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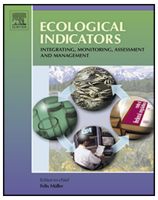

Original article

The consideration of time step in calculating grey water footprints of agricultural cropping systems

X. Vergé[a,b,*], A. VanderZaag[a], W. Smith[a], B. Grant[a], R. Gordon[b]

[a] Agriculture and Agri-Food Canada, Ottawa Research and Development Center, Canada
[b] Wilfrid Laurier University, Waterloo, Ontario, Canada

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ABSTRACT

A water footprint considers both the water volumes involved in production processes and the resulting waste water generated. The grey water (GW) footprint represents the volume of fresh water required to assimilate pollutants to acceptable concentrations—a concept proposed by the water footprint network—but it faces several difficulties when applied to agricultural production systems. Crop production cannot be fully controlled and it is weather-dependent, which greatly affects the year-to-year GW calculations.

In this study, we examined the effect of time step on the calculation of annual GW footprints by utilizing 30 years of daily average nitrate-nitrogen (NO_3-N) concentrations in drainage water (both leachate and runoff water derived from a process-based model) from corn and soybean production systems. For each crop year, the volume of water required to assimilate NO_3-N to an acceptable threshold concentration (i.e. $<10\,mg\,L^{-1}$) was calculated over different time steps (daily, weekly, monthly, seasonally and yearly), and each case was summed to an annual GW value. Daily average NO_3-N concentrations in the effluent water were generally below the acceptable threshold concentrations, with intermittent exceedances. Thus, the fields often provided their own ‘dilution’ water, and annual average concentrations were only $2.0\,mg\,L^{-1}$ and $0.4\,mg\,L^{-1}$ for corn and soybean, respectively.

The GW footprint varied significantly when calculated for different time steps. The greatest annual footprint occurred when calculated daily (shortest time step). The GW footprint for corn ranged from $2.7 \times 10^3\,m^3\,ha^{-1}$, or 2700 mm of water, when estimated daily to zero for the yearly time step. For soybean it ranged from $0.5 \times 10^3\,m^3\,ha^{-1}$, or 500 mm of water, to zero. The GW footprint results are therefore highly dependent on the time step of calculation. The effect of this issue extends beyond crop production as it is exported and amplified through feed rations to affect the GW footprint from animal production. To be able to reconcile these problems, the GW calculation pathways should be reconsidered and standardized.

1. Introduction

Over the past several years water availability and quality have become major environmental considerations. The water footprint (WF) is a metric of water sustainability that attempts to quantify water use in a consistent manner (Galli et al., 2012; De Souza and Leãor, 2013) to facilitate improved water management. Agriculture is by far the highest WF contributor, representing up to 86% of the world water use (Hoekstra and Chapagain, 2006) and 90% of international virtual water flows (Hoekstra and Mekonnen, 2012) which accounts for all water used in production processes and which are virtually attached to the imported product. The WF of crops is critical for the WF of animal products higher in the food chain, since crops provide livestock feed. Hoekstra and Chapagain (2006) estimated the beef production WF to be $155\,L\,kg^{-1}$ of boneless meat when the water from the feed crop was not considered, compared to 15,340 L when the crop WF was included.

The WF considers both the quantity of water transferred (green and blue water) and the water quality impairment caused by an activity (i.e. the production of the crop). The water footprint network (WFN) methodology accounts for water pollution through the “grey water” (GW) footprint component. This is explained by Hoekstra et al. (2011) as “the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards”. Nitrate-nitrogen

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[*] Corresponding author at: Agriculture and Agri-Food Canada, Ottawa Research and Development Center, Canada.
E-mail address: Xavier_vrg@yahoo.fr (X. Vergé).

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(NO_3-N) is one of the key pollutants as agricultural crop production represents a major point and non-point source (Gordon et al., 2000; Fuller et al., 2010).

Water quality is an important aspect of the WF but toxicity is a multi-faceted issue which makes the indicator development challenging. Water quality standard takes toxicity into account but it raises another concern related to the fact that several standards adapted to different situations such as drinking water, irrigation-use and ambient water, have been developed (Liu et al., 2012; Wang et al., 2014).

When considering an ecological indicator for water quality, it is important to realize that water and nutrient discharges from agricultural crops are quite different from industrial facilities. Agricultural water and nutrient balances are governed by biophysical properties and weather conditions. Losses of water and nutrients from cropping systems are highly intermittent and time dependent. Unlike an industrial facility that produces similar water discharge day-to-day, agricultural fields generate variable water discharge amounts from year-to-year, season-to-season, and even day-to-day. Excess water that is not lost by evapotranspiration is cycled through drainage and is either leached or is runoff throughout the year. Nitrogen inputs required for crop production (and could contribute to the GW footprint) may occur only once per year (e.g. fertilizer application) or gradually throughout the growing season (e.g. N-fixing legumes).

While the GW approach calls for virtual water to dilute discharged pollution down to an acceptable level/concentration, agricultural cropping systems are, to-some-extent, self-diluting since peak concentrations are generally extremely brief. Thus, it should be evaluated whether broad guidance on calculating the GW footprint is appropriate for crop production.

The GW footprint calculation method presented by Hoekstra et al. (2011) does not explicitly define the appropriate time step. Thus, we evaluated the GW volumes for crop production systems (corn and soybeans) over a 30-year period using five different time steps (from daily, weekly, monthly, seasonally and yearly). We hypothesized that the chosen time step of calculation would have a major impact on the resulting GW footprint and will in turn highlight the importance of developing an appropriate standardized methodology for calculating the GW footprint of crops.

2. Materials and methods

2.1. Estimates of N leaching and runoff

To demonstrate the temporal scale importance on GW footprint we derived representative long-term leaching and runoff estimates from corn and soybean production systems for a range of weather conditions. This was accomplished using a tested mechanistic crop model that simulates a full mass balance of water and N (Denitrification-Decomposition – DNDC; Li et al., 1992), which utilized 30 years (1971–2000) of daily meteorological data observed at the Central Experimental Farm Ottawa, Ontario, Canada. In using a long-term daily dataset our goal was to highlight the temporal dynamics of leaching and runoff, and the relative values as affected by calculation approach. The DNDC model has been validated for its ability to estimate the temporal dynamics of water and N movement for several cropping systems including corn-soybean in rotation (Tonitto et al., 2006a,b; David et al., 2009). We focused on simulating a grain corn-soybean system since these crops have contrasting N requirements and supply (fertilizer vs N-fixation). These two crops are sizeable contributors to the global WF, and represent about 14% of all crop water uses globally (Hoekstra and Chapagain, 2006).

The DNDC model was used to simulate a corn-soybean rotation on a loam soil over 30 years, using the historical weather inputs. The loam soil was selected as it represents ~50% of all agricultural soils in Canada (Schut et al., 2011). Simulations were constructed such that each phase of the corn-soybean rotation would be represented in each year. Prior to the 30 years of interest, the model simulated 10 years of production as a "spin-up" period to stabilize the soil C and N pools. Simulated outputs of interest were the daily total volume of runoff and leaching water, per ha, and the concentration of NO_3-N in the runoff and leached water.

Corn was annually planted on 15-May and received 170 kg ha^{-1} of inorganic N fertilizer (Yang et al., 2006), and was harvested on 15-October. Corn grain yields ranged from 7.2 to 10.3 t ha^{-1} with a mean of 8.9 t ha^{-1} of dry biomass. Each soybean crop was planted on 15-May, harvested 15-September, and received no fertilizer (reliant on N-fixation instead). Soybean yields ranged from 1.5 to 2.2 t ha^{-1} with a mean of 1.8 t ha^{-1} of dry biomass.

2.2. Grey water footprint calculations

To study the temporal aspect on the GW calculation, we focused on N losses. Calculations were applied to the model outputs for daily volumes of water and NO_3-N concentrations in leaching and runoff from corn and soybean over 30 years. We calculated the grey water for leaching (L) and runoff (R) separately and summed to determine the total GW as:

$$GW_{annual} = GW^{L}_{annual} + GW^{R}_{annual} \tag{1}$$

This analysis presents GW volumes on a yearly basis; however, each annual value has been calculated using the different temporal scales (day, week, month, season, and year). For example, daily calculations were based on 365 d of concentration and flow in each year; whereas weekly calculations were based on 52 weekly average concentrations and weekly total flow volumes. Annual total GW volumes (GW_{annual}) were the sum of k values of GW_t, the volume of grey water (m^3 ha^{-1}) for each time step, t and each category (L or R):

$$GW^{LorR}_{annual} = \sum_{t=1}^{t=k} GW_t \tag{2}$$

where k depends on the calculation time step: $k = 365$ for daily; 52 for weekly; 12 for monthly; 4 for seasonal; 1 for annual.

The GW was calculated as the volume of water required to dilute the concentration of NO_3-N to meet the provincial drinking water quality standard (10 mg L^{-1}; Ontario Regulation, 2016). Thus GW was calculated when the concentration in leaching or runoff water exceeded the water quality standard, using the following logic and equations for each time step:

$$if \overline{C}_N \leq C_{Standard} then GW_t = 0 \tag{3}$$

$$if \overline{C}_N > C_{Standard} then GW_t = \frac{\left(\overline{C}_N - C_{Standard}\right)}{C_{Standard}} \times V_{LorR} \tag{4}$$

where $\overline{C}_N$ is the mean NO_3-N concentration in the leaching or runoff water, averaged over each time step (mg L^{-1}); $C_{standard}$ is the water quality standard (10 mg L^{-1}); and, V is the volume of water (leached or runoff) per time step (m^3 ha^{-1}). As a simplifying assumption, we used a natural background NO_3-N concentration of zero, which was appropriate for the focus on relative changes caused by the temporal dynamics and calculation approach.

Finally the probability of occurrence (Fa) has been calculated using equation 5 as described by Ward and Trimble (2003), where