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Water quality assessment of bioenergy production

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Abstract: Water quality is a measurement of the biological, chemical, and physical characteristics of water against certain standards set to ensure ecological and/or human health. Biomass production and conversion to fuels and electricity can impact water quality in lakes, rivers, and aquifers with consequences for aquatic ecosystem health and also human water uses. Depending on how the bioenergy system is located and managed, it can lead to both water quality deterioration and to improvements. This review focuses on the effects of bioenergy on water quality, on ways to quantify these effects, and on options for reducing negative impacts. © 2011 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction: Sources of water pollution in bioenergy production

The growing market for biofuels has raised questions in the last years regarding their sustainable production throughout the supply chain. This involves the production of the feedstock and the conversion technologies. Several mechanisms to promote a sustainable production have been implemented ranging from regulations (e.g. EU Renewable Energy Directive 209) to voluntary standards (e.g. RSPO, Bonsucro). Some of the sustainability issues considered include environmental, social, and economic measures. Nevertheless, among the environmental ones, water availability and quality have not been clearly addressed.

Water quality needs to be considered in an integrated form. According to Perry and Vanderklein[1] it needs to be account for within a wider context including hydrology, chemistry, biology, geology, land use, demographics, public attitude, and policy. The water quality may be affected by natural impacts (e.g. volcanic eruptions) and by human activities. Bioenergy production can affect water quality through physical, chemical, biological as well as thermal pollution loading. The following sections present a review of effects from forestry and agricultural practices that are part of the process chains that also include the biomass conversion various to solid, liquid, and gaseous biofuels and to electricity.

The examples presented are not exhaustive and this is also discussed in the paper demonstrating the need for more data

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specially for some feedstocks (e.g. Jatropha) and some conversion technologies.

Agricultural inputs and impacts on water quality

The water quality impacts of cultivating conventional crops as feedstock for first-generation biofuels are the same as from other farm crops. Direct impacts on water quality arise from pollution through runoff from intensive agricultural production employing fertilizers and different types of pesticides (herbicides, insecticides, fungicides) and other malpractices in agriculture, such as tillage of unsuitable soils.

Pesticides

Pesticides can have a profound effect on aquatic life and water quality. As pesticide residues are carried to ponds, rivers, and lakes by surface runoff or spray drift they can cause acute poisoning (e.g. fish kills) and also chronic poisoning (e.g. when wildlife is exposed to pesticide levels not immediately lethal). Negative effects on fish that receive repeated sub-lethal doses of pesticides include reduced fish egg production and hatching, lower resistance to disease, decreased body weight, and reduced avoidance of predators. The overall consequences can be lowered population abundance. There are also risks of secondary poisoning when predators consume prey that contain pesticides. This can be of particular concern in relation to persistent chemicals that accumulate and move in food chains. Indirect effects can also occur when habitats or food chains are modified, i.e. when insecticides diminish insect populations fed on by fish and other aquatic animals.

Pesticides kept in sub-standard conditions pose a threat to both human health and the environment, particularly when kept in urban areas or near water bodies. Farmers with insufficient knowledge in pesticide management commonly use older, more toxic, and environmentally persistent chemicals.[2] This may especially be a problem in some developing countries. Absence of stringent regulations, or lack of enforcement of existing regulations, contribute to the problem.[3]

Fertilizers

Fertilizers used in order to increase agricultural yields – mainly nitrogen (N) and phosphorous (P) – may end up in waterways and groundwater. They can have significant impact on the quality of groundwater and river water, and may also result in eutrophication of wetlands and water bodies.[4] High nutrient concentrations stimulate algae growth leading to imbalanced aquatic ecosystems, which can experience phytoplankton blooms, production of excess organic matter, and an increase in oxygen consumption leading to oxygen depletion and death benthic organisms that live on or near the seabed.

The Baltic Sea is surrounded by nine countries and five more countries are in the drainage basin but do not border on the sea. Fertilizer runoff from surrounding agriculture lands contribute to a large nutrient load on the Baltic Sea primarily via river discharges which has changed from an oligotrophic clear-water sea into a eutrophic marine environment experiencing summertime algal blooms, where especially the blue-green algae that are potentially toxic to humans and animals are a major problem (Fig. 1). All sources of pollution to the Baltic Sea were made subject to a convention that was signed in 1974 and entered into force in 1980. A new convention – Convention on the Protection of the Marine Environment of the Baltic Sea Area – was signed in 1992 by all bordering states and the European Union. This convention entered into force in 2000. Similarly, the excess nitrogen in the Mississippi river has resulted in an anoxic 'dead zone' in the Gulf of Mexico.[5,6] The Black Sea, which is an inland sea, is a third example where large phytoplankton blooms have been observed annually. During the last decades, increased nutrient loads from human sources together with pollution and over-harvesting of fisheries have resulted in a sharp decline in water quality in the Black Sea.

Sediments

Pollution by sediments is also associated with agriculture practices as they can develop erosion and sedimentation which may produce physical (e.g. turbidity in water) and chemical impacts (e.g. organic chemicals associated with sediments).

Manure and sludge

Manure and sludge from wastewater treatment can be valuable sources of nutrients and contribute to maintaining/improving the soil carbon content and productivity. But,

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Figure 1. Algal blooms in the Baltic Sea, which is surrounded by nine countries. Five more countries are in the drainage basin but do not border on the sea. Fertilizer runoff from surrounding agriculture lands contributes to a large nutrient load on the Baltic Sea that can stimulate harmful algal blooms and eutrophication. All sources of pollution to the Baltic Sea were made subject to a convention that was signed in 1974 and entered into force in 1980. A new convention – Convention on the Protection of the Marine Environment of the Baltic Sea Area – was signed in 1992 by all bordering states and the European Union. This convention entered into force in 2000. (Photo Credit: SMHI, Sweden.)

especially when spreading takes place on frozen ground, high nutrient runoff can result in high levels of contamination of receiving waters by pathogens, metals, phosphorus, and nitrogen leading to eutrophication and potential contamination.[4] Additionally, groundwater can be polluted, specifically by nitrogen.

Irrigation

Irrigation in agriculture also has effects; for example, the runoff of salts leads to the salinization of surface waters; the runoff of fertilizers and pesticides leads to surface waters with ecological damage and bioaccumulation in edible fish species.[4] Box 1 presents a case study from Senegal on the effects on water of a sugarcane plantation and mill. The effects are both on quality and on the availability of water.

Tillage and plowing

Tillage and plowing in unsuitable soils can promote sediment/turbidity (sediments carry phosphorus and pesticides adsorbed to sediment particles) and siltation of river beds and loss of habitat, spawning ground.[4] Tillage and plowing should also be considered when removing agricultural residues for lignocellulosic process, as it encourages erosion.

Forestry inputs and impacts on water quality

Besides impacts associated with the cultivation, other practices associated with biomass production for energy, such as harvest residue extraction and the growing of trees without undergrowth, can lead to negative impacts, including soil erosion causing sedimentation of water bodies and reduced ability of precipitation to penetrate the soil and replenish groundwater supplies.

Increased demand for lignocellulosic biomass can change the way bioenergy production affects water qual-

Box 1. Sugarcane production in Senegal

The Senegalese Sugar Company (CSS, Compagnie Sucrière Sénégalaise) located in northern Senegal on the left bank of the Senegal river near Richard Toll, is the largest agro-industrial unit in operation in the basin since 1972. It has a production potential of more than 8000 hectares of sugarcane with an average yield of 120 tons/hectare, using water from both the Senegal river and Lake Guiers. The company employs 3000 permanent workers and 2000 seasonal workers. In 2008, CSS inaugurated a new bioethanol plant. The distillery from molasses has an annual production capacity of 10 to 12 million liters of ethanol. The ethanol production covers the company's energy consumption and supplies the Senegalese market with clean fuel as alternative energy for household and other sectors, such as pharmaceutical alcohol and alcoholic drinks.

The irrigation of 8000 hectares of sugarcane fields require approximately 188 million cubic meters of water a year which is directly pumped from Lake Guiers and the Senegal river.

Lake Guiers, the largest reserve of surface freshwater in the country, is connected with the Senegal river by a canal. Its hydrological regime was submitted to the fluvial rising, but is now regulated by the dams constructed on the river. The main uses include irrigation for sugarcane and the supply of drinking water. In future, the lake could serve as a starting point of a canal to Dakar (250 km) for supplying the town with water. From the Ngnith station pumps, the lake provides a drinking water volume over 100 000 m^3 per day for the city of Dakar.

In these arid areas, irrigation made suitable by the availability of surface water from the lake and the river, is also associated with environment impacts, where the use of mineral fertilizers and pesticides in sugarcane production is one specific concern. Studies have been conducted to assess water pollution from sugarcane cropping in the lake and river. The quality of effluents has been measured at different points, upstream and downstream of the receptor point and from the surface pumping water in order to monitor the diffusion of water pollution. The pollution was found to be more significant in the lake than in the river, but in general the nutrient (primarily nitrogen and phosphorous) concentrations were found to be relatively low. Lake pollution was also found to be lower in deeper waters.

ity. As described earlier, removal of lignocellulosic harvest residues can lead to ‘negative impacts, but if increased demand for lignocellulosic biomass leads to shifts in land use toward a larger share of perennial herbaceous plants and woody plants (e.g. willow, poplar, eucalyptus) that are grown in multiyear rotations, positive effects for water quality can be expected. Such plants are generally considered as more beneficial for the water quality in a certain area due to their less-intensive management practices, for example, employing weed control only during the establishment phase, tillage only before the establishment phase, and lower inorganic fertilization than conventional food/feed crops (Box 2).

Based on the observation that replacement of arable crops with perennial grasses and SRC can lead to an improvement of water quality, integration of SRC into the agricultural landscape has been proposed as a strategy to meet EU obligations in terms of water quality expressed in the Water Framework Directive.[7-9] On good land, SRC is likely to increase water quality compared with land used for agriculture because of its lower agro-chemical requirements. There is some evidence that in particular locations, nitrate

Box 2. Water quality effects of lignocellulosic plant production.[7,55]

Most studies of water quality aspects of cultivating short-rotation coppice (SRC) plants have dealt with nitrogen and phosphorous leaching to groundwater. Reported big differences in nitrogen leaching between SRC and conventional food/feed crops can in some cases be attributed to the lower input of fertilizer applied to SRC. However, results for SRC fields intensively irrigated with nutrient-rich wastewater (usually nitrogen but also phosphorous) suggest that in general leaching of nitrogen from SRC in comparison to arable crops is significantly lower and a shift from arable crops to SRC can lead to improvement of the groundwater quality and consequently of the surface water quality in a certain area. Results from experiments involving applications of municipal sewage sludge to willow and poplar can in the same way give insights into the effects of SRC on phosphorous leaching.

Today, sludge application to SRC is a common practice in Sweden and in the UK where it compensates phosphorous losses in newly harvested fields.[53] Here, studies point to low phosphorous concentrations in drainage water also in instances of relatively high phosphorous input. Phosphorous is usually bound to soil particles and its leaching patterns differ from these of nitrogen which is in most cases related to water drainage. However, future phosphorous leaching cannot be excluded if sewage sludge is applied for a number of years at high rates.

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leaching could be a problem from applications of fertilizers and sewage sludge. However, it has also been suggested that mixtures of trees and grasses used as energy crops could be cultivated along waterways to act as a buffer preventing nutrient runoff from agricultural land.[10]

The use of SRC as vegetation filters for cleaning nutrient-rich water is further discussed, including the case where SRC is established as buffer strips to capture nutrient-rich runoff water from intensively managed agriculture lands.

The production of energy from wood has a life cycle that produces environmental burdens and impacts on the hydrologic system at various stages.[11,12] Most concerns have been focused on forest operations such as harvesting, road network, development, site preparation, fertilization, herbicide use, ash recycling, and regeneration site preparation.[13] These impacts are transitory but generally well-dispersed throughout watersheds. They can also affect the hydrological process and pollute water directly or indirectly through the use of fertilizers, pesticides, and sediments among others. These impacts include:

Hydrologic processes

Hydrological process can be affected, for instance, by harvesting. The hydrologic cycle quantifies the interactions between the atmosphere, geosphere, biosphere, and hydrosphere. Since water is a primary driving force in ecosystem processes and fluxes, water quality reflects the net effects of these processes and disturbances that occur on watersheds.

A generalized breakdown of the inputs, fluxes, and outputs in undisturbed forested watersheds in humid regions was described Neary[12] and Hewlett.[14] The percentage distribution of water movement changes somewhat in arid shrub, grassland, and woodland ecosystems, and can vary considerably in watersheds disturbed by climate change, harvesting, burning, insect defoliation, windthrow, land-use conversions, mining, and agriculture Precipitation inputs consist of rain, snow, and sleet (100%). Fluxes, or movement pathways for water within watersheds, consist of interception, evaporation, transpiration, stemflow, throughfall, infiltration, surface runoff, interflow, baseflow, and stormflow. They convey variable amounts of dissolved or suspended solids that constitute the physical component of water quality.[15]

Erosion and peakflows

When a watershed is in good condition, rainfall infiltrates into the soil, and baseflows are sustained between storms. Well-vegetated watersheds in good condition generally do not produce damaging peakflows (flash-floods watershed condition is a term that describes the ability of a watershed system to receive, route, store, and transport precipitation without ecosystem degradation.[16]

However, in some regions of the world, these destructive streamflows are common, irrespective of watershed condition. Nevertheless, severe fires, poor harvesting practices, over-grazing, conversion to agriculture and urban uses, and other disturbances may alter watershed condition, reducing it to a moderate or poor level. With poor watershed condition, the percentage of infiltrated rainfall is reduced significantly and may produce erosion.

Disturbances that destroy, remove, redistribute, or increase plant litter and vegetation, and change soil physical properties, alter the infiltration and percolation capacity of soil. When watershed conditions deteriorate, the result is increased flood flows and erosion as watershed condition goes from good to poor. Additionally, loss of organic material by severe burning, harvesting, respiration, oxidation, site preparation, or other disturbances could result in adverse changes in hydrologic conditions in some instances.

Chemical pollution

A number of research studies have examined the effects of forest harvesting on water quality.[12,17-20] The water quality parameters typically examined by these studies are nitrate-nitrogen (NO_3-N), ammonia nitrogen (NH_3-N), total N, total phosphorus (P) and orthophosphate (PO_4-P), cations such as sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg), micronutrients, sediment, and temperature. These parameters are of concern for streams being used as water supplies, and for their potential impact on aquatic biota, particularly threatened and endangered species.

Changes in water quality parameters discussed here are mostly from studies where entire watersheds were treated uniformly. They rarely examined situations where forest harvesting was done within the confines of much larger catchments where most of the area was not treated at the same

Table 1. Changes in hydrologic processes in forests after harvesting.[12,18]

Hydrologic Process	Type of Change	Specific Effect
1. Interception	Reduced	Moisture storage smaller Greater runoff in small storms Increased water yield
2. Throughfall	Increased	Baseflow increase Soil moisture increase
3. Evaporation	Increased	Baseflow decreased Soil moisture decreased
	Decreased	Baseflow increase Soil moisture increase
4. Litter Storage	Litter Reduced	Less water stored (0.5 mm cm-1)
	Litter Not Affected	No change
	Litter Increased	Storage increase
5. Transpiration	Temporary Elimination	Baseflow increase Soil moisture increase
6. Infiltration	Reduced	Overland flow increase Stormflow increase
	Increased	Overland flow decrease Baseflow increase
7. Streamflow	Changed	Increase in most ecosystems Decrease in snow systems Decrease in fog-drip systems Decrease with type conversion
8. Baseflow	Changed	Decrease with less infiltration Increase with less transpiration Summer low flows (+ and -)
9. Stormflow	Increased	Volume greater Peakflows larger Time to peakflow shorter
10. Snowpack	Changed	Cuts <4 ha, increase snowpack Cuts > 4 ha, decrease snowpack Snowmelt rate increase Evaporation/ sublimation greater

time. Water quality effects usually attenuate as the untreated area increases due to dilution effects (Table 1).

Nutrients

Nitrate-nitrogen is often used as an indicator of watershed health and water quality. It is a good integrator and indicator of disturbance,[15] and also a critical water quality parameter for human health. For the most part, large increases in NO_3-N levels in streams draining harvested watersheds have not been observed. The largest increases in NO_3-N reported in the literature[21] were measured where herbicides were specifically applied to suppress vegetation regrowth and also to nitrogenous fertilizers during forest regeneration,[18] or where nitrogen saturation of ecosystems has reached a critical level due to atmospheric deposition. Severe fire can also cause similar nutrient release.[22]

Fertilizers and wood ash

Compared to agricultural lands, even managed forests have much higher water quality. Certainly fertilizer use in the forest bioenergy lifecycle is not expected to cause water quality problems, especially when best management practices (BMPs) are used.[23] Inter-rotation forest fertilization programs can be a source of additional nutrient inputs into streams, but mitigation practices can limit those inputs.[24]

The review by Pitman[25] cautioned that the environmental problems associated with wood ash use are less likely to come from its heavy metal content, which can be partly removed at source during the burn, and more likely to be associated with its high calcium content. This may create a rise in soil pH, increasing microbial populations and the potential mobilization of nitrogen. Although the rise in pH is potentially beneficial to tree growth on acidic or nutrient poor soils, it can be accompanied by changes to the ecology and functioning of forest ecosystems.

Pesticides

Herbicides and insecticides are sometimes used in bioenergy plantation establishment to reduce weed competition or deal with insect infestations. Analyses conducted in regional environmental impact statements indicate that the low concentrations and short persistence of forestry pesticides in surface and groundwater do not pose a significant risk to water quality, aquatic biota, or human health.[26]

Sediment inputs

Yields of sediment during and after forest harvesting are highly variable depending on such factors as soils, climate, topography, ground cover, and watershed condition. Although sediment yields increase after harvesting as a result of physical disturbance of soil they are usually transient due to vegetation regrowth. The largest increases documented in the literature have been associated with post-harvest mechanical site preparation, slope instability, road construction, or naturally highly erosive soils. The cumulative effects of erosion and sedimentation that occurred centuries ago from agriculture or forestry can present forest managers with many challenges.[27] Sediment is an important water quality parameter since it can harm aquatic organisms and habitats, and render water unacceptable for drinking water supply or recreation purposes. The natural variability of sediment regimes in bioenergy forests must be understood before making judgments on the effects of harvesting. Use of the appropriate BMPs and carefully planned harvesting can result in minimal or no additions to stream sediments[28] (Table 2). BMPs are most effective in minimizing sediment inputs to streams or lakes when they are properly planned and implemented prior to, during, and after harvesting.[23]

Table 2. Effects of forest harvesting and related disturbances on water quality – sediment.[12,18,26]

Forest Type	Location	Treatment	Sediment Increase	Sediment Increase
			%	Mg ha^{-1} yr^{-1}
Harvesting Alone				
Northern hardwoods	New Hampshire USA	Clearcut	769	0.323
Mixed hardwoods	West Virginia USA	Clearcut	0	0.000
Loblolly pine	S. Carolina USA	Clearcut	655	0.131
Mixed Hardwoods	Georgia USA	Clearcut	154	0.103
Upland Hardwoods	Tennessee USA	Clearcut	2,020	10.600
Loblolly Pine	Arkansas USA	Clearcut	1,875	0.225
Loblolly/ shortleaf pine	Arkansas USA	Clearcut	6,500	0.260
Lodgepole Pine	Montana USA	Clearcut	661	0.119
Douglas-fir	Oregon USA	Clearcut	8,182	0.202
Mixed conifer	Arizona USA	Clearcut	38	0.003
Beech-podocarp	New Zealand	Clearcut	42	0.182
Beech-podocarp	New Zealand	Clearcut	700	3.003
Beech-Podocarp	New Zealand	Clearcut	2,100	2.100
Harvesting & Site Preparation				
Loblolly pine	Mississippi USA	Clearcut, bed	2,198	13.630
Slash pine	Florida USA	Clearcut, windrow	1,100	0.033
Loblolly Pine	North Carolina USA	Clearcut, blade	1,939	9.695
Loblolly Pine	Arkansas	Clearcut, shear	653	0.464
Shortleaf Pine	Arkansas	Clearcut, windrow	1,926	0.578
Loblolly Pine	Texas USA	Clearcut, shear	750	0.170
Roads				
Mixed Hardwoods	North Carolina USA	Roads	11,900	1.190
Loblolly Pine	Georgia USA	Roads	96,700	3.868
Douglas-fir	Oregon USA	Roads	175	0.930
Mixed conifer	Arizona USA	Roads	1,012	0.081

Temperature effects

A water quality parameter that affects stream biota in temperate forests is water temperature. Forest vegetation shades stream channels from solar radiation, thereby producing stream temperatures that are cooler and less variable than for unshaded sites.[12,18] Increases in temperature that result from canopy removal or thinning in forest harvesting temporarily affect physical, chemical, and biological processes. The impact on aquatic biota varies considerably, depending on whether or not individual species are eurythermic and the degree to which stream temperature is controlled by solar heating or stream baseflow.

Adverse changes in stream temperature can be buffered by using streamside management zones as a BMP. The cumulative effects of stream temperature increases are often moderated, as streamflow from harvested areas merge with those from larger, uncut areas. In some ecosystems, stream temperatures are primarily controlled by the temperature of baseflow inputs. Therefore, canopy removal by thinning or whole-tree harvesting has little impact on temperature.

Biomass conversion and impacts on water quality

Water quality impacts from the conversion technologies for biofuels production are well reported for some specific feedstocks such as sugarcane and palm oil. Furthermore, in addition to the identified impacts from a water quality perspective, there is also a difference in that the biomass production phase represents a diffuse and distributed source of pollution in contrast to the conversion phase that can be considered a point source of pollution.

Impacts on water quality associated with the *discharges* from the conversion plants are caused by the potential chemical, biological, and thermal pollution loading to aquatic systems. Some of the impacts associated with the conversion of the feedstocks for biofuels include:

- Industrial effluents (chemical and physical effects). Discharges without control and impacts on lakes, rivers, and land. The case of sugarcane in Brazil is highly efficient and there is control in the discharge.
- Application of waste water in agriculture. The case of sugarcane vinasses as a fertilizer has been reported for the case of Brazil and other sugarcane producers. This has been controlled to avoid saturation in soils.
- Discharge standards differ according to policies and regulations. In the USA, some of the regulations vary from one state to another.
- Water quality and greenhouse gas (GHG) emissions. Wastewater can also be a substantial contributor to GHG emissions. For instance, the effluent from processing the fruit of oil palm is called palm oil mill effluent (POME) and is generated mainly from oil extraction, washing, and cleaning up. As water quality discharge guidelines and regulations have been implemented, POME is now frequently discharged first into open lagoons (without methane capture) where the wastewater is treated. Biological oxygen demand (BOD) is the key measurable parameter of water quality, and microbial activity in the anaerobic conditions – a natural process that reduces BOD – produces methane as well (a GHG 25 times the global warming potential of carbon dioxide according to the Fourth IPCC Assessment Report).[29]

Without capture of these methane emissions, the wastewater treatment process is a substantial contributor to GHG emissions. One comprehensive study of the emissions of various biofuels[30] has calculated that biofuel production only saves 44% GHG emissions when compared to a fossil diesel if POME emissions are not captured. If the POME gas emissions were captured and used the GHG savings would be 72%.* Methane capture from wastewater treatment for use as a process energy source (methane can be used as the gas within boilers, for example) would be a significant step toward reducing the GHG emissions associated with biofuels and wastewater specifically.

Some of these impacts are better explained through the different feedstocks and production systems. The following section includes the cases of Brazil for sugarcane use for the production of ethanol and the case of Australia related to the harvesting of the feedstock (forestry) including the impacts mentioned earlier.

Sugarcane process in Brazil

In Brazil, the recovery and treatment of industrial effluents from sugar mills and distilleries are basically composed of

* This assumes a fossil fuel reference of 86gCO2eq/MJ.

internal controls through preventive control. The practices of reuse and recycling of effluents for the purpose of reducing pollution (discharge and physicochemical parameters) and the reduction of water use have been used in industrial plants for a long time. The techniques used include recirculation, wastewater reuse, more efficient equipment, less polluting processes, and fertirrigation of crops. The advantage of implementing these techniques include less use of power and water pumping; better use of raw materials; lower costs; and better management of nutrients (nitrogen and potassium) and organic matter in farming producing better yields and soil improvement.

The main effluent from the sugarcane industry and its treatment systems are:

- Water washing of the cane: 180–500 mg/L BOD_5 and high concentration of solids. Treated by sedimentation and stabilization ponds for the case of release into water bodies. For reuse, treatment consists of settling and correction of pH between 9 and 10.
- Waters cooling multijets and barometric condensers of sugar mills: low pollution potential (10–40 mg/L BOD_5) and high temperature (~50° C). Treatment by spray ponds or cooling towers, recirculation or release.
- Water cooling of the fermentation and distillation: high temperature (~50° C). Treatment by cooling towers or spray ponds to return or release.
- Effluent gas scrubber flue gas from boiler bagasse: to retain the particulate matter (PM), with low potential for organic matter (range 100–150 mg BOD5/L and 200–300 mg/L COD) and high temperature, reaching 80 °C. They are usually treated by sedimentation-flotation systems for recirculating the gas scrubber. The sludge, containing a great deal of solid (generally referred to as soot) is forwarded to the crop as solid waste.
- Stillage (vinasse or spentwash) and wastewater: large volume, ranging from 11 to 12 L / L of ethanol, with high organic load (25 000–40 000 mg/L of COD). The stillage is applied in sugarcane fields together or not with wastewater (washing floors, purges of closed circuits, excess condensate), promoting the fertirrigation with use of nutrients.

Table 3 presents briefly the sewage generated in the sugarcane industry, its volumes, and its main features. The characteristics of effluents and the availability of simple

Table 3. Summary of the characteristics of wastewater sugar-ethanol sugarcane mills.[57]

Wastewater		Flow	Physic-chemical characteristics					
			pH	Temperature [°C]	Settleable Solids [mL/L]	COD [mg/L]	BOD [mg/L]	Oil & Grease [mg/L]
Sugarcane washing		2 a 5 m^3/t cane	5–6	room	5–10	280–700	180–500	0
Cooling equipment (mills, turbines and turbo generators)		0.665 m^3/t cane	7	<30	<0.5	0	0	-
Cooling condensers/multi-jets evaporation and cookers		70 a 100 L/kg sugar	6–7	50	<0.2	20–80	10–40	0
Cooling Distillery for	sugarcane juice	30 L/L ethanol	7	<45	0	0	0	0
	fermentation	60 a 80 L/L ethanol	7	<35	0	0	0	0
	ethanol condenser	80 – 120 L/L etanol	7	50–60	0	0	0	0
	subtotal	200 L/L etanol	7	50	0	0	0	0
Effluent gas scrubber flue gas from boiler bagasse		2 L/kg steam	8	80	50–100	200–300	100–150	-
Condensate of	steam escape	40 a 50 L/kg sugar	7	80	0	0	0	0
	steam juice	50 a 60 L/kg sugar	5–6	80 a 60	0	600 – 1500	300–800	0
Cleaning floors and equipment		50 l/t cane	5–6	room	<0.5	1000–3000	800–1500	>20
Domestic sewage		70 L/personal.day	6–7	room	5–20	600	300	-
Stillage (vinasse or spentwash) and flegmass		12–18 L/L ethanol	4–4.5	80	3–5	25 000–40 000	15 000–20 000	8

treatment systems allow their immediate reuse. The more recalcitrant sewage, as stillage (spent wash) and purges of reuse systems, with high levels of organic matter and salts are re-used in fertirrigation of sugarcane.

There are a number of solutions available for mitigating most of these impacts; for example, processing water can be treated and recirculated for further use in the conversion plant, or be returned to water bodies.

Key indicators to measure water quality related to biofuels production

Indicators to measure quality of water refer to chemical, physical, and biological characteristics of the water and also to its final purpose. In the case of agriculture and forestry systems, indicators tend to be related to the use of agrochemicals which may pollute underground and ground water. According to Smeets *et al.*[31] some regulations and international standards and agreements exist, such as the Stockholm Convention on Persistent Organic Pollutants,[32] the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Annexes I, II, III, VII),[33] World Bank guidelines,[34] and the Global Reporting Initiative reporting guidelines on water use and pollution.[35] Water quality indicators can be classified on drinking water, bathing water, water pollution, and depending on other uses, agriculture, and industrial uses.

Water pollution main indicators have been extensively used for a number of years. They are used in most countries and regulated using reference maximum permissible of pollutants or physical characteristics. These include:

- Biochemical oxygen demand (BOD) to determine the oxygen-consuming organic material.
- TSS (total suspended solids mg/L) that measures the total quantity of suspended matter (primarily inorganic substances from cane and beet washing water).
- pH as extreme pH changes are harmful to water fauna.

The Environmental Protection Agency has set some of the standards for water pollution for best available technologies (Table 4).

Other indicators include conductivity, oxygen reduction potential (ORP). The indicators will also vary according to the goal or standard for the measurement and include physical, environmental, and chemical characteristics.

Table 4. EPA standards for water pollution.[31]

	BOD	A	pH
Raw sugar factory	Kg/t cane	Kg/t cane	(-)
Max. Daily value	0.10	0.24	
30 day			6.0–6.9
Mean	0.05	0.08	
White sugar factory	Kg/t raw syrup	Kg/t raw syrup	(-)
30 day			6.0–6.9
Mean	0.09	0.035	
Liquid sugar factory	Kg/t raw syrup	Kg/t raw syrup	(-)
Max. Daily value	0.30	0.09	
30 day			6.0–6.9
Mean	0.15	0.03	

Notes: A = volume of suspended solids (indicator).

The standards and regulations vary from regions and countries and in the case of the EU it is also regulated by different Directives and Acts including the EU Water Directive.

The National Research Council of the USA[36] has proposed a metric to compare water quality impacts of various crops by measuring the inputs of fertilizers and pesticides *per unit of the net energy gain* captured in a biofuel. Out of the potential feedstocks, corn has the greatest application rates of both fertilizer and pesticides per hectare. Per unit of energy gained, biodiesel requires just 2% of the nitrogen and 8% of the phosphorous needed for corn ethanol. Pesticide use differs similarly. Low-input, high-diversity prairie biomass and other native species would also compare favorably relative to corn using this metric.

The NRC[36] has also reported soil erosion from the tillage of crops as another possible impact on water quality. Soil erosion moves both sediments and agricultural pollutants into waterways. There are various farming methods that can help to reduce soil erosion. However, if biofuel production increases agricultural area, especially on marginal lands that are more prone to soil erosion, erosion problems could increase. An exception would be native grasses such as switchgrass, which can reduce erosion on marginal lands.

There are many possible metrics, but NRC[36] proposes an index that builds on inputs of fertilizers and pesticides *per unit of the net energy gain* captured in a biofuel. This requires the calculation of a biofuel's net energy balance

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(NEB) (the energy content of the biofuel divided by the total fossil energy used throughout the full lifecycle of the production of the feedstock), its conversion to biofuel, and transport. This has been calculated for ethanol from corn in the USA.[36]

Smeets *et al.*[31] report on the sustainability production of biofuels in Brazil stated that the emission standards used to monitor water pollution in Brazil are in most cases different to the international ones as some of them have been implemented specially for the country. This is the case of BOD and pH. In the case of the pH, the standards from the EPA differ also from those of Brazil and the World Bank which use different parameters. Some certification and standardization schemes also consider the use of the agro-chemicals and pesticides linked to water pollution.[37,38]

An alternative possibility for assessing the impacts on water quality is the water footprint which is expressed in terms of a water volume per unit of product or as a water volume per unit of time. The water footprint of a process is expressed as water volume per unit of time. Regarding biofuel production, the grey water footprint is more relevant to assess. This is the footprint of a process step as an indicator of the degree of freshwater pollution that can be associated with the process step. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. The footprint is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards.[39]

Energy and water links with ecosystem services and MDG

The UNEP Water Quality Outlook[36] reported that water quality management contributes to the achievement of the Millennium Development Goal particularly Goal 7 on 'Ensuring Environmental Sustainability' by:

- Integrating the principles of sustainable development into country policies and programmes and reversing the loss of environmental resources.
- Halving, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation.
- Significantly reducing biodiversity loss by 2010.
- Achieving significant improvements in the lives of at least 100 million slum dwellers, by 2020.

One form to demonstrate progress toward the achievement of the MDGs is through the use of water quality indicators. The GEMS/Water report[40] states the link between human health and aquatic systems depending on the physical, chemical, and biological composition of water.

In the case of bioenergy projects, water availability is probably the most obvious link that could jeopardize the achievement of the MDGS at local level if water is deviated for the sole production of bioenergy crops. Nevertheless, proper land management and use of resources for different agricultural products can contribute to a more efficient use of water for food and bioenergy crops production. A better management of resources including water can contribute in general for better ecosystem services.

The possibilities of new bioenergy projects in developing infrastructure at local level can also contribute to improvement of local water access and quality.

Mitigation strategies

A commonly expressed precondition for large-scale bioenergy is that the agricultural sector manages to improve the land-use efficiency drastically so as to require less land for meeting the food demand. Nevertheless, there can be negative impacts of increasing yield levels given the negative aspects of further intensification depending on large inputs of nutrients, fresh water, and pesticides. Even so, a significant potential exists to increase the currently low productivity of rain-fed agriculture in large parts of the world – especially in developing countries – through improved soil and water conservation, efficient fertilizer use and crop selection (including drought adapted crops), and employment of best practices, involving mulching, low tillage, contour plowing, bounds, terraces, rainwater harvesting and supplementary irrigation, crop rotation and fallow time reduction.[41-44]

Conservation agriculture and mixed production systems (double-cropping, crop with livestock, and/or crop with forestry) hold potential to sustainably increase land and water productivity as well as carbon sequestration and to improve food security.[45-47] Integrated approaches can also be based on combining feedstock production with conversion, for instance, producing animal feed that can replace cultivated fodder such as soy and corn[48,49] and also reduce grazing requirement.[50] Multifunctional systems providing multiple ecosystem services represent alternative options for the production of bioenergy on agricultural lands that could contribute to the development of farming systems and landscape structures that are beneficial for soil and water use as well as the conservation of biodiversity. Examples include systems that are established to provide specific environmental services, such as when trees are established as a windbreak to reduce wind erosion or integrated into the landscape to reduce water erosion and mitigate flooding. Plantations of suitable species can also be used to remove cadmium and other heavy metals from cropland soils.[51] For example, certain Salix clones are very efficient at accumulating heavy metals – notably cadmium but also, to some degree, zinc – which are then removed from the field with the harvest. Other systems provide environmental services of a more general nature, for instance soil carbon accumulation leading to improved soil fertility and enhanced climate benefit.[52]

Mitigation measures along the supply chain

The mitigation measures for water quality can be incorporated at different stages of the supply chain from the production of the feedstock to the transformation of it.

Mitigation measures at feedstock production

As described earlier, depending on how bioenergy development translates to feedstock demand in forestry and agriculture, the outcome for water quality can be very different. This section includes selected examples of how bioenergy demand can contribute to water quality improvements by opening for new land-use practices.

Shifts from conventional food/feed crops to increased production of perennial herbaceous plants and short rotation woody plants for energy will likely reduce the problem of nutrient pollution loads since these biomass plantations commonly use less inputs. In addition, similar to when plantations are established as irrigated vegetation filters, certain types of plantations can be located in the agriculture landscape and managed as buffer strips for capturing the nutrients in passing runoff water. The expansion of these types of irrigated/non-irrigated biomass production systems can help to address problems of eutrophication of aquatic ecosystems due to nutrient losses in agriculture.

Plantations can be located and managed for reduction of water erosion and for flood prevention. Besides the onsite benefits of reduced soil losses, there are also offsite benefits, such as reduced sediment load in reservoirs and irrigation channels, as well as reduced deterioration in the quality of river water due to the suspended load that accompanies flood waters formed mostly by runoff.

One specific case of water quality problems where certain biomass plantations can offer mitigation is when replacement of forests with pastures or other vegetation types having lower evapotranspiration rates than the original forests have resulted in productivity losses due to soil salinity induced by rising water tables. In such situations, biomass plantations with high water usage can be planted to intercept water moving through the soil and to reduce groundwater recharge. When planted upslope of salt-prone areas, plantations with high evapotranspiration capacity can contribute to preventing salinity by reducing the amount of water reaching the recharge zones. When planted within salt-prone areas, plantations can lower the water table and also reduce evaporation losses by proving ground cover.

Two case studies are presented below regarding some of the mitigation measures and best practices to aid to improve water quality where feedstocks used for biofuels are used.

Australian case study

Another important measure besides mitigation is the avoidance of the impacts through best practices. A study conducted in northwest Tasmania, Australia, to evaluate the water quality benefits of BMPs during tree harvesting in a streamside management zone demonstrated the benefits of these practices.[28] This case study consisted of cutting a 20-year-old *Eucalyptus nitens* in a pulpwood plantation along an intermittent stream according to the Tasmanian State Code of Forest Practice. A machinery exclusion zone immediately adjacent to the stream limited machinery traffic, but tracked harvesters were used to cut and extract tree stems without entering the exclusions zone (Fig. 2). Ground cover and water quality pre- and post-harvesting were measured to identify the major sources of sediment in this

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Figure 2. Tigercat tracked harvester delimbing and topping a felled *Eucalyptus nitens* stem during a streamside harvesting study that utilized Best Management Practices. Note the slash coverage remaining in the harvested area. (© Daniel G. Neary.)

headwater catchment, and to determine the effect of tree harvesting.

The study demonstrated that post-harvesting turbidity levels in streamflow were similar to pre-harvest levels (<2.5 Nephelometric Turbidity Units - NTUs) of streamflow exiting the catchment. A road, a dam (that was accessible to cattle), and a cultivated paddock were much more significant sediment sources. These sources led to turbidities of about 300 NTUs in Dam 10 immediately below the road and paddocks and above the harvested stream reach during a storm in late June 2009 and subsequent winter storms through October of 2009. At Dam 13, below the harvesting areas, stream turbidities were mostly less than 10 NTUs. The in-stream dams functioned as very effective sediment traps. This study demonstrated how BMPs can be effective in limiting adverse impacts to water quality. Forest harvesting operations for bioenergy can be conducted without increasing stream turbidity, if existing BMPs are followed.

Swedish case study

In Enköping, central Sweden, (20 000 inhabitants), a 75-ha willow plantation is used to treat and utilize decanted water from dewatering of sewage sludge. This water contains approximately 25% of the nitrogen entering the wastewater treatment plant, but less than 1% of the water volume. Thus, by treating this water separately instead of pumping it back into the treatment plant, the total nitrogen load is reduced by 25%.

The relatively limited water volume (around 15 000 m^3 per year containing some 20 000 kg N and 600 kg P) enables storing in ponds during wintertime, which also is required to reduce the number of pathogens. During the period May–September, the water is used for irrigation of the adjacent willow plantation by use of drip pipes laid in every double-row in order not to obstruct the harvest. To boost growth and further improve the overall nitrogen treatment efficiency of the wastewater treatment plant, the system is designed so that conventionally treated wastewater is added through the irrigation system. The irrigation load is approximately 250 mm per year resulting in a load of some 200 kg nitrogen and 10 kg phosphorus per hectare.

Ongoing monitoring has this far shown low nitrogen leaching losses, and thus, the system is apparently capable of transforming the large quantities of nitrogen added.The municipality covered all costs for the storing ponds, pumps, automatic filters, and irrigation pipes (which were lower than the estimated costs for improved conventional nitrogen treatment), whereas the farmer/landowner planted the willows and is responsible for maintenance of the irrigation pipes. The produced biomass is used in the local district heating plant thereby contributing to the local supply of heat and electricity. The ash from the boiler is then recycled back to the willow plantation, and thus, the treatment system is an excellent example of how treatment and recycling of society's waste products can be combined with production of biomass for energy (Fig. 3).

The Swedish quality requirements for sewage sludge recycling in agriculture are among the most restrictive in the world. Nevertheless, most sludge in Sweden is formally accepted for agricultural use. The high quality has been reached due to an effective and persistent work with, for example, control of industrial wastewater connected to the sewerage and disconnection of polluted storm waters and landfill leachates. Still, the demand for sewage sludge for use in conventional farming is very weak, while utilization of sewage sludge in willow plantations has a considerably higher acceptance (Fig 4). There are three main reasons why sludge is utilized in willow plantations:

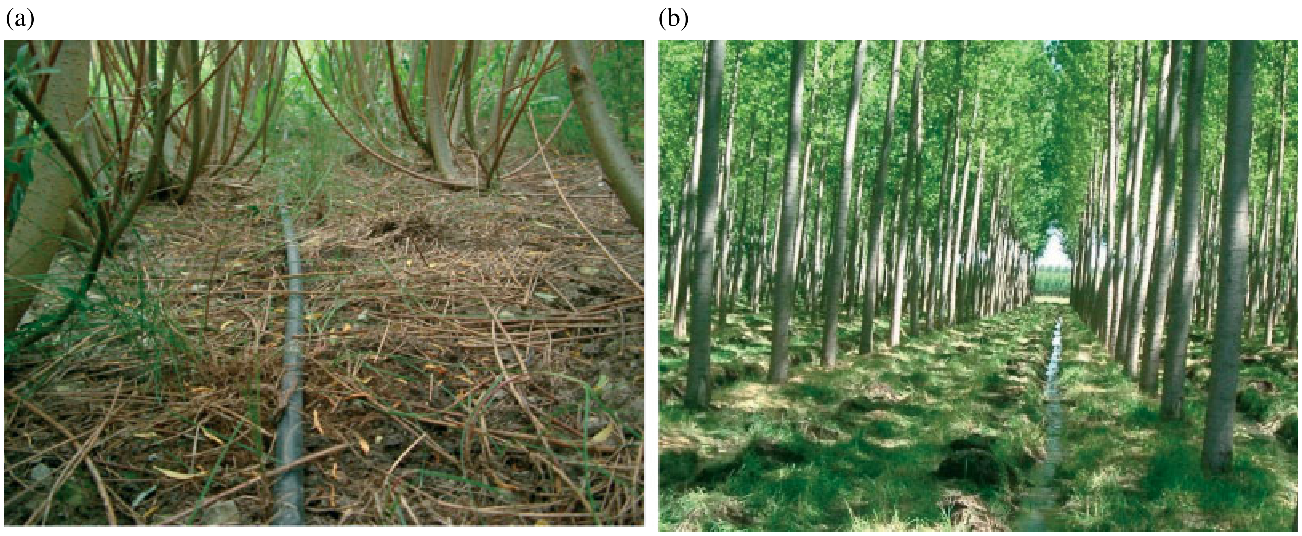

Figure 3 (a) Drip irrigation pipes in the above-described field; (b) Irrigated poplar plantation in Chile.[55]

1. Willow is not included in the food production – willows are not eaten.
2. Existing routines and equipments for sludge management can be utilized – it is just another crop.
3. Sewage sludge replaces to large extents commercial fertilizers, especially phosphorus, and increases the soil content of organic material.

Mitigation measures at the transformation stage

Cleaner production approaches can be very good for business as they focus the attention on maximizing output, minimizing wasted resources of any kind, and recycling and reusing all byproducts. Technology change is only one aspect of this approach and cause better management if it is part of a voluntary programme than if it is dictated by legislation.

In order to protect the environment and to save water resources, many actions can be undertaken such as environmental policies framework, and the minimization of pollution. Liquid waste from industries is a valuable resource for biogas production owing to its characteristics described earlier. So, its high organic load and low concentration of chemical products (sulfate, sodium, copper, iron, zinc) justify why such industrial wastewater is suitable for biogas production (Table 5).

Fermentation of wastewater from bioenergy factories integrated in a sewage treatment system is well developed. However, conventional wastewater treatment plants widely used in developing countries are different; they have an anaerobic system of liquid waste treatment.

Figure 4. View of the municipal wastewater plant, with water storage ponds and (behind the ponds) the willow fields that are used as vegetation filters. (Photo credit: Pär Aronsson, Swedish Agriculture University.)

Scheme 1 presents a decentralized wastewater treatment plant.

The approach to reduce water pollution is:

- to know wastewater characteristics such as flow, physical, chemical, and biological parameters;
- to define the objective to treat and reuse water effluent;

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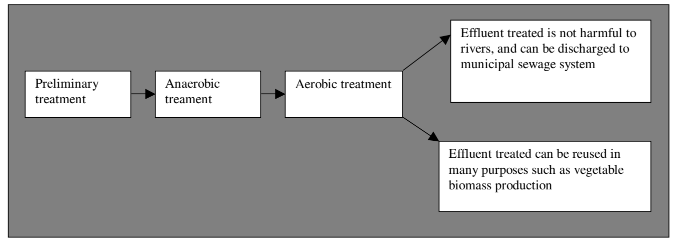
- to define the reduction necessary; and
- to develop options for reduction.

The objective of treating or reusing effluent is to discharge effluent to surface water without any damage to the environment, to discharge to a municipal sewage system, or to reuse for irrigation.

The goal of preliminary treatment is to adjust ph and temperature after flow equalization, and to remove large and heavy solids by collecting, screening, and degritting. In anaerobic treatment where effluent is fermented, about 85% of suspended solids and BOD/COD are removed.

At this level, the digester widely used is called UASB (Upflow Anaerobic Sludge Blanket) reactor which is applied successfully in municipal and industrial sectors. Several advantages are associated with the application of anaerobic treatment, including (i) low-energy requirement, (ii) little sludge produced and (iii) production of methane gas as a source of energy. Generally, anaerobic processes are followed by an aerobic second stage that can employ conventional activated sludge, extended aeration and rotating biological contactors. With aerobic treatment, organic loads continue to decrease; nutrients like nitrogen and phosphorus are removed. Aerobic treatment systems may consist of one or three oxidation ponds.

After these treatments, wastewater is not harmful to the environment and can be discharged to municipal sewage systems with the lowest cost for industry, if the capacity exists and if the relevant authority approves the discharge. It is important to note that in the field of wastewater treatment,



Scheme 1. Decentralized wastewater treatment plant.

the first step is called 'primary treatment' and the combination of anaerobic and aerobic treatment is known as 'secondary treatment'.

An advanced or 'tertiary treatment' can be applied to liquid waste disposal. Natural systems for wastewater treatment, such as constructed wetlands, may be used for tertiary treatment. Constructed wetlands are regarded as an emerging technology for industrial effluent and are designed to treat wastewater by using emergent plants such as cattails (*Typha spp*), reeds (*Phragmites spp*), and rushes (*Juncus spp*). Natural systems can provide a huge quantity of vegetable biomass which can be burned additionally for electricity generation in sugarcane mills at the same level as solid waste constituted by bagasse and cane trash.

Finally, besides considering technical mitigation measures, resource management is also an alternative to increasing biofuels activities. Water management should consider multidimensional concerns and a sustainable development view. It needs to include: (i) an understanding of the resource condition (e.g. levels and types of pol-

Table 5. Results of experience about biogas production from effluent factories.

Type of substrates	Temperature (°C)	Loading rate volatile solids kg/m^3/day	Retention time days	Gas yield per kg of COD m^3/kg
Sugar-refining waste	35	1.5	5.1	0.76
Molasses stillage	35			0.35
	37	2.2	10	0.12
		5.4	4.1	0.04
		7.5	3	0.02
Rum Distillery waste	35	10.4	12–15	0.28–0.29
		8.8	8–10	0.27–0.29
Palm oil mill effluent	35		11–20	0.24
	55		13–7	0.42

lution); (ii) goals of the society/community and/or the decision-maker; and (iii) the appropriate physical and institutional mechanisms to fulfill the goals. Therefore the management implications in terms of policy-making are significant, mainly for larger geographical areas and the decision of development and/or regulations (e.g. land use areas with better possibilities for crop production for biofuels). The failure of the water management plans has been related to the lack of a clear definition of goals, and the ignoring of the geological, hydrological, and biological realities of the water resource.[1]

Conclusions and recommendations

Water quality from biofuels production and transformation is more clearly linked to production activities such as agriculture and forestry. The main sources of pollution are clearly identified from the use of pesticides and fertilizers but also from some of the coproducts from the industrial paths of some feedstocks (e.g. vinasses). The effect of these on water quality depends upon several natural factors as well as on the severity of the impacts and their effects, i.e. indirect and cumulative.

Nevertheless, despite that the main impacts originate from sectors such as agriculture and forestry, it is not possible to attribute the impacts on water quality solely to the production of bioenergy crops.

Innovative forms of integrated production will prove to be the best form to avoid and mitigate impacts. Additionally, water use in processing also contributes to GHG emissions as in the case presented of wastewater treatment for oil palm. Future technologies, probably associated with biorefineries, could also incorporate better water quality management.

One of the main constrains in some areas is the lack of updated data in developing countries as the case in Senegal has demonstrated. Some of the monitoring measures should be conducted on a regular basis but some are conducted just once which is not enough to comply with regulations and with sustainable production.

There are several case studies and research that demonstrate that good practices and standards are already available with affordable measures to avoid and mitigate the impacts as in the cases of Brazil sugarcane growth and ethanol production, the harvesting of SRC in Australia, and the use of willow for water cleaning in Sweden.

Finally, the consideration of water resource management as part of policy and decision-making can contribute to mitigating water quality impact and promote better practices for the production of feedstocks and their transformation into biofuels.

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Dr Diaz-Chavez is a Research Fellow at CEP Imperial College London. She has over 15 years' experience in EIA and on sustainability assessment and certification of bioenergy projects. She has authored numerous reports on sustainability and bionergy and coordinated projects on the topic in Latin America, Africa and Europe. In 2010, she received the Young Researcher Environmental Management Award from SCOPE.

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Dan Neary

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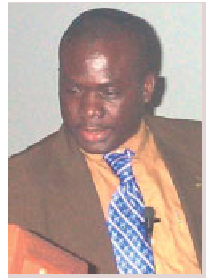
A civil engineer specializing in environmental study and graduated from the School of Engineering of the University of São Paulo (EESC-USP) in 1977, Mr. Neto has been working in the area of environment and water resources since then. He started his career in Cetesb period from 1978 to 1982 in the areas of control and wastewater projects, then work at the CTC - Sugarcane Technology Center, a research firm successor Technology Center Copersucar in the areas of R & D and environmental consulting and water resources for sugar and ethanol. He has represented the segment of industrial users by UNICA (Union of Sugar Cane Industry), the Basin Committees and CRH - Board of Water Resources, State of Sao Paulo, Brazil.



Mamadou Fall

Mamadou Fall has academic qualifications in rural development (forestry, agriculture), energy, sanitation, MSW and wastewater management and treatment. He has seven years experience in decentralised rural electrification for household and rural infrastructure application, and for small scale irrigation and water supply. He also has more than 10 years' experience in household energy issue with an informed understanding of Sahelian area sustainable energy policy; and 10 years' relevant experience both in advisory/consultancy and in management roles.

