Mini-review

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Understanding the impact of crop and food production on the water environment – using sugar as a model

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Abstract

The availability of fresh water and the quality of aquatic ecosystems are important global concerns, and agriculture plays a major role. Consumers and manufacturers are increasingly sensitive to sustainability issues related to processed food products and drinks. The present study examines the production of sugar from the growing cycle through to processing to the factory gate, and identifies the potential impacts on water scarcity and quality and the ways in which the impact of water use can be minimised. We have reviewed the production phases and processing steps, and how calculations of water use can be complicated, or in some cases how assessments can be relatively straightforward. Finally, we outline several ways that growers and sugar processors are improving the efficiency of water use and reducing environmental impact, and where further advances can be made. This provides a template for the assessment of other crops.

Keywords: footprint; impact; sugar; water

INTRODUCTION

The impact that the production of crops and processing of raw materials into food products and drinks has on the water environment is under increasing scrutiny by consumers, producers and environmental groups. The relevance of water management in the agricultural sector, which is responsible for 70% of global water withdrawals, is widely recognised.[1] There are pressures on the water environment arising from water withdrawal and pollution, while the lack of water for agriculture, domestic and other uses can adversely impact on social requirements, in part through effects on the economy at a local to a global scale. The challenge of meeting the increasing global demand for food could result in significantly increased environmental impacts, however adoption of technologies to increase production and reduce environmental impacts may allow 'sustainable intensification'.[2]

The impacts of water use in the supply chain have often been overlooked but are increasingly subject to scrutiny by government, business and society. Consequently, food and drink companies are changing the way they address water and are increasingly seeking to promote sustainable water management outside their fence-lines to reduce and mitigate water-related risks and impacts from raw material production through processing to the final product particularly in processed food and drink manufacture.

The present study examines sugar, from both cane and beet, from the growing cycle through processing to the factory gate, and identifies how much water is consumed and polluted and the ways in which the impact of water use can be minimised. Sugar provides a useful model crop to investigate water sustainability in crop and food production. Sugar is a major food ingredient, used in a range of processed foods and global sugar production is estimated at 175 million metric tonnes.[3] It is grown on over 30 million hectares[4] in a range of climatic zones which include both rain-fed and irrigated crops. Approximately 85% is derived from sugar cane, grown primarily in the tropics and subtropics, while the rest comes from sugar beet primarily in temperate regions. Water use is fundamental to both the growing and processing stages and sugar production is a major user of global freshwater resources.[5] Although there are important differences in how the crops are grown and how the sugar is extracted from plant tissues in the factory, which have an impact on the volumes of water used (consumed and polluted) to produce sugar, there are significant opportunities to reduce water-related risks in both the growing and processing stages.

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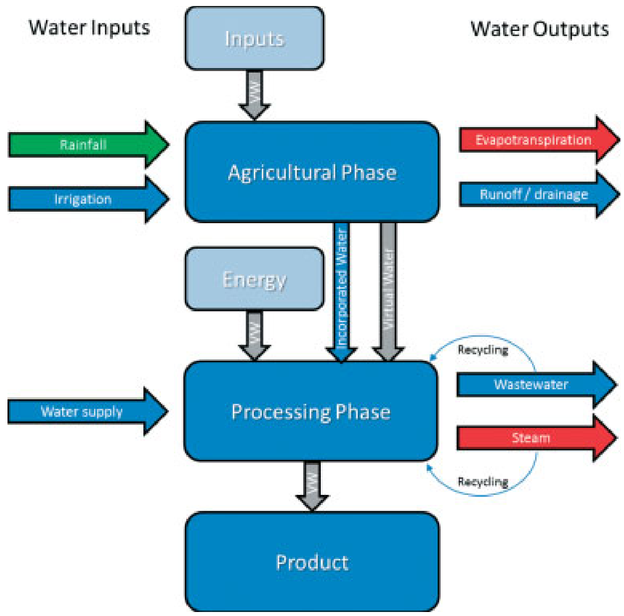

Figure 1. Water use in the sugar supply chain, differentiating between green and blue water inputs, virtual water flows (shown in grey) and water consumption (shown in red).

WATER CONSUMPTION IN SUGAR PRODUCTION

In order to understand the impact of water used in sugar production on the freshwater environment, it is important to make two distinctions. First, it is necessary to distinguish between freshwater, which is withdrawn from surface or groundwater resources ('blue water'), and rainfall, which is stored in the soil and used for the growth of plants ('green water').[6] This differentiation is important as green water can only be used for growing crops or other vegetation whereas blue water use is in competition with other industrial, domestic and environmental uses. Reducing blue water consumption will make more water available for other uses. Second, it is also important to differentiate between water withdrawal and water consumption. Some water may be withdrawn from a waterbody, used, and returned to the environment in good condition, with negligible impact on water availability. Water is considered to be 'consumed' if it does not return, in the short term, to the waterbody from which it was withdrawn.

In the agricultural phase, both green and blue water are consumed in varying proportions by evapo-transpiration according to the climate of the growing region and agricultural practices. In addition, the agricultural phase 'inherits' the indirect, or 'virtual' water associated with inputs (such as agrochemicals, fertilisers and energy). Some of the water used in the processing phase is blue water, which is lost as steam released to the atmosphere, and some is recovered, re-used, treated, and returned to the environment. Virtual water inputs in the processing stage include the indirect water from the production stage and water associated with external energy generation (Fig. 1); however, these are generally small in comparison to other water uses and are often ignored.[7,8]

In any crop, the vast majority of water 'used' by the crop is drawn from the soil by the roots and evaporated into the atmosphere through the leaves (evapo-transpiration). Only a small proportion remains in the tissues of the crop plants. The quantity of water required to grow a crop of sugar beet or sugar cane depends on the soil and climatic conditions, the timing and duration of the growing season, whether or not the crop grows under water-replete or water-deficit conditions and other agricultural practices. As it is not feasible to measure evapo-transpiration directly and partition this between blue and green water, the consumptive use of water in the agricultural phase is generally estimated using water balance modelling techniques.

The water requirement for growing sugar can differ considerably, ranging from 4 000 m^3 ha^{-1} for a sugar beet crop grown for 8 months in relatively cool, temperate, rain-fed conditions such as the UK;[9,10] to 18 000 m^3 ha^{-1} for a 12-month ratoon cane crop grown in irrigated, tropical conditions such as South Africa[11] or Australia.[12]

The biomass accumulation of sugar cane and sugar beet is a linear function of the amount of solar energy absorbed and the water consumed by the crop.[13,14] The slope of this latter relationship is the water use efficiency (WUE), which in agronomic terms is the yield obtained per unit water transpired. WUE can be affected by environmental, genetic and management factors. There are numerous values reported for the WUE of cane and beet crops[10] and the WUE for an individual crop depends greatly on the environmental conditions in which the crop is grown. For sugar beet, examples of WUE values range from 1.2 g sugar kg^{-1} water for an irrigated crop grown under hot, arid conditions in California, USA,[15] to 3.6 g sugar kg^{-1} water typical of the cooler, humid conditions in the UK.[13] Typical values for WUE in sugarcane range from 0.9 g sugar kg^{-1} water for a water-limited crop[16] to 1.5 sugar kg^{-1} water for irrigated crops.[14,17]

According to theory, plants with a C4 photosynthetic pathway (e.g. cane) have greater intrinsic WUE than plants exhibiting C3-type photosynthesis (e.g. beet)[18] and C3 crops often show greater rates of water loss than C4 crops when grown in the same environment.[19] Few, if any, experiments have compared the WUE of sugar beet and sugarcane within the same experiment. However, tall crops such as sugar cane, which cause greater 'stirring' of the atmosphere than sugar beet, can lead to greater water loss from the crop surface. Therefore, crop canopy architecture and the growing environment may have a greater influence on total water consumption than photosynthetic strategy. Even though a C4 cane plant may have greater intrinsic WUE than a C3 beet, long-season plants grown in hot, dry conditions will inevitably tend to use more water than a short-season temperate crop.

Insufficient water is the largest single factor that limits crop productivity worldwide,[20] and sugar crops are no exception. Lack of adequate moisture can reduce yields even before plants appear wilted or stressed. In many temperate countries beet is a rain-fed crop, or receives supplementary irrigation in dry years and about half the global sugar cane crop is grown without irrigation.[21] In rain-fed conditions, the blue-water consumption associated with growing the crop is negligible (comprising water used in crop spraying, general farm operations and indirect virtual water embodied in inputs).

The impact of food crops on water availability for other uses will depend on whether the crop is entirely rain-fed (green water) or requires additional water through irrigation (blue water). Although even rain-fed crops can affect local water balance, green water cannot be transferred to other uses, apart from agricultural uses. It is only available through access to and occupation of land and, as such, generally has a low opportunity cost,[22] except when replacing high value ecosystems. Therefore, in most cases only the blue water consumption is relevant to environmental impacts.

Where the crop is irrigated, the blue water consumption may be considerable. Mekonnen and Hoekstra[23] estimated the country-average blue water consumption per ton of crop between 0 and 350 $m^3\ t^{-1}$ for beet and between 5 and 230 $m^3\ t^{-1}$ for cane, whilst the global averages (weighted by production) were 26 and 57 $m^3\ t^{-1}$ crop for beet and cane, respectively.

Water is important to sugar processing. In some sugar beet factories, beet roots are washed and moved by water flume to the slicer for making cossettes, which are then hot-water extracted. Cane is also washed to remove soil before shredding and crushing. The extracted raw juice is clarified and filtered, and this 'thin juice' is then heated and evaporated to remove more water to create 'thick juice'. The final heating and evaporation leads to the formation of sugar crystals, which are centrifuged out of solution and collected. The extracted crystals are given a final wash with clean water to remove any discoloration. The volume of freshwater withdrawn per ton of sugar produced depends on the degree of recycling of water within the facility[24] and the refining process[25] and can vary widely from one facility to another. For example, Ramjeawon[24] found that freshwater input ranged from 1.8 to 12.6 $m^3\ t^{-1}$ cane for six facilities in Mauritius. However, a large volume of water is contained in the fresh beet and cane which is removed during processing, so the net water consumption can be small or even negative. Cid Quintas[26] estimated the water consumption of a cane mill in Swaziland to be 0.9 $m^3\ t^{-1}$ sugar, whereas Nieto-Sandoval[27] showed that a cane facility in Tanzania produced a net excess of 4 $m^3\ t^{-1}$ sugar. Similarly, DeLorey[28] showed that, without recycling, a sugar beet facility in Idaho (USA) excess water produced by the facility was more than 10 times the freshwater input. Thaler *et al.*[29] estimated that 8% of the total water consumption in European sugar production (beet) was in the processing phase. In terms of total volumes of water consumed therefore, the processing phase is almost negligible compared to the agricultural phase.[5]

The net water consumption can be expressed as a volume of water per unit output. In addition to sugar, there are several co-products – including bagasse, filter cake and molasses from cane and beet pulp – that have an economic value. Therefore the total water consumption must be allocated between the products according to their relative mass or values.[30] In this way, the total water consumption per unit of output ($m^3\ t^{-1}$) – sometimes referred to as the volumetric water footprint – can be estimated. Gerbens-Leenes and Hoekstra[31] estimated the global average (blue) water consumption at 730 and 450 $m^3\ t^{-1}$ sugar for cane and beet, respectively; however, such figures conceal considerable local variability. Thaler *et al.*[29] for example, estimated the average blue water consumption of 59 sugar beet growing regions in Europe at 37 $m^3\ t^{-1}$ sugar.

The blue water consumed comes from different sources, from different locations around the world and at different times (seasons) and the total water consumption does not distinguish between the impacts associated with these different sources. For example, 1 m^3 of water withdrawn from a water-stressed catchment is likely to have a significantly higher impact on other water users than an equivalent volume taken from a catchment where water is abundant. It is therefore critical that the blue water consumption is put into the context of water availability in the place of withdrawal. Gerbens-Leenes and Hoekstra[5] compared the blue water consumption for sugar beet and cane with water resource availability in the region of production. They identified three 'hotspots' where large-scale sugar production is taking place in river basins experiencing water stress; The Dnieper basin (Ukraine, beet) and the Indus and Ganges basins (India and Pakistan, cane).

Whereas 'hotspot' mapping is essentially a qualitative process, the blue water consumption can be weighted according to quantitative assessments of the vulnerability of the water source to withdrawal. Such characterisation factors have been based on human water requirements, water resources or environmental requirements[32–34] which results in a range of indicators, developed with different scopes, which may or may not provide a consistent picture of water vulnerability. These indicators have been increasingly used in life cycle analyses (LCA) of food crops and guidelines are being developed for the application of LCA to assessing impacts on water.[35]

WATER QUALITY IMPACTS

Although discharge of wastewater, and management of agricultural nutrients, is closely regulated in many sugar producing regions, cultivation and processing of sugar crops has been shown to have had an adverse impact on water quality and aquatic ecosystems in a number of locations around the world, including Brazil,[36] Swaziland[37] and India.[38] In the extreme case of Gorakhpur district of Nepal for example, discharge of improperly treated water from two sugar factories and a distillery into a stream rendered the stream's water unfit for drinking, bathing or irrigation.[39] Reports of pollution from beet sugar-processing effluents in Europe also include impacts on coastal ecosystems.[40]

In relation to cultivation, the main considerations arise from run-off and leaching, which can lead to pollution of groundwater and surface water with nutrients (notably nitrates and phosphates), agrochemicals, and sediments.[40] Johnson *et al.*[41] conclude that downstream impacts of any form of agriculture are largely governed by the periodicity, volume and intensity of rainfall. Although based on observations in Australian cane growing areas, this probably holds true for most other (particularly tropical) regions.

In relation to processing of sugar crops, the main consideration is pollution arising from the discharge of effluents from cane mills and beet factories. These effluents tend to be relatively rich in organic matter, including carbohydrates, when compared with those from other sources. Consequently, sugar processing effluents can represent pollutants with very high biological/chemical oxygen demands (BOD/COD), but other potential pollutants include suspended solids, heavy metals, oil/grease and cleaning agents.[24] In addition the pH and temperature of receiving waters can be affected with potential impacts on aquatic ecosystems. Hence, most factories treat water before discharge into water courses.

Accounting for water quality and related impacts on water resources is arguably even more complex and problematic than for water quantity due to many factors. These include: the various different types of pollutants coming from industrial facilities and agriculture; the interactions among pollutants; the status of the receiving water body; and the variety of ways water quality can be compromised. The various approaches to account for the resulting impacts to ecosystems and communities include: use of physico-chemical measurements,[25] environmental risk assessment; the 'grey water footprint' approach,[42] and LCA approaches.[43]

The 'grey water footprint' is the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards[42] and is complementary to the traditional emission/effluent standards. Estimates of the impact in the growing phase of sugar production have concentrated on the leaching of nitrogen, which Gerbens-Leenes and Hoekstra[31] estimated represents an additional 4–10% of the total (blue and green) water consumption of sugar crops. However, the grey water footprint is a theoretical volume that can only be calculated if the ambient water quality standard is known for a particular pollutant as well as its natural concentration in the receiving water

LCA indicators or measures for assessing potential impacts on water quality include ecotoxicity, eutrophication and acidification, which can cover the whole life cycle of a product or ingredient such as sugar, and provide a potential (midpoint) indicator of impact.[30,44,45]

MITIGATING THE IMPACT OF WATER USE

It is important that all stages and their water use are properly considered to determine how the impact can be reduced. There are significant opportunities to reduce the negative impacts of the sugar crop cultivation which could also provide economic benefits for farmers through cost savings from more efficient resource use without necessarily implying reduced productivity and profits.

The volume of water consumed per unit output of sugar can be reduced by (1) increasing the output per unit of water or (2) reducing the non-productive water losses.

Increased output per unit of water consumed

At the biological level, because of the linear relationship between water consumption and dry matter production, a shift in WUE is difficult to achieve. Thus, within a particular environment, in well-managed crops that are performing near the biological optimum, improvements in WUE will probably be small. There is evidence that small but significant differences in WUE exist between sugar cane and beet varieties,[46,47] although more work is needed to enable breeders to identify and select water efficient types in their breeding programmes. Careful management of irrigation has the potential to save water in water-stressed areas by matching the timing of irrigation to plant requirements. Controlled deficit irrigation at certain growth stages has been shown to increase irrigation water use efficiency in both beet[48–50] and cane crops.[51]

In many farming situations, there are factors present that depress yield below potential and more than half of the variation in estimates of water use per ton sugar among countries presented by Mekonnen and Hoekstra[23] can be explained by differences in average yield; those with the highest yield per hectare have the lowest water use per ton and vice versa. Good management of soil, nutrients, pests and diseases can therefore have positive effects on WUE.

Reducing the non-productive water losses

Considering the denominator of the WUE ratio, water often can be managed in a way that reduces consumption without diminishing yield or farm profits. When crops are slow to develop because of nutrient deficiencies, or when poor establishment leads to crop stands that are too sparse, a greater soil surface is exposed to evaporation.[52,53] This water loss does not benefit the growth of the crop, but nevertheless is counted as removal from the system.

Where crops are irrigated, water savings can be made by various techniques, including (1) improved methods of irrigation that deliver water to the roots of the plant with the minimum of loss, and (2) irrigation water delivery systems that reduce leaks and surface evaporation from canals and furrows.[54] The use of drip irrigation systems in place of furrow irrigation has been shown to deliver increased irrigation water use efficiency[55] and water savings of 40–50%.[56] The combination of drip irrigation with controlled deficit irrigation was shown to result in 25% water savings compared to sprinkler irrigation in irrigated sugar beet in Italy.[57]

Improved soil management, in conservation agriculture, such as using mulch cover or minimum or no tillage techniques, can reduce the need for supplementary irrigation by encouraging deep rooting and increasing the water holding capacity of the soil, reducing water losses through soil evaporation and making more soil water available to the crop.[58]

WATER QUALITY

The leaching of nutrients can be minimised by good husbandry and reduced quantities of fertilisers applied. Increasingly, growers of sugar beet and sugar cane are matching fertiliser applications to crop and soil characteristics, resulting in reduced application and leaching,[59] driven by high prices, environmental regulations and the impact of high nitrogen levels on processing quality.[60] In the EU27, the average fertiliser N-supply for sugar beet[61] is 120 kg ha^{-1} but there is scope to reduce this by using precision fertiliser placement techniques,[62] which may allow for reductions of 10–20%.

Various measures can be taken and forms of treatment used to reduce the quantity and pollution potential of sugar-mill effluent without changing the water-treatment technology.[63] Water that is minimally contaminated from a late stage in the process may be re-used for an earlier stage that does not require such high quality or used for irrigation of the growing crop, reducing water withdrawals as well as the volume of effluent. Such measures are attractive, provided that large discharges of low concentration effluents are not simply replaced by smaller discharges of more concentrated effluents.[40] Some companies have invested heavily in optimising use and re-use of water within factories[64] and using treated waste water for irrigation of crops surrounding the factory. Lacoste and Ribera[65] showed how sugar beet factories in Europe had decreased water consumption by one-third between 2001 and 2008 by improving factory water re-use and Žbontar Zver and Glavič[66] demonstrated how the water consumption of a sugar beet factory could be reduced by 69% by the use of water minimisation options. However, it is critical that the quality of the water does not result in adverse impacts on product quality or damage to the crop. For example, irrigation with cane effluent at high concentrations was found to suppress germination of peas.[67] Therefore water re-use is easier if wastewater streams with different water qualities are kept separate.

A range of techniques is available for treating sugar mill effluents, including the treatment of mill sludge with microorganisms that accelerate the rate of decomposition[68] and constructed wetlands.[69] Treatment in an open fermentation chamber decreased wastewater COD by 82% in 3 days in a Polish sugar beet factory.[39] Zero pollution has been achieved in some Indian sugar mills by totally recycling treated effluents as make-up water for cooling towers and spray ponds.[39]

DISCUSSION

Although sugar production from beet has remained static, global production of sugar from cane has increased steadily over the past 50 years.[4] Rising population, changing dietary preferences and increasing use of sugar for ethanol production will mean that global demand for sugar is likely to continue to increase and there will be a need to produce more sugar whilst reducing the environmental impacts of production. Recent international initiatives point to the need for decoupling economic growth from water use and environmental impacts.[34] The case study of sugar in this paper provides some evidence of the need for and feasibility of decoupling from a practical perspective.

The cultivation and processing of cane and beet to produce sugar can impact the local water environment through depletion of water resources and degradation of water quality. The largest potential impact on water resources is associated with the growing stage especially where the crop is irrigated in river basins that experience high water scarcity. The net volume of blue water consumed in the production of agricultural inputs, the processing of sugar and transport is very small in comparison ($<$0.5% on average), but varies according to the processing technology used and the degree of recycling. In some cases sugar processing facilities may even be net water producers where the volume of water extracted from the crop exceeds the loss of water due to evaporation.

There is significant potential to increase the productivity of water use in sugar crop production by increasing the productivity of the crop. Plant breeding for water use efficiency and drought tolerance can increase yield without increasing water use, whilst good agricultural practices – including soil, water and nutrient management as well as pest and disease control – can help to close the gap between actual and potential yields; reduce the water use per unit of output; and reduce crop losses. The WUE of cane and beet are conservative and, due to the climatic requirements of the two crops, they generally cannot be substituted in the same region; however, the WUE could be increased (by plant breeding) and good irrigation water management can reduce the non-productive water losses and therefore the volume of water withdrawn per unit of production. Comparisons of total water consumption are potentially misleading and it is important to separate green water consumption (with little impact) and blue water consumption. Even so, the greatest impact on water resources is not necessarily associated with the greatest blue water consumption, and local water scarcity and potential impacts on livelihoods must be considered.

Both the growing of the crop and processing can have significant impacts on water quality. Currently there are several methods and approaches to assess the impact on water quality that yield different results. The assumption of a fixed percentage of nitrogen that is lost to leaching,[31] for example, can lead to over-estimation of the impacts in the agricultural stage.[59] Further efforts are needed to provide comparability and the link between different scales, as shown by the differences between the accounting methodologies, life-cycle and footprint assessments.[34] In the agricultural stage, potential impacts are diffuse in nature and difficult to manage, although the high level of management of nutrients in commercial agriculture can minimise the potential loss of nutrients to aquatic ecosystems. Discharge of wastewater from processing facilities is a point-source and can be managed by reducing wastewater volumes (by increased recycling within the facility) in combination with waste water treatment.

CONCLUSION

This paper has illustrated how the impact of cultivation and processing of food ingredients on the water environment can vary enormously depending on plant type, cultivation practices, climate and the local water resource status. In some places, where production is rainfed or sufficient water resources are available for irrigation, and good crop husbandy and processing technologies prevent discharge of contaminated water, production may be benign in relation to aquatic ecosystems. In others, it may be making a major contribution to local water scarcity and degradation; however, adoption of agricultural, water management and industrial technologies can mitigate these impacts.

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