanol stillage, or vinasse, in Brazil is applied to the fields as produced, i.e., without concentration. Usual rates vary from 80 to 200 m³ ha⁻¹. In addition to the nutrients, such vinasse load represents 8 to 20 mm of water added, an irrigation input usually applied in the dry months. The disposition of vinasse to the soil is regulated to protect surface waters from eutrophication. Stillage represents an opportunity for biomethane generation as well.

18.5.4.2 Municipal Solid Waste and Wastewater Digestion (Biogas)

Municipal wastes have the potential to generate sizeable amounts of bioenergy (Kalogo et al. 2007; Shi et al. 2009) and, at the same time, reduce landfill and its associated negative impacts. Anaerobic digestion (AD) of organic components in municipal solid waste (e.g. food waste, yard trimmings), manures, residues from food, feed, and biofuel processing, and wastewater can generate biomethane. This process reduces waste volume, controls GHG emissions, and provides a means to remove unwanted contaminants and recycle nutrients (Chapters 12, this volume). AD is one of the few technologies that can effectively handle wet biomass and is adaptable from small scale to large scale (Chapters 12 and 14, this volume). Recovery of nutrients through the process is variable. Phosphorous and potassium can be recovered at rates ranging from 76-99% (Yilmazel and Demirel 2011). Removal of phosphate as struvite (MgNH₄PO₄•6H₂O) facilitates simultaneous recovery of soluble nitrogen and magnesium. Nitrogen recovery is variable but innovative ion exchange and membrane technologies could allow substantial (>90%) recovery (Mehta et al. 2014). Because nutrients are in organic form, which can be accessed by plants slowly over time, soils treated with digester residues tend to have less nutrient leaching while promoting plant growth (Walsh et al. 2012).

18.5.4.3 Ash and Biochar

Thermochemical conversions of biomass produce chars and ash, which contain mineral nutrients and variable amounts of carbon (Chapter 12, this volume). Depending on the biomass source, ash from combustion and gasification may contain unacceptable levels of alkali and heavy metals, which can present leaching hazards and affect soil pH (Vassilev et al. 2013). However, recycling of mineral nutrients from ash has been successful in many forest applications (Omil et al. 2011), and in sugarcane (Magalhães et al. 2012). Biochar is the solid charcoal-like product of pyrolysis that is used as a soil amendment. Many biomass materials can be pyrolyzed, including wood waste, manures, and crop residues. The properties of biochar vary widely depending on the feedstock and pyrolysis conditions. Biochar is highly recalcitrant, stabilizing carbon for decades to centuries (Singh et al. 2012). Furthermore, biochars may substantially reduce nitrous oxide (N_2O) emissions from soil (Singh et al. 2010). However, the magnitude and longevity of these effects are likely to be context-specific (Jones et al. 2012). Biochar benefits to soil properties can include reduced acidity (McCormack et al. 2013), increased nutrient retention, increased water holding capacity (Karhu et al. 2011), and stimulation of beneficial microbes (Lehmann et al. 2011). The chemical, biological and physical interactions between biochars, soil minerals and organic matter are the subject of on-going investigation. Combining pyrolysis with other bioenergy technologies may offer advantages. For example, pyrolyzing the digestate from anaerobic digestion could yield bioenergy products (from bio-oil and/or pyrolysis gas), while producing biochar as a soil amendment that enhances soil fertility, thus increasing biomass production for other bioenergy applications.

18.6 Policy and Governance

Worldwide, there is progress toward consensus on goals for sustainable use of soil and water resources, although differences in governance approaches and concerns for sovereign control of resources continue to interfere with progress at the regulatory level. The move beyond political boundaries to basin-level collaborative governance that is taking place in many regions of the world including the US, EU, China and Brazil is encouraging. There is an absolute requirement for clear and transparent goals and leadership for such activities to be successful (Steinzor and Jones 2013; Gupta et al. 2013). The inclusion of water and soil metrics in voluntary sustainability certification schemes (See Chapter 15, this volume) is a useful step toward mainstream implementation of sustainable water and soil stewardship (Gheewala et al. 2011). However, large deficiencies in governance remain (Chapters 19 and 20, this volume). The most glaring of these is continued weak governance of water withdrawals in stressed regions, insufficient prioritization of water use rights (i.e. antiquated rights provisions), and insufficient water pricing in cash-rich nations (Rogers et al. 2002; Srinivasan et al. 2012). There is also a need for harmonization and integration of water and soil sustainability criteria in many regional and national policies, especially

with regards to non-point source emissions, which are typical of biomass production activities (Endres 2013; Moraes et al. 2011) (Chapter 19, this volume). While these issues and the policies they spurn are not specific to bioenergy production (Table 18.2), they will affect sustainability of bioenergy systems.

Table 18.2. Frameworks can be developed for watershed impacts of land cover change – In South Africa afforestation of 1.4 million ha of trees reduced annual runoff by 1417 million m³ (3.2%) and reduced annual low flows by 101 million m³ (7.8%) (Scott, 1998). Several policies were enacted to address the issue. The Afforestation Permit System in 1972, followed by the Forest Act of 1984 regulated the area of afforestation and required a rough calculation of effect on flow. The early regulation ignored other water users and did not consider catchment size or low flow (seasonal effects). The National Water Act of 1998 and the implementation of the Stream Flow Reduction Allocations (SFRA) Water Licensing System in 1999 integrated catchment management and established catchment agencies to examine streamflow. The areas were categorized according to three levels of activity (below). The system requires a publically available Strategic Environmental Assessment that considers biophysical, economic, social components including a soil survey, and a preliminary assessment of impacts on allocatable water and on the water resource, subject to environmental and statutory constraints. Under the system, water use licenses extend for 40 years, conditional to periodic review every 5 years.

Category	Description	Restriction
I	Biggest demand with other purposes with higher priority	No more new afforestation
II	Sporadic water shortages with existing priority rights to be protected	New afforestation limited to levels where Mean Annual Runoff (MAR) would not be reduced more than 5% of pre-1972 levels
III	Remainder of catchments	New afforestation limited to where MAR would not be reduced by more than 10% of pre-1972 levels

18.7 Conclusions

Water and soil are inextricably linked. Assessment of positive and negative effects of bioenergy production on soils and water should be part of an integrated analysis considering environmental, social, and economic dimensions. Metrics, such as water footprints, have little informative value unless combined with information about resource availability and competing use at relevant spatial and temporal scales. Soil and water effects depend largely on whether bioenergy implementation induces changes in management of land, water and other resources, and on how the previous management has influenced the state of soil and water.

Forest bioenergy systems following BMPs are judged compatible with maintaining soil quality and high-quality water supplies in forested catchments. Excessive removal of plant material from the field or forest may jeopardize soil and water quality. Extended or intensified

cultivation of conventional annual crops as bioenergy feedstock will cause the same impacts as when these crops are cultivated for food. The cultivation of perennial grasses and woody plants commonly causes less impacts. These production systems can – through well-chosen siting, design, management, and system integration – help mitigate soil and water problems associated with current or past land use and improve soil and water use efficiency.

Advances in water recovery and recycling reduce water requirements for conversion processes as well as effluent production. Feedstock production and conversion stages can, in some cases, be integrated to use resources more effectively and support good land and water management. Examples include the recirculation of sludge to willow plantations, vinasse application to sugarcane fields, and possibly, the use of biochar as a soil amendment.

Water withdrawals (both quantity and timing) should be carefully considered in context of watershed needs, vulnerability, and resilience. Water scarcity may limit bioenergy potentials in some regions, but suitable bioenergy cropping systems can take advantage of currently unused water resources such as saline water, pre-treated wastewater, and rain falling outside the growing season for conventional food/feed crops.

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

18.8 Recommendations

- The effects of bioenergy systems on water and soil resources must be assessed as part of a comprehensive analysis considering environmental, social, and economic dimensions. Metrics such as footprints and water- and nutrient-use efficiencies are insufficient and can be misleading and irrelevant if used as the sole basis for decisions and policy development to promote sustainable production and environmental security at relevant spatial and temporal scales.
- Bioenergy systems that offer good opportunities to address soil and water problems should be promoted where their establishment does not cause other negative impacts that outweigh these benefits. Examples of such systems include energy and nutrient recovery from waste materials and the strategic integration of suitable feedstock cultivation systems into agriculture landscapes to address soil and water problems. Payments for such additional environmental services might be needed since system costs are sometimes higher than for conventional bioenergy systems.
- Matching bioenergy feedstocks, management practices, and conversion technologies to local conditions and constraints is possible and essential. The use of irrigation for bioenergy must be subject to a high level of scrutiny. Caution,

periodic evaluation, and appropriate water pricing and allocation systems can help avoid unwanted effects in water-stressed regions.

- Crop and forest intensification, enabled by active management and the use of inputs such as fertilizers and irrigation, can spare land and enable more efficient resource allocation. However, possible negative impacts on water availability and water and soil quality should be assessed and minimized. In most cases, bioenergy solutions can be found that contribute to energy and climate security and which are compatible with local and regional constraints.
- As in other agricultural and silvicultural activities, the adoption of BMPs is important in crop intensification because it tends to minimize risks of excessive input use.

18.9 The Much Needed Science

1. Site-specific and regional data are needed to guide practices regarding use of residual biomass from current agricultural and forest systems to understand where there may be risks associated with excessive removal of plant material from the field or forest which can jeopardize soil and water quality, causing economic and environmental losses.
2. Breeding and selection of plants should favor those species and genotypes tolerant to poor conditions including drought, waterlogging, salt accumulation, etc., in addition to those with high WUE and NUE.
3. Long-term research is needed on soil nutrient and carbon cycles under perennial crop and forest systems, and concerning land use change effects on water and soils.
4. Improved methods should be developed to leverage remote sensing capabilities for monitoring land use and soil and water status.
5. Continued innovation in use of waste materials and in water and nutrient reuse and recycling in bioenergy systems is needed to fulfill the potential contribution of biomass to sustainable energy production.
6. Long-term studies on use of ash and biochar as fertilizers and soil amendments should be supported.
7. In addition to research and data collection, assessment frameworks, including relevant indicators and dissemination tools are required to support the development of strategies for integrating bioenergy systems into existing agriculture and forestry practices. Such strategy development needs broad stakeholder involvement in order to capture synergies and strike a balance between social, economic and environmental objectives. The development and use of relevant indicators is one critical part of this work.

Literature Cited

- AFDC (Alternative Fuels Data Center) (2012) <http://www.afdc.energy.gov/> Accessed December 2012.
- Anderies, J. M. (2005). Minimal models and agroecological policy at the regional scale: An application to salinity problems in Southeastern Australia. *Regional Environmental Change* 5:1, 1–17.
- Anderson-Teixeira, K. J., Masters, M. D., Black, C. K., Zeri, M., Hussain, M. Z., Bernacchi, C. J., and DeLucia, E. H. (2013) Altered belowground carbon cycling following land-use change to perennial bioenergy crops. *Ecosystems* Published online January 5 2013.
- AQUASTAT (2012) UN Food and Agriculture Association Water Statistics http://www.fao.org/nr/water/aquastat/water_use/index.stm - accessed September 2014
- Bakar, R. A., Darus, S. Z., Kulaseharan, S. and Jamaluddin, N. (2011) Effects of ten year application of empty fruit bunches in an oil palm plantation on soil chemical properties. *Nutrient Cycling in Agroecosystems* 89, 341-349.
- Baldock, J. and Nicoll, R. (2008) Soil carbon: the basics. <http://www.csiro.au/Outcomes/Environment/Australian-Landscapes/soil-carbon.aspx> Updated 2011.
- Baligar, V. C., Fageria, N. K. and He, Z. L. (2001) Nutrient use efficiency in plants. *Communications in Soil Science and Plant Analysis* 32:7-8, 921-950 .
- Bartle, J., Olsen, G., Cooper, D. and Hobbs, T. (2007) Scale of biomass production from new woody crops for salinity control in dryland agriculture in Australia. *International Journal of Global Energy Issues* 27, 115-137.
- Berch, S. M., Curran, M., Dymond, C., Hannam, K., Murray, M., Tedder, S., Titus, B. and Todd, M. (2012). Criteria and guidance considerations for sustainable tree stump harvesting in British Columbia. *Scandinavian Journal of Forest Research* 27(8), 709-723.
- Beringer, T. I. M., Lucht, W. and Schaphoff, S. (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Global Change Biology Bioenergy* 3, 299-312.
- Berndes, G. (2002) Bioenergy and water—the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change* 12, 253-271.
- Berndes, G., Fredrikson, F. and Börjesson, P. (2004) Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden. *Agriculture, Ecosystems & Environment* 103, 207-223.
- Berndes, G. (2008) Water demand for global bioenergy production: trends, risks and opportunities. *Commissioned Expert Study* (Berlin: German Advisory Council on Global Change), 1-46.
- Bernoux, M., Cerri, C. C., Cerri, C. E. P., Neto, M. S., Metay, A., Perrin, A. S., Scopel, E., Razafimbelo, T., Blavet, D., Piccolo, M. D., Pavei, M. and Miine, E. (2006) Cropping systems, carbon sequestration and erosion in Brazil, a review. *Agronomy for Sustainable Development* 26, 1-8.
- Bhardwaj, A. K., Zenone, T., Jasrotia, P., Robertson, G. P., Chen, J., & Hamilton, S. K. (2010) Water and energy footprints of bioenergy crop production on marginal lands. *Global Change Biology Bioenergy*, 3(3), 208–222. doi:10.1111/j.1757-1707.2010.01074.x.
- Blanco-Canqui, H. and Lal, R. (2009) Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Science* 28, 139-163.
- Boddey, R. M., Jantalia, C. P., Conceição, P. C., Zanatta, J. A., Bayer, C., Mielniczuk, J., Dieckow, H. S., Aita, C., Giacomini, S. J., Alves, B. J. R. and Urquiaga, S. (2010) Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture. *Global Change Biology* 16, 784-795.

- Bordonal, R. O., Figueiredo, E. B. and La Scala Jr., N. (2012) Greenhouse gas balance due to the conversion of sugarcane areas from burned to green harvest, considering other conservationist management practices. *Global Change Biology Bioenergy* 4, 846-858. 10.1111/j.1757-1707.2012.01193.x (online first).
- Börjesson, P. and Berndes, G. (2006) The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy* 30, 428-438.
- Bourke, D., Stanley, D., O'Rourke, E., Thompson, R., Carnus, T., Dauber, J., Emmerson, M., Whelan, P., Hecq, F., Flynn, E., Dolan, L. and Stout, J. (2013) Response of farmland biodiversity to the introduction of bioenergy crops: effects of local factors and surrounding landscape context. *Global Change Biology Bioenergy* 6, 275-289. doi: 10.1111/gcbb.12089.
- Cabral, O. M. R., Rocha, H. R., Gash, J. H., Ligo, M. a. V., Tatsch, J. D., Freitas, H. C. and Brasílio, E. (2012) Water use in a sugarcane plantation. *Global Change Biology Bioenergy* 4, 555-565.
- Cadoux, S., Riche, A. B., Yates, N. E. and Machet, J.-M. (2012) Nutrient requirements of *Miscanthus x giganteus*: Conclusions from a review of published studies. *Biomass and Bioenergy* 38, 14-22.
- Cantarella, H. and Rossetto, R. (2012) Fertilizer concerns. In "Sustainability of Sugarcane Bioenergy" (M. K. Poppe and L. A. B. Cortez, eds.), pp. 71-94. CGEE - Center for Strategic Studies and Management, Brasília.
- Cantarella, H., Cerri, C. E. P., Carvalho, J. L. N. and Magalhaes, P. S. G. (2013) Editorial: How much sugarcane trash should be left on the soil. *Scientia Agricola* 70, 1-2.
- Carvalho, J. L. N., Otto, R., Franco, H. C. J. and Trivelin, P. C. O. (2013) Input of sugarcane post-harvest residues into the soil. *Scientia Agricola* 70, 336-344.
- Chiu, Y.W. and Wu, M. (2012) Assessing county-level water footprints of different cellulosic-biofuel feedstock pathways. *Environmental Science and Technology* 46, 9155-9162. doi:10.1021/es3002162.
- Cleary, M. R., Arhipova, N., Morrison, D. J., Thomsen, I. M., Sturrock, R. N., Vasaitis, R., Gaitnieks, T. and Stenlid, J. (2013) Stump removal to control root disease in Canada and Scandinavia: A synthesis of results from long-term trials. *Forest Ecology and Management* 290, 5-14.
- Cowie, A. L., Smith, P. and Johnson, D. (2006) Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? *Mitigation and Adaptation Strategies for Global Change* 11, 979-1002.
- Dale, V. H., Kline, K. L., Wiens, J., Fargione, J. (2010) Biofuels: Implications for land use and biodiversity. *Biofuels and Sustainability Reports* (Washington, DC: Ecological Society of America), 1-13.
- Dale, V. H., Kline, K. L., Wright, L. L., Perlack, R. D., Downing, M., and Graham, R. L. (2011) Interactions among bioenergy feedstock choices, landscape dynamics and land use. *Ecological Applications* 21, 1039-1054.
- Dale, V. H., Efroymsen, R. A., Kline, K. L., Langholtz, M. H., Leiby, P. N., Oladosu, G. A., Davis, M. R., Downing, M. E., Hilliard, M.R. (2013) Indicators for assessing socioeconomic sustainability of bioenergy systems: A short list of practical measures. *Ecological Indicators* 26, 87-102.
- da Silva, V. P. R., da Silva, B. B., Albuquerque, W. G., Borges, C. J. R., de Sousa, I. F. and Dantas Neto, J. (2013) Crop coefficient, water requirements, yield and water use efficiency of sugarcane growth in Brazil. *Agricultural Water Management*, 128, 102-109.
- Davis, S., Boddey, R. M., Alves, B. J. R., Cowie, A. L., George, G. H., Ogle, S. M., Smith, P., van Noordwijk, M. and van Wijk, M. T. (2013) Management swing potential for bioenergy crops. *Global Change Biology Bioenergy* 5, 623-638.
- de Fraiture, C., Giordano, M. and Liao, Y. (2008) Biofuels and implications for agricultural water use: blue impacts of green energy. *Water Policy* 10, 67-81. doi:10.2166/wp.2008.054.

- de Fraiture, C. and Berndes, G. (2009) Biofuels and water. In R.W. Howarth and S. Bringezu (eds.) *Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment*, 22-25 September 2008, Gumpersbach Germany. 139-153. Cornell University, Ithaca NY, USA. (<http://cip.cornell.edu/biofuels/>)
- de Jong, J., Akseleson, C., Berglund, H., Egnell, G., Gerhardt, K., Lönnberg, L., Olsson, B., von Stedingk, H. (2014). Consequences of an increased extraction of forest biofuel in Sweden - a synthesis from the biofuel research programme 2007-2011. *Summary of synthesis report. IEA Bioenergy Task 43 report 2014:01*.
- de Moraes Sá, J. C., Bürkner dos Santos, J., Lal, R., de Moraes, A., Tivet, F., Machado Sá, M. F., Briedis, C., de Oliveira Ferreira, A., Eurich, G., Farias, A. and Friedrich, T. (2013) Soil-specific inventories of landscape carbon and nitrogen stocks under no-till and native vegetation to estimate carbon offset in a subtropical ecosystem. *Soil Science Society of America Journal* 77, 2094-2110 doi:10.2136/sssaj2013.01.00.
- Dimitriou, I., Baum, C., Baum, S., Busch, G., Schulz, U. Köhn, J., Lamersdorf, N., Leinweber, P., Aronsson, P., Weih, M., Berndes, G. and Bolte, A. (2011) Quantifying environmental effects of short rotation coppice (SRC) on biodiversity, soil and water. *IEA Bioenergy Task 43 Report 2011:01*, 34pp.
- Dominguez-Faus, R., Powers, S. E., Burken, J. G. and Alvarez, P. J. (2009) The water footprint of biofuels: A drink or drive issue? *Environmental Science and Technology* 43, 3005-3010. doi:10.1021/es802162x.
- Donnelly, A., Styles, D., Fitzgerald, J. and Finnan, J. (2010) A proposed framework for determining the environmental impact of replacing agricultural grassland with *Miscanthus* in Ireland. *Global Change Biology Bioenergy* 3, 247-263. doi:10.1111/j.1757-1707.2010.01086.x.
- Dosskey, M. G., Helmers, M. J. and Eisenhauer (2008) A design aid for determining width of filter strips. *Journal of Soil and Water Conservation* 63, 232-241.
- Dwivedi, P., Bailis, R., Carter, D. R. and Sharma, A. (2011) A landscape-based approach for assessing spatiotemporal impacts of forest biomass-based electricity generation on the age structure of surrounding forest plantations in the Southern United States. *Global Change Biology Bioenergy* 4, 342-357. doi: 10.1111/j.1757-1707.2011.01133.x.
- Dymond, C. C., Titus, B. D., Stinson, G. and Kurz, W. A. (2010) Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *Forest Ecology and Management* 260, 181-192.
- Efroymson, R. A., Dale, V. H., Kline, K. L., McBride, A. C., Bielicki, J. M., Smith, R. L., Parish, E. S., Schweizer, P. E., Shaw, D. M. (2013) Environmental indicators of biofuel sustainability: What about context? *Environmental Management* 51, 291-306.
- Eglin, T., Ciais, P., Piao, S. L., Barre, P., Bellassen, V., Cadule, P., Chenu, C., Gasser, T., Koven, C., Reichstein, M. and Smith, P. (2010) Historical and future perspectives of global soil carbon response to climate and land-use changes. *Tellus B* 62, 700-718. doi: 10.1111/j.1600-0889.2010.00499.x.
- Egnell, G. (2011) Is the productivity decline in Norway spruce following whole-tree harvesting in the final felling in boreal Sweden permanent or temporary? *Forest Ecology and Management* 261, 148-153.
- EMBRAPA Satellite Monitoring. (2012) SOMABRASIL (Observation and Monitoring System of Brazilian Agriculture). <http://www.cnpem.embrapa.br/projetos/somabrazil> - accessed September 2014
- Endres, J. (2013) U.S. federal and state water laws' impact on bioenergy policy. *European Commission Joint Technical Report EUR 26160EN*, 211-224.
- English, A., Tyner, W. E., Sesmero, J., Owens, P. and Muth, D. J. (2013) Environmental tradeoffs of stover removal and erosion in Indiana. *Biofuels Bioproducts & Biorefining* 7, 78-88.

- EuroStat (2014) Development of waste treatment in the EU-27, 2004–10. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/File:Development_of_waste_treatment_in_the_EU-27,_2004%E2%80%932010_-_28million_tonnes%29_YB14.png - accessed October 2014.
- FAOStat (2010) Food and Agriculture Organization of the United Nations. Statistics Division. <http://faostat.fao.org/>
- Fernando, A. L., Duarte, M. P., Almeida, J., Boléo, S. and Mendes, B. (2010) Environmental impact assessment of energy crops cultivation in Europe. *Biofuels, Bioproducts and Biorefining* 4, 594–604. doi:10.1002/bbb.249.
- Figueiredo, E. B. and La Scala Jr., N. (2011) Greenhouse gas balance due to the conversion of sugarcane areas from burned to green harvest in Brazil. *Agriculture Ecosystems & Environment* 141, 77–85.
- Fingerman, K. R., Torn, M. S., O'Hare, M. H. and Kammen, D. M. (2010) Accounting for the water impacts of ethanol production. *Environmental Research Letters* 5, 014020. doi:10.1088/1748-9326/5/1/014020.
- Fingerman, K., Berndes, G., Orr, S., Richter, B., Vugteveen, P. (2011) Impact assessment at the bioenergy-water nexus. *Biofuels, Bioproducts and Biorefining* 5, 375–386.
- Foster, W. A., Snaddon, J. L., Turner, E. C., Fayle, T. M., Cockerill, T. D., Ellwood, M. F., Broad, G. R., Chung, A. Y. C., Eggleton, P., Khen, C. V. and Yusah, K. M. (2011) Establishing the evidence base for maintaining biodiversity and ecosystem function in the oil palm landscapes of South East Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences* 366, 3277–3291.
- Franco, H. C. J., Pimenta, M. T. B., Carvalho, J. L. N., Magalhaes, P. S. G., Rossell, C. E. V., Braunbeck, O. A., Vitti, A. C., Kolln, O. T., and Neto, J. R. (2013). Assessment of sugarcane trash for agronomic and energy purposes in Brazil. *Scientia Agricola* 70, 305–312.
- Frank, S., Fürst, C., Witt, A., Koschke, L. and Makeschin, F. (2014) Making use of the ecosystem services concept in regional planning—trade-offs from reducing water erosion. *Landscape Ecology* 29, 1–15 doi 10.1007/s10980-014-9992-3.
- Frazão, L. A., Paustian, K., Pellegrino Cerri, C. E. and Cerri, C. C. (2013) Soil carbon stocks and changes after oil palm introduction in the Brazilian Amazon. *Global Change Biology Bioenergy* 5, 384–390.
- Fthenakis, V. and Kim, H. C. (2011) Lifecycle uses of water in U.S. electricity generation. *Renewable and Sustainable Energy Reviews* 14, 2039–2048.
- Galdos, M. V., Cerri, C. C. and Cerri, C. E. P. (2009) Soil carbon stocks under burned and unburned sugarcane in Brazil. *Geoderma* 153, 347–352.
- Galdos, M. V., Cerri, C. C., Cerri, C. E.P., Paustian, K., Van Antwerpen, R. (2009) Simulation of Soil Carbon Dynamics under Sugarcane with the CENTURY Model. *Soil Science Society of America Journal* 73, 802–811.
- Galdos, M. V., Cerri, C. C., Lal, R., Bernoux, M., Feigl, B. and Cerri, C. E. P. (2010) Net greenhouse gas fluxes in Brazilian ethanol production systems. *Global Change Biology Bioenergy* 2, 37–44.
- Garg, K., Karlberg, L., Wani, S., Berndes, G. (2011) Biofuel production on wastelands in India: opportunities and trade-offs for soil and water management at the watershed scale. *Biofuels, Bioproducts and Biorefining* 5, 410–430.
- Gentry, L. F., Ruffo, M. L., & Below, F. E. (2013). Identifying factors controlling the continuous corn yield penalty. *Agronomy Journal* 105, 295–303.
- Gerbens-Leenes, W., and Hoekstra, A. Y. (2012) The water footprint of sweeteners and bio-ethanol. *Environment International* 40(C), 202–211. doi: 10.1016/J.Envint.2011.06.006.

- Gerbens-Leenes, P. W., Hoekstra, A. Y. and Meer, T. H. (2008) Water footprint of bio-energy and other primary energy carriers. *UNESCO Value of Water Research Report Series* No. 29, 1-44.
- Gerbens-Leenes, W., Hoekstra, A. and Meer, T. V. D. (2009) The water footprint of bioenergy. *Proceedings of the National Academy of Science PNAS* 106, 10219-10223.
- Gheewala, S. H., Yeh, S., Fingerman, K. R., Diaz-Chavez, R. A., Moraes, M., Fehrenbach, H., et al. (2011) *The bioenergy and water nexus*. United Nations Environment Programme (UNEP), Oeko-Institut, IEA Bioenergy Task 43, 1-40.
- Gollany, H. T., Rickman, R. W., Liang, Y., Albrecht, S. L., Machado, S., and Kang, S. (2011) Predicting agricultural management influence on long-term soil organic carbon dynamics: implications for biofuel production. *Agronomy Journal* 103, 234-246.
- Gordon, L. J., Steffen, W., Jönsson, B. F., Folke, C., Falkenmark, M. and Johannessen, A. (2005) Human modification of global water vapor flows from the land surface. *Proceedings of the National Academy of Sciences* 102, 7612-7617, doi: 10.1073/pnas.0500208102.
- Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K. D., Dixon, J., and Dendooven, L. (2009) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. *Critical Reviews in Plant Science* 28, 97-122.
- Gronowska, M., Joshi, S. and MacLeana, H. L. (2009) A review of US and Canadian biomass supply studies. *BioResources* 4, 341-369.
- Gupta, J., Pahl-Wostl, C. and Zondervan, R. (2013) 'Global' water governance: a multi-level challenge in the anthropocene. *Current Opinion in Environmental Sustainability* 5, 573-580.
- Harper, R. J., Sochacki, S. J., Smettem, K. R. and Robinson, N. (2013) Managing water in agricultural landscapes with short-rotation biomass plantations. *Global Change Biology Bioenergy*. DOI: 10.1111/gcbb.12090.
- Hassuani, S. J., Leal, M. R. L. V., and Macedo, I. C. (2005) "Biomass power generation: sugarcane bagasse and trash," 1/Ed. PNUD - Programa das Nações Unidas para o Desenvolvimento e CTC - Centro de Tecnologia Canavieira, Piracicaba.
- Helmisaari, H.S., Hanssen, K. H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A., Tamminen, P. and Tveite, B. (2011) Logging residue removal after thinning in Nordic boreal forests: long-term impact on tree growth. *Forest Ecology and Management* 261, 1919-1927.
- Helmisaari, H. S. and Kaarakka, L. (2013). Nutrient management for sustainable production of energy biomass in boreal forests. In *Forest BioEnergy Production* Springer New York. 81-94.
- Herrero, M., Thornton, P. K., Notenbaert, A. M., Wood, S., Msangi, S., Freeman, H. A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Parthasarathy Rao, P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., and Rosegrant, M. (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* 327, 822-825.
- Hickman, G. C., Vanloocke, A., Dohleman, F. G. and Bernacchi, C. J. (2010) A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. *Global Change Biology Bioenergy* 2, 157-168.
- Hoekstra, A.Y., Chapagain, A. K., Aldaya, M. M. and Mekonnen, M. M. (2011) The water footprint assessment manual: Setting the global standard, Earthscan, London, UK
- Hooper, B. P. (2003) Integrated water resources management and river basin governance. *Universities Council on Water Resources, Water Resources Update* 126, 12-20.
- Huggins, D. R., Karow, R. S., Collins, H. P. and Ransom, J. K. (2011) Introduction: evaluating long-term impacts of harvesting crop residues on soil quality. *Agronomy Journal* 103, 230-233.

- IBGE. 2012. Land use map. Brazilian Institute of Geography and Statistics. www.ibge.gov.br - accessed September 2014
- Ice, G. G. (2011) Assessing best management practices effectiveness at the watershed scale. *Applied Engineering in Agriculture* 27, 925-931.
- Jackson, R. B., Jobbagy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., le Maitre, D. C., McCarl, B. A. and Murray, B. C. (2005) Trading water for carbon with biological carbon sequestration. *Science* 310, 1944-1947.
- Jewitt, G. P. W and Kunz, R. P (2011) The impact of biofuel feedstock production on water resources: a developing country perspective. *Biofuels, Bioproducts and Biorefining* 5, 387-398
- Jones, D. L., Rousk, J., Edwards-Jones, G., DeLuca, T. H. and Murphy, D. V. (2012) Biochar-mediated changes in soil quality and plant growth in a three year field trial. *Soil Biology and Biochemistry* 45, 113-124.
- Kaenchan, P. and Gheewala, S. H. (2013) A review of the water footprint of biofuel crop production in Thailand. *Journal of Sustainable Energy & Environment* 4, 45-52.
- Kalogo, Y., Habibi, S., Maclean, H. L. and Joshi, S. V. (2007) Environmental implications of municipal solid waste-derived ethanol. *Environmental Science & Technology* 41, 35-41.
- Khanal, S., Anex, R. P., Anderson, C. J., Herzmann, D.E. and Jha, M. K. (2013) Implications of biofuel policy-driven land cover change for rainfall erosivity and soil erosion in the United States. *Global Change Biology Bioenergy* 5, 713-722.
- Karhu, K., Mattila, T., Bergström, I. and Regina, K. (2011) Biochar addition to agricultural soil increased CH₄ uptake and water holding capacity—Results from a short-term pilot field study. *Agriculture, Ecosystems & Environment* 140, 309-313.
- Karlen, D. L., Varvel, G. E., Johnson, J. M. F., Baker, J. M., Osborne, S. L., Novak, J. M., Adler, P. R., Roth, G. W., and Birrell, S. J. (2011) Monitoring soil quality to assess the sustainability of harvesting corn stover. *Agronomy Journal* 103, 288-295.
- King, J. S., Ceulemans, R., Albaugh, J. M., Dillen, S. Y., Domec, J. C., Fichot, R., Fischer, M., Legget, Z., Sucre, E., Trnka, M., Zenone, T. (2013) The challenge of lignocellulosic bioenergy in a water-limited world. *BioScience* 63, 102-117.
- Lal, R. (2008) Carbon sequestration. *Philosophical Transactions of the Royal Society B-Biological Sciences* 363, 815-830.
- Lal, R. (2009a) Challenges and opportunities in soil organic matter research. *European Journal of Soil Science* 60, 158-169.
- Lal, R. (2009b) Soil quality impacts of residue removal for bioethanol production. *Soil & Tillage Research* 102, 233-241.
- Lal, R., Follett, F., Stewart, B. A. and Kimble, J. M. (2007) Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science* 172, 943-956.
- Lamers, P., Thiffault, E., Paré, D. and Junginger, M. (2013) Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. *Biomass and Bioenergy* 55, 212-226.
- Lapola, D. M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., Priess, J. (2010) Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences* 107, 3388-93.
- Leal, M. R. L. V., Da Fonseca, A. F., Herpin, U. and Melfi, A. J. (2011) Agricultural utilization of treated sewage effluent: Experience from Brazil. *Israel Journal of Plant Sciences* 59, 235-248.

- Leal, M. R. L. V., Firme, L. P., Herpin, U., Da Fonseca, A. F., Montes, C. R., Dos Santos Dias, C. T. and Melfi, A. J. (2010) Carbon and nitrogen cycling in a tropical Brazilian soil cropped with sugarcane and irrigated with wastewater. *Agricultural Water Management* 97, 271-276.
- Leal, R. M. P., Galdos, M. V., Scarpore, F. V., Seabra, J. E. A., Walter, A. and Oliveira, C. O. F. (2013) Sugarcane straw availability, quality, recovery and energy use: A literature review. *Biomass and Bioenergy* 53, 11-19.
- Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C. and Crowley, D. (2011) Biochar effects on soil biota—a review. *Soil Biology and Biochemistry* 43, 1812-1836.
- Loarie, S. R., Lobell, D. B., Asner, G. P., Mu, Q., and Field, C. B. (2011) Direct impacts on local climate of sugar- cane expansion in Brazil. *Nature Climate Change* 1, 105–109.
- Kalogo, Y., Habibi, S., Maclean, H. L. and Joshi, S.V. (2007) Environmental implications of municipal solid waste-derived ethanol. *Environmental Science & Technology* 41, 35-41.
- Maetens, W., Vanmaercke, M., Poesen, J., Jankauskas, B., Jankauskiene, G. and Ionita, I. (2012) Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: A meta-analysis of plot data. *Progress in Physical Geography* 36, 599-653.
- Magalhães, P. S. G., Nogueira, L. A. H., Cantarella, H., Rossetto, R., Franco, H. C. J., and Braunbeck, O. (2012) Agro-industrial technological paths. In Sustainability of Sugarcane Bioenergy (M. K. Poppe and L. A. B. Cortez, eds.), pp. 27-69. CGEE - Center for Strategic Studies and Management, Brasília.
- Maquere, V., Laclau, J. P., Bernoux, M., Saint-Andre, L., Goncalves, J. L. M., Cerri, C. C., Piccolo, C. and Ranger, J. (2008) Influence of land use (savanna, pasture, Eucalyptus plantations) on soil carbon and nitrogen stocks in Brazil. *European Journal of Soil Science* 59, 863-877.
- Martinelli, L. A., Filoso, S., Aranha, C. D. B., Ferraz, S. F. B., Andrade, T. M. B., Ravagnani, E. D. C. and Coletta, L. D. (2013) Water Use in Sugar and Ethanol Industry in the State of São Paulo (Southeast Brazil). *Journal of Sustainable Bioenergy Systems* 3, 135–142.
- Mateos-Naranjo, E., Andrades-Moreno, L. and Redondo-Gómez, S. (2012) Tolerance to and accumulation of arsenic in the cordgrass *Spartina densiflora* Brongn. *Bioresource Technology* 104, 187-194.
- McCormack, S. A., Ostle, N., Bardgett, R. D., Hopkins, D. W. and Vanbergen, A. J. (2013) Biochar in bioenergy cropping systems: impacts on soil faunal communities and linked ecosystem processes. *Global Change Biology Bioenergy* 5, 81-95.
- Mead, D. and Smith, C. (2012) Principles of nutrient management for sustainable forest bioenergy production. *Wiley Interdisciplinary Reviews: Energy and Environment* 1, 152-164.
- Mehta, C. M., W. O. Khunjar, V. Nguyen, S. Tait and D. J. Batstone (2014) Technologies to recover nutrients from waste streams: A critical review. in *Environmental Science and Technology* 45, 1–43.
- Mello, F. F. C., Cerri, C. E. P., Davies, C. A., Holbrook, N. M., Paustian, K., Maia, S. M. F., Galdos, M. V., Bernoux, M., and Cerri, C. C. (2014). Payback time for soil carbon and sugar-cane ethanol. *Nature Climate Change* . Published Online: 8 June 2014 | DOI: 10.1038/NCLIMATE2239, 1-5.
- MMA. (Environmental Ministry of Brazil). 2005. Mapa de cobertura vegetal dos biomas brasileiros (Brazilian biomes land cover map) PROBIO. <http://mapas.mma.gov.br/mapas/aplic/probio/datadownload.htm?/> - accessed September 2014.
- Moradi, A., Sung, B., Teh, C., Joo, G. K., Hanif, M., Husni, A. and Ishak, C. F. (2012) Evaluation of four soil conservation practices in a non-terraced oil palm plantation. *Agronomy Journal* 104, 1727-1740.
- Moraes, M. M. G. A., Ringler, C., Cai, X. (2011) Policies and instruments affecting water use for bioenergy production. *Biofuels, Bioproducts and Biorefining* 5, 431-444

- Morais, R. F., Souza, B. J., Leite, J. M., Soares, L. H. B., Alves, B. J. R., Boddey, R. M. and Urquiaga, S. (2009) Elephant grass genotypes for bioenergy production by direct biomass combustion. *Pesquisa Agropecuaria Brasileira* 44, 133-140.
- Mu, Q., Heinsch, F. A., Zhao, M. and Running, S. W. (2007) Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sensing of Environment* 111, 519-536. doi: 10.1016/j.rse.2007.04.015.
- Muth D. J, Bryden K. M, Nelson R. G. (2013) Sustainable agricultural residue removal for bioenergy: A spatially comprehensive US national assessment. *Applied Energy*, 102, 403-417.
- Mutton, M. A., Rosetto, R. and Mutton, M. J. R. (2010) Agricultural use of stillage, In: Cortez, L.A.B. (Ed.) *Sugarcane bioethanol: R&D for productivity and sustainability*. São Paulo: Blucher, p.423-440.
- Nafziger, E. D., and Dunker, R. E. (2011). Soil organic carbon trends over 100 years in the Morrow Plots. *Agronomy Journal* 103, 261-267.
- Neary, D. G., Bush, P. B., and Michael, J. L. (1993) Fate of pesticides in southern forests: A review of a decade of progress. *Environmental Toxicology and Chemistry* 12,411-428.
- Neary, D. G. (2002) Chapter 6: Environmental sustainability of forest energy production, 6.3 Hydrologic values. Pp. 36-67. In: Richardson, J.; Smith, T.; Hakkila, P. *Bioenergy from Sustainable Forestry: Guiding Principles and Practices*. Elsevier, Amsterdam. 344 p.
- Neary, D. G., Ice, G. G., and Jackson, C. R. (2009) Linkages between forest soils and water quantity and quality. *Forest Ecology and Management*. 258, 2269-2281.
- Neary, D. G., Smethurst, P. J., Baillie, B. and Petrone, K. C. (2011) Water quality, biodiversity, and codes of practice in relation to harvesting forest plantations in Streamside Management Zones. *CSIRO Special Report* (Canberra: The Commonwealth Scientific and Industrial Research Organisation). 99 p.
- Neary, D. G. and Koestner, K. A. (2012) Forest bioenergy feedstock harvesting effects on water supply. *Wiley Interdisciplinary Reviews: Energy and Environment* 1, 270-284.
- Neary, D. G. (2013) Best Management Practices in forest bioenergy for protecting water quality. *WIREs Energy Environ*. 2013. Doi:10.1002/wene77 *Wiley Interdisciplinary Reviews in Energy and Environment*.
- Omil, B. Sanchez-Rodriguez, F. and Merino, A. (2011) Effects of ash applications on soil status, nutrition, and growth of *Pinus radiata* D. Don plantations. In *Recycling of Biomass Ashes*. Insam, H. and Knapp, B. (eds.) Springer Berlin Heidelberg. 69-86.
- Page, S. E., Morrison, R., Malins, C., Hooijer, A., Rieley, J. O. and Jauhiainen, J. (2011) Review of peat surface greenhouse gas emissions from oil palm plantations in Southeast Asia. *International Committee on Clean Transportation (ICCT) Indirect Effects of Biofuel Production Series*. White Paper No. 15, 1-80.
- Pannell, D. J., Ewing, M. A. and Ridley, A. M. (2004) Dryland salinity in Australia: Overview and prospects. In *Dryland Salinity: Economic Issues at Farm, Catchment and Policy Levels*. Grahnan, T. W., Pannell, D. J. and White, B. (eds.) Co-operative Centre for Plant-Based Management of Dryland Salinity, University of Western Australia. 3-18.
- Parish, E. S., Hilliard, M., Baskaran, L. M., Dale, V. H, Griffiths, N. A., Mulholland, P. J., Sorokine, A., Thomas, N. A., Downing, M. E., Middleton, R. (2012) Multimetric spatial optimization of switchgrass plantings across a watershed. *Biofuels, Bioproducts and Biorefining* 6, 58-72.
- Pereira, P. A. A., Martha Jr., G. B., Santana, C. A. M. and Alves, E. (2012) The development of Brazilian agriculture: future technological challenges and opportunities. *Agriculture and Food Security* 1, 1-12.
- Perrin, A. S., Fujisaki, K., Petitjean, C., Sarrazin, M., Godet, M., Garric, B., Horth, J. C., Balbino, L. C., Silveira, A., Machado, P., and Brossard, M. (2014). Conversion of forest to agriculture in Amazonia with the chop-and-mulch method: Does it improve the soil carbon stock? *Agriculture Ecosystems & Environment* 184, 101-114.

- Persson, T. (Ed.) (2013) Environmental effects of tree-stump harvesting. *Forest Ecology and Management* 290, 1-94.
- Pittman, J. K., Dean, A. P. and Osundeko, O. (2011) The potential of sustainable algal biofuel production using wastewater resources. *Bioresource Technology* 102, 17-25.
- Popp, A., Dietrich, J. P., Lotze-Campen, H., Klein, D., Bauer, N., Krause, M., Beringer, T., Gerten, D. and Edenhofer, O. (2011). The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environmental Research Letters* 6, 34-44.
- RFA (US Renewable Fuels Association) (2012) Industry Statistics <http://www.ethanolrfa.org/pages/statistics> - accessed September 2014
- Rio Carrillo, A. M. and Frei, C. (2009) Water: A key resource in energy production. *Energy Policy* 37, 4303-4312.
- Robertson, F. A. and Thorburn, P. J. (2007) Management of sugarcane harvest residues: consequences for soil carbon and nitrogen. *Australian Journal of Soil Research* 45, 13-23.
- Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engwall, M. (1999) Linkages among water vapor flows, food production, and terrestrial ecosystem services. *Conservation Ecology* 3, 5.
- Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z. (2010) Managing water in rainfed agriculture—The need for a paradigm shift. *Agricultural Water Management* 97(4), 543-550.
- Rogers, P., Silva, R. D. and Bhatia, R. (2002) Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. *Water Policy* 4, 1-17.
- Saarinén, V. M. (2006) The effects of slash and stump removal on productivity and quality of forest regeneration operations—preliminary results. *Biomass and Bioenergy* 30, 349-356.
- Saarsalmi, A., Smolander, A., Kukkola, M., Moilanen, M., and Saramäki, J. (2012) 30-Year effects of wood ash and nitrogen fertilization on soil chemical properties, soil microbial processes and stand growth in a Scots pine stand. *Forest Ecology and Management* 278, 63-70.
- Schornagel, J., Niele, F., Worrell, E. and Böggemann, M. (2012) Water accounting for (agro)industrial operations and its application to energy pathways. *Resources Conservation and Recycling* 61, 1-15. doi:10.1016/j.resconrec.2011.12.011.
- Scott, D. F. (1998) Forestry and Water Resources: Correct Figures. *South African Forestry Journal* 181, 51-52.
- Scown, C., Horvath, A. and McKone, T. (2011) Water footprint of US transportation fuels. *Environmental Science and Technology* 45, 2541-2553
- Segnini, A., Carvalho, J. L. N., Bolonhezi, D., Milori, D. B. P., Silva, W. T. L., Simões, M. L., Cantarella, H., de Maria, I. C. and Martin-Neto, L. (2013) Carbon stock and humification index of organic matter affected by sugarcane straw and soil management. *Scientia Agricola* 70, 321-326.
- Shepard, J. P. (2006) Water quality protection in bioenergy production: the US system of forestry Best Management Practices. *Biomass and Bioenergy* 30, 378-384.
- Shi, A. Z., Koh, L. P. and Tan, H. T. W. (2009) The biofuel potential of municipal solid waste. *Global Change Biology Bioenergy* 1, 317-320.
- Singh B. P., Cowie A. L. and Smernik R. J. (2012) Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environmental Science & Technology* 46, 11770-8
- Singh, B. P., Hatton, B. J., Singh, B., Cowie, A. L. and Kathuria, A. (2010) Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *Journal of Environmental Quality* 39, 1224-1235.

- Smith, C. M., David, M. B., Mitchell, C. A., Masters, M. D., Anderson-Teixeira, K. J., Bernacchi, C. J. and DeLucia, E. H. (2013) Reduced nitrogen losses after conversion of row crop agriculture to perennial biofuel crops. *Journal of Environmental Quality* 42, 219-228.
- Snyder, C. S., Bruulsema, T. W., Jensen, T. L. and Fixen, P. E. (2009) Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture Ecosystems & Environment* 133, 247-266.
- Srinivasan, V., Lambin, E. F., Gorelick, S. M., Thompson, B. H. and Rozelle, S. (2012) The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. *Water Resources Research*, 48(10), W10516. doi:10.1029/2011WR011087.
- Steinzor, R. and Jones, S. (2013) Collaborating to nowhere: The imperative of government accountability for restoring the Chesapeake Bay. *Journal of Energy & Environmental Law* Winter, 51-67.
- Sterling, S. M., Ducharme, A. and Polcher, J. (2013) The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change* 3, 385-390, doi:10.1038/nclimate1690.
- Sutton, M. A., Bleeker, A., Howard, C. M., Bekunda, M., Grizzetti, B., de Vries, W., van Grinsven, H. J. M., Abrol, Y. P., Adhya, T. K., Billen, G., Davidson, E. A., Datta, A., Diaz, R., Erisman, J. W., Liu, X. J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R. W., Sims, T., Westhoek, H. and Zhang, F. S. (2012) Our Nutrient World: The challenge to produce more food and energy with less pollution. *Global Overview of Nutrient Management*. Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative. 128pp.
- Tarkalson, D. D., Brown, B., Kok, H. and Bjorneberg, D. L. (2011) Small grain residue management effects on soil organic carbon: a literature review. *Agronomy Journal* 103, 247-252.
- Trivelin, P. C. O., Franco, H. C. J., Otto, R., Ferreira, D. A., Vitti, A. C., Fortes, C., Faroni, C. E., Oliveira, E. C. A. and Cantarella, H. (2013) Impact of sugarcane trash on fertilizer requirements for São Paulo, Brazil. *Scientia Agrícola* 70, 345-352.
- Tyndall, J. C., Berg, E. J. and Colletti, J. P. (2011) Corn stover as a biofuel feedstock in Iowa's bioeconomy: an Iowa farmer survey. *Biomass and Bioenergy* 35, 1485-1495.
- USDA 2013. National Agricultural Statistics. QuickState 2.0 http://www.nass.usda.gov/Quick_Stats/index.php - accessed September 2014
- US National Research Council. (2008) Water implications of biofuels production in the United States. Report 12039, 1-87.
- VanLoocke, A., Bernacchi, C. J. and Twine, T. E. (2010) The impacts of *Miscanthus×giganteus* production on the Midwest US hydrologic cycle. *Global Change Biology Bioenergy* 2, 180-191. doi: 10.1111/j.1757-1707.2010.01053.x
- Vassilev, S. V., Baxter, D., Andersen, L. K. and Vassileva, C. G. (2013) An overview of the composition and application of biomass ash.: Part 2. Potential utilisation, technological and ecological advantages and challenges. *Fuel* 105, 19-39.
- Vilela, L., Martha Jr., G. B., Macedo, M. C. M., Marchão, R. L., Guimarães Jr., R., Pulrolnik, K. and Maciel, G. A. (2011) Sistemas de integração lavoura-pecuária na região do Cerrado (Integrate crop-livestock systems in the Cerrado region). *Pesquisa Agropecuária Brasileira* 46, 1127-1138.
- Walmsley, J. D. and Godbold, D. L. (2010) Stump harvesting for bioenergy—a review of the environmental impacts. *Forestry* 83, 17-38.
- Walsh, J. J., Jones, D. L., Edwards-Jones, G. and Williams, A. P. (2012) Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost. *Journal of Plant Nutrition and Soil Science* 175(6), 840-845.

- Watanabe, M. D. B. and Ortega, E. (2014) Dynamic emergy accounting of water and carbon ecosystem services: A model to simulate the impacts of land-use change. *Ecological Modelling* 271, 113-131.
- Wicke, B., Smeets, E., Dornburg, V., Vashev, B., Gaiser, T., Turkenburg, W. and Faaij, A. (2011) The global technical and economic potential of bioenergy from salt-affected soils. *Energy & Environmental Science* 4, 2669-2681.
- Wigmosta, M. S., Coleman, A. M., Skaggs, R. J., Huesemann, M. H. and Lane, L. J. (2011) National microalgae biofuel production potential and resource demand. *Water Resources Research*, 47(3). DOI: 10.1029/2010WR009966.
- Woodbury, P. B., Smith, J. E. and Heath, L. S. (2007). Carbon Sequestration in the Us Forest Sector From 1990 to 2010. *Forest Ecology and Management* 241(1-3), 14-27.
- Wu, M., Mintz, M., Wang, M. and Arora, A. S. (2009) Water consumption in the production of ethanol and petroleum gasoline. *Environmental Management*, 44(5), 981-997.
- Yeh, S., Berndes, G., Mishra, G., Wani, S., Neto, A., Suh, S., Karlberg, L., Heinke, J., Garg, K., (2011) Evaluation of water use for bioenergy at different scales. *Biofuels, Bioproducts and Biorefining* 5, 361-374.
- Yilmazel, Y. D. and Demirer, G. N. (2011) Removal and recovery of nutrients as struvite from anaerobic digestion residues of poultry manure. *Environmental Technology* 32(7), 783-794.
- Zabowski, D., Chambreau, D., Rotramel, N. and Thies, W. G. (2008). Long-term effects of stump removal to control root rot on forest soil bulk density, soil carbon and nitrogen content. *Forest Ecology and Management* 255(3- 4), 720-727.
- Zomer, R. J., Trabucco, A., van Straaten, O. and Bossio, D. A. (2006) Carbon, Land and Water: A Global Analysis of the Hydrologic Dimensions of Climate Change Mitigation through Afforestation/ Reforestation, *IWMI Research Report 101* (Colombo: International Water Management Institute), 1-48.
- Zuazo, V. H. D. and Pleguezuelo, C. R. R. (2008) Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development* 28, 65-86.