Water Policy 12 (2010) 129–134

Protecting water resources in biofuels production

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Abstract

The Energy Independence and Security Act of 2007 mandates a five-fold increase in current biofuels production. This will substantially increase the current production of corn-based ethanol despite widespread concerns over its negative impact on the availability and quality of already stressed water resources. The National Academy of Sciences' (NAS) recently-released report on water use in biofuels production (principally corn-based ethanol) proposes improved on-farm irrigation efficiency and water recycling within biorefineries to reduce the impact on water availability. In a classic case of unintended consequences, we demonstrate that these measures may decrease the sustainability of biofuels production by increasingly stressing water supplies. Instead, these measures may be more effective in reducing the water quality impact of biofuels production—a role that the NAS report does not emphasize.

Keywords: Biofuel production; Irrigation efficiency; Water conservation

1. Introduction

Some policymakers have enthusiastically touted biofuels as a sustainable partial-remedy for high oil prices, energy dependence on foreign oil, global warming and rural economic decay. The USA's Energy Independence and Security Act of 2007 (EISA) mandates 36 billion gallons of biofuels by 2022 (42 USCS §7545(o)(2)(B)(i)(I)). This constitutes a five-fold increase over current biofuel production and approximately 20% of current motor fuel use. The mandate envisions eventual substitution of advanced cellulosic biofuels for currently produced corn-based ethanol. In the meantime, it doubles the use of corn-based ethanol despite widespread concerns about increased food prices, unsustainable mining of scarce water resources and increased nutrient pollution of aquatic ecosystems (Mufson, 2007).

The National Academy of Sciences (NAS) recently investigated the impact of biofuels production on water availability and quality and identified "agricultural practices and technologies" to reduce negative impacts (National Research Council, 2007). The NAS report focuses on corn-based ethanol. At present, cellulosic ethanol is not produced commercially and the water demands of cellulosic crops (e.g. native grasses) under various cultural practices are uncertain.

doi: 10.2166/wp.2009.113

Regarding water availability, the report finds that expanded ethanol production could increasingly stress water resources by expanding biofuel crops into dryer regions requiring new irrigation, or substituting biofuel crops for others requiring less irrigation. It identifies "[e]fficient application of irrigation water [as] one of the most important ways to mitigate any effects that increased biofuels [crop] production may have on water resources", noting that "[t]here are several irrigation techniques that reduce the amount of water applied per unit of biomass produced, thus improving irrigation efficiency regardless of crop type" (p. 28). The report finds that the water demands of biorefineries, while modest in absolute terms compared with the irrigation demands of biofuel crops, could substantially impinge on local water users. It identifies water recycling within biorefineries as a means of reducing "consumptive use of water" (p. 5).

Regarding water quality, the report finds that fertilizer applied in corn agriculture can result in excess nutrients (nitrogen and phosphorous) that pollute aquatic ecosystems by surface runoff to rivers or infiltration to aquifers. An oft-cited example is the role of increased ethanol corn production in the Corn Belt states in extending the "dead zone" of oxygen-depleted water in the Gulf of Mexico (Jackson, 2007). To reduce nutrient pollution, the NAS report recommends better nutrient management techniques (precision agriculture), biotechnology (increased nitrogen-use efficiency of biofuel crops) and policies encouraging cellulosic biofuel production. The report finds that biorefineries can pollute the environment with waste streams composed of salts, brine effluent and water high in biochemical oxygen demand (BOD). It does not identify associated mitigation measures.

In a classic case of unintended consequences, the NAS report's "conservation" measures could decrease the sustainability of biofuels production by increasing water consumption in crop production and biofuel refining. Instead, these measures may be more effective in mitigating the water quality impacts of biofuel production—a role that the NAS report does not emphasize. We ask the following questions: Will reductions in applied water resulting from improved on-farm irrigation efficiency conserve water in biofuels crop production? Will water recycling conserve water by reducing consumptive use in biorefineries? How might these measures mitigate water quality impacts?

2. Improved on-farm irrigation efficiency and water conservation

Irrigation water is consumed in crop production by evapotranspiration (ET)—the sum of evaporation from open-water or moist-soil surfaces and transpiration from vegetation. On-farm irrigation efficiency (ε) is the ratio of ET to the water applied to the field (A): $\varepsilon = \mathrm{ET}/A$. For example, 50% efficiency means that 4 units of applied water are converted to 2 units of ET. If efficiency improves to 66%, the application required for 2 units of ET decreases to 3 ($= 2/0.66$) units. By focusing on "irrigation techniques that reduce the amount of water applied…" to mitigate the impact of biofuel production on water availability, the NAS report effectively applies a "rule-of-thumb" that measures conserved water as the 1 ($= 4 - 3$) unit reduction in application.

A rule-of-thumb equating reduced application with conserved water is unreliable in practice. For example, improved on-farm irrigation efficiency reduced pumping rates by 50%, but failed to stem the rapid decline of groundwater in the North China Plain (Kendy *et al.*, 2003). In another example, efficiency improvements reduced irrigation diversions in the upper Snake River Plain (Idaho), but have been linked to declining ground-water levels and spring discharges in the lower portion (Johnson *et al.*, 1999).

The accuracy of the rule-of-thumb in measuring conserved water depends on the fate of applied water not converted to ET ("unconsumed" water). Unconsumed water recharges freshwater surface and groundwater sources if it is not severely degraded in quality, or does not flow into a saline water body (Allen *et al.*, 1997). For ease of communication, we will refer to both surface and groundwater recharge as "irrigation return flow". For example, irrigation return flows are estimated to constitute almost half of the water diverted in western USA rivers (Pulver, 1988). Water quality concerns over increased runoff from fields growing corn for biofuel production also indicate the importance of irrigation return flow.

The rule-of-thumb inaccurately measures conserved water in river systems with significant irrigation return flows. We illustrate this with a hypothetical stretch of river characterized by a single farm irrigating a single crop and irrigation return flows (Figure 1). For the purposes of this illustration and without loss of generality, we assume that surface return flows directly recharge the river. The numbers in parentheses are streamflows after an assumed increase in on-farm irrigation efficiency from 50% to 66%. The river stretch (horizontal curve) has an inflow of 10 units of water in each irrigation season. In the *status quo*, the farm diverts 4 units from the river for irrigation (upward arrow), leaving 6 units in-stream. Given on-farm irrigation efficiency of 50%, 2 of the 4 units of applied water are converted to ET (encircled quantity). The 2 ($= 4 - 2$) units of unconsumed irrigation water return to the river (downward arrow), so that 8 ($= 6 + 2$) units flow out of the stretch for other water users (outflow).

An impact of improving on-farm irrigation efficiency to 66% is that ET may increase (Allen *et al.*, 1997). Improved on-farm irrigation efficiency increases the "transpiration" component of ET. Traditional low-efficiency irrigation systems (e.g. flood irrigation) meet crop demand for transpiration by over-irrigating portions of the field and under-irrigating others. Yields decrease in both over-irrigated portions (plants are water-logged) and under-irrigated portions (plants are water-stressed). More efficient modern irrigation technologies (e.g. drip and sprinkler systems) apply water more uniformly over the field, which reduces the need to meet crop requirements by over- and under-irrigating. Plant stress is reduced and transpiration increases.

Improved on-farm irrigation efficiency can either increase or reduce the "evaporation" component of ET depending on the irrigation technology adopted. For example, shifting to sprinkler from flood

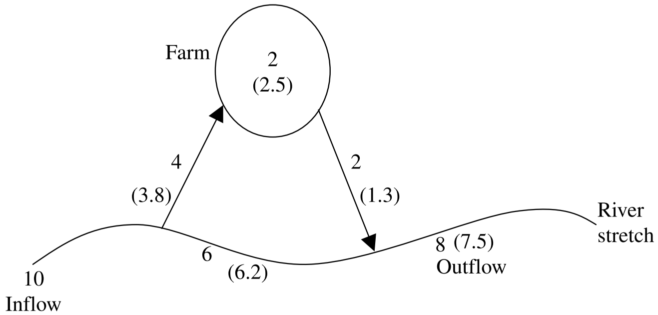

Fig. 1. Streamflow impacts of improved on-farm irrigation efficiency in a hypothetical river stretch. The numbers in parentheses are streamflows after an assumed increase in on-farm irrigation efficiency from 50% to 66%. In the *status quo*, there is a single farm diverting 4 units water (upward arrow) from a river (horizontal curve) to meet 2 units of ET (encircled) required by a single crop. There are 2 ($= 4 - 2$) units of unconsumed water that return (downward arrow) to replenish water outflow from the stretch totaling 8 ($= 6 + 2$) units. Compared with the *status quo*, improved efficiency decreases diversion by 0.2 ($= 4 - 3.8$) units and increases ET by $0.5 = 2.5 - 2$ units. Streamflow after the point of diversion increases by 0.2 ($= 6.2 - 6$) units—exactly the reduction in diversion—giving the illusion of water conservation. However, after accounting for a more-than-offsetting 0.7 ($= 2 - 1.3$) unit reduction in return flow, outflow is seen to decrease by 0.5 ($= 8 - 7.5$) units—exactly the increase in consumptive water use. This is the opposite of conservation.

irrigation may increase evaporation by spraying or misting water into warm air. Alternatively, shifting to subsurface drip irrigation can reduce evaporation of water that flood irrigation exposes to the surface. ET increases when the "evaporation" and "transpiration" components both increase, or when reduced evaporation fails to compensate for increased transpiration.

To demonstrate the inaccuracy of the rule-of-thumb in measuring water conservation, we investigate the case in which ET increases from 2 to 2.5 units when efficiency improves to 66%. The diversion required for 2.5 units of ET is 3.8($\approx$2.5/0.66) units, leaving 6.2 ($= 10 - 3.8$) units in-stream. Irrigation return flow is 1.3 ($= 3.8 - 2.5$) units. Basin outflow is 7.5 ($= 6.2 + 1.3$) units.

Applying the rule-of-thumb, water appears to be conserved because, compared with the *status quo,* in-stream flow after the point of diversion increases by 0.2 ($= 6.2 - 6$) units—exactly the reduction in required diversions ($0.2 = 4 - 3.8$). However, after accounting for the more-than-offsetting 0.7 ($= 2 - 1.3$) unit reduction in return flow, basin outflow is seen to decrease by 0.5 ($= 8 - 7.5$) units—exactly the increase in ET ($0.5 = 2.5 - 2$). In sum, the rule-of-thumb gives the appearance of conservation while concealing increased consumptive use and subsequent reduced streamflow. Conservation requires a reduction in ET after an improvement in on-farm irrigation efficiency.

Here is another way of viewing this result. Consider a person who withdraws money from his bank account for cash to spend during a trip and then re-deposits the unspent cash. He saves money by spending less on the trip, not by reducing withdrawals beforehand. Similarly, irrigation water is not saved in a return-flow hydrologic system unless consumptive use decreases.

Like any tool, improved on-farm irrigation efficiency is most effective when applied for the right purpose. It provides several important benefits at the field scale including reduced water-logging, reduced leaching of fertilizers and other chemicals, reduced soil erosion and improved salinity control (Allen *et al.*, 1997). However, it is an unreliable policy tool for conserving agricultural water on a broader geographic scale owing to possible increases in ET. Policymakers need to understand the hydrologic impact of improved on-farm irrigation efficiency at the farm- and basin-scales to avoid unintended consequences.

3. Recycling and consumptive water use in biorefineries

Corn ethanol production requires substantial process water, which is consumed by evaporation from cooling towers and evaporators during distillation. For example, ethanol plants in Minnesota consumptively use 3.5 to 6 gallons of water per gallon of ethanol produced (Institute for Agriculture and Trade Policy, 2006). Modern ethanol plants employ expensive water treatment technologies allowing unconsumed process water to be recycled within the plant, or discharged to freshwater sources in various states of purity required by regulators.

Does water recycling conserve process water by reducing the "consumptive use of water" in biorefineries, as suggested in the NAS report? We investigate this question with another hypothetical stretch of river characterized by a single biorefinery and treated discharges of process water into the river (Figure 2). In the *status quo*, the biorefinery does not recycle process water (Figure 2(a)). We assume that the stretch has an inflow of 10 units of water for each period. The biorefinery withdraws 6 units of water (leaving 4 units in the river) and consumptively uses 3 units. The remaining 3 ($= 6 - 3$) units of unconsumed water are allocated between the distillers' grain sold at 65% moisture content for cattle feed (assumed—without loss of generality—to be 0.6 units) and treated water which is discharged back into

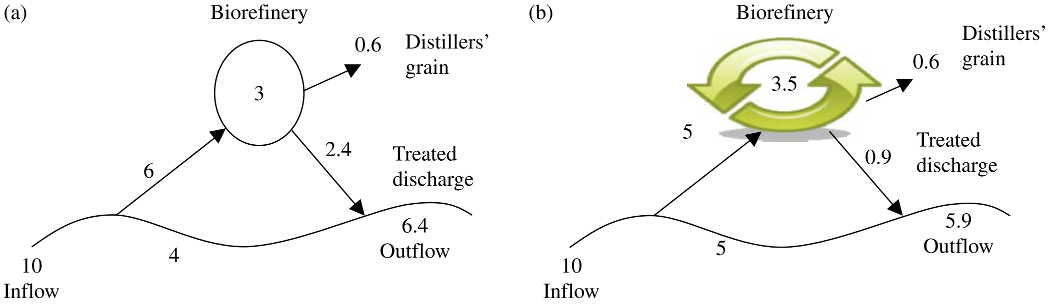

Fig. 2. Streamflow impacts of recycling water in biorefineries in a hypothetical river stretch: (a) The biorefinery does not recycle process water. There is a single biorefinery withdrawing 6 units of process water (upward arrow), 3 units of which is consumed by evaporation in the biorefinery (encircled). Unconsumed process water (3 = 6 − 3 units) is allocated between distillers' grain sold for cattle feed (0.6 units) and treated discharge (2.4 units) into the river (downward arrow). Outflow totals 6.4 (= 4 + 2.4) units; (b) The biorefinery recycles process water. Water use efficiency owing to recycling (circular arrows) increases consumptive water use to 3.5 units for a smaller required withdrawal of 5 units. Compared with the *status quo*, recycling does not conserve water because outflow decreases by 0.5 (= 6.4 − 5.9) units—exactly the increase in consumptive evaporative losses.

the river (2.4 units). Outflow equals streamflow after the point of withdrawal plus treated discharge (6.4 = 4 + 2.4).

The biorefinery recycles process water in Figure 2(b). Contrary to the NAS report, recycling does not decrease consumptive use by biorefineries. Each time water is recycled through the refinery, more is lost by evaporation. Accordingly, we assume for illustration that evaporative losses increase from 3 to 3.5 units. We further assume that increased water use efficiency from recycling allows the biorefinery to increase consumptive use with reduced withdrawals of 5 units. Unconsumed recycled water (1.5 = 5 − 3.5) is allocated between distillers' grain in the same amount as before recycling (0.6 units) and the remaining treated discharge (0.9 units). Outflow equals streamflow after the point of withdrawal plus treated discharge (5.9 = 5 + 0.9).

Water is not conserved by recycling because, compared with the *status quo*, outflows decrease by 0.5 (= 6.4 − 5.9) units (equal to the 0.5 unit increase in consumptive use). Similar to increased on-farm irrigation efficiency, increased water use efficiency in biorefineries does not conserve water basin-wide when treated discharge is returned to the stream. Actually to conserve water in biorefineries, new technologies are required that reduce evaporative losses from the refinery process.

Alternatively, the NAS report "considers water withdrawals [in biorefineries] as the measure of water use…[which] includes both consumptive and non-consumptive use" (p. 34). Lumping withdrawals and consumptive use together gives the illusion of water conservation from recycling by concealing the role of increased evaporative losses in reducing outflow at the stream discharge point to the detriment of downstream water users.

4. Mitigating water quality impacts

Although improved on-farm irrigation efficiency and water recycling within biorefineries may not increase the amount of water available downstream, they may improve downstream water quality by reducing the throughput of water into production. By reducing required withdrawals and increasing consumptive use, each measure leaves more water at the source and reduces discharges of unconsumed water back to the source.

5. Conclusion

Policymakers attempting to conserve water in biofuels production may unintentionally increasingly stress surface and ground water supplies if policies target increases in on-farm irrigation efficiency and water recycling in biorefineries. We demonstrated that improvements in on-farm irrigation efficiency that increase ET fail to conserve water on a broader geographic scale when irrigation return flows are an important component of basin-wide hydrology. In this case, a rule-of-thumb equating reductions in withdrawals with water conservation is inaccurate. Agricultural water conservation policies should target reduced ET, not simply reduced water withdrawals. We further demonstrated that water recycling increases evaporative losses in biorefineries. This reduces downstream water supplies when treated wastewater is discharged back to the stream. Policies attempting to conserve water in biofuel processing should promote the adoption of new technologies that reduce evaporative losses.

Although policies targeting increases in on-farm irrigation efficiency and water recycling in biorefineries may not reliably conserve agricultural water on a basin-wide scale, they can mitigate the water quality impacts of biofuels production. Both measures mitigate water pollution by reducing the throughput of water into farm and biorefinery production.

These results stress the need for policymakers to understand the true benefits and costs of adopting proposed water conservation measures in biofuel production so that policies achieve the desired outcomes and minimize unintended consequences.

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Received 17 January 2008; accepted in revised form 4 June 2008. Available online November 2009