Science of the Total Environment 626 (2018) 962–970

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Trade-off between blue and grey water footprint of crop production at different nitrogen application rates under various field management practices

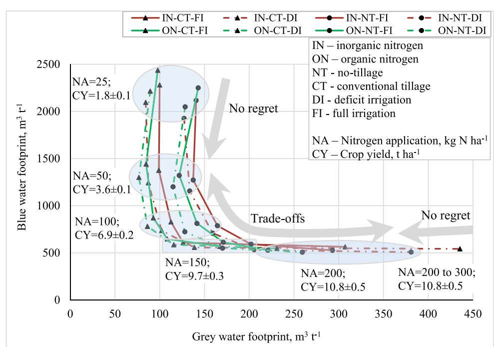
Abebe D. Chukalla [a,*], Maarten S. Krol [a], Arjen Y. Hoekstra [a,b]

[a] Twente Water Centre, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands
[b] Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore

HIGHLIGHTS

- Trade-off between water consumption and pollution in crop production is quantified.
- Blue and grey WF are minimum, and crop yield is maximum at different N rates.
- The economical optimal nitrogen rate varies if cost of water pollution is included.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 July 2017
Received in revised form 17 January 2018
Accepted 17 January 2018
Available online xxxx

Editor: D. Barcelo

Keywords:
Water pollution
Nitrogen balance
Soil water balance
Irrigation
Crop growth
APEX model

ABSTRACT

In irrigated crop production, nitrogen (N) is often applied at high rates in order to maximize crop yield. With such high rates, the blue water footprint (WF) per unit of crop is low, but the N-related grey WF per unit of crop yield is relatively high. This study explores the trade-off between blue and grey WF at different N-application rates (from 25 to 300 kg N ha^{-1} y^{-1}) under various field management practices. We first analyse this trade-off under a reference management package (applying inorganic-N, conventional tillage, full irrigation). Next, we estimate the economically optimal N-application rate when putting a price to pollution. Finally, we consider the blue-grey WF trade-off for other management packages, a combination of inorganic-N or organic-N with conventional tillage or no-tillage, and full or deficit irrigation. We use the APEX model to simulate soil water and N balances and crop growth. As a case study, we consider irrigated maize on loam soil for the period 1998–2012 in a semi-arid environment in Spain. The results for the reference package show that increasing N application from 50 to 200 kg N ha^{-1}, with crop yield growing by a factor 3, involves a trade-off, whereby the blue WF per tonne declines by 60% but the N-related grey WF increases by 210%. Increasing N application from 25 to 50 kg N ha^{-1}, with yield increasing by a factor 2, is a no-regret move, because blue and grey WFs per tonne are reduced by 40% and 8%, respectively. Decreasing N application from 300 to 200 kg N ha^{-1} is a no-regret move as well. The minimum blue WF per tonne is found at N application of 200 kg N ha^{-1}, with a price of 8 $ kg^{-1} of N load to water pollution the economically optimal N-application rate is 150 kg N ha^{-1}.

* Corresponding author at: Water Resources Management (WRM) Group, Wageningen University, Wageningen, The Netherlands.
E-mail address: abebe.chukalla@wur.nl (A.D. Chukalla).

https://doi.org/10.1016/j.scitotenv.2018.01.164

1. Introduction

It has often been argued that increasing crop yield through increased use of inputs (intensification) is preferred over expanding the areal extent of less intensive production methods, in order to fulfil increasing global food demand, as it avoids disruption of the ecosystems and greenhouse gas emissions that come along with enlarging the agricultural area (Edgerton, 2009; Pradhan et al., 2015). In water-scarce areas, intensification is expected to be achieved on existing irrigated areas (Playán and Mateos, 2006). Research on 'closing the yield gap' tends to focus on maximizing land productivity through increasing the necessary inputs. Closing the yield gap, however, requires a careful balance between increasing land productivity and the efficient use of water and nutrients, because a focus on maximizing yields may come at the price of intensified resource use and pollution (Foley et al., 2011). With increasing inputs, the additional yield gain can be steep initially, but becomes less and less at higher input levels. This holds for adding more nutrients (Godard et al., 2008) as well as for adding more irrigation water (Steduto et al., 2012; Amarasinghe and Smakhtin, 2014). While intensification of agriculture comes along with widespread eutrophication of water (Carpenter et al., 1998), it also increasingly faces the problem of limitations in water availability (Davis et al., 2017). It is therefore relevant to consider not only crop yield, but also irrigation water consumption (blue water footprint) per tonne of crop produced and water pollution (grey water footprint) per tonne of crop (Hoekstra et al., 2011).

With increasing irrigation rate, the blue water footprint (WF) per tonne of crop will initially reduce, because of the high marginal yield gain per additional unit of water, but it will start to increase after the point of highest marginal water productivity (Chukalla et al., 2015). Similarly, with increasing N-application rate, the N load to fresh water per tonne of crop, and thus the grey WF per tonne, may initially decrease, but it will quickly increase at higher N-application rates (Valero et al., 2005; Zhou et al., 2011; Good and Beatty, 2011). Therefore, considerations on intensification are confronted with trade-offs between crop yield (and linked to it revenue per hectare) and environmental impacts (blue and grey WF).

The intensity of irrigation links to the blue WF and the intensity of N inputs to the grey WF. Crop yields depend on the combination of N and irrigation water inputs, however, so that the blue WF per tonne also depends on the N-application rate, and the grey WF per tonne also depends on the irrigation water volume applied. Previous studies show that increasing the irrigation rate may increase nitrogen productivity and increasing the N-application rate may increase water productivity (McMaster et al., 2005; Molden et al., 2010; Al-Kaisi and Yin, 2003). Other studies show that N leaching, and thus the grey WF per tonne, increases not only with N-application rate, but also with irrigation (Valero et al., 2005; Schröder et al., 2007; Al-Kaisi and Yin, 2003). A smart combination of management practices can increase the efficient use of both water and N fertilizer, by reducing unproductive losses like soil evaporation and N losses to freshwater and the atmosphere (Zhou et al., 2011; Carpenter et al., 1998). Important managerial factors include the irrigation technique and application strategy, the mulching practice and the tillage practice (Chukalla et al., 2015; Derpsch et al., 2010; Grandy et al., 2006; Huang et al., 2015). Some earlier studies provide insight in the effect of individual or combined management practices on the blue WF per tonne, or the N load to freshwater, but do not consider trade-offs that may occur between the blue and grey WF in crop production. The current study focuses on this blue-grey WF trade-off. Since experimental field studies are expensive in terms of time and resources when one wants to study a wide variety of management conditions, we have chosen here a model-based approach to study water and nutrient balances and crop growth.

The objective of the current study is to explore the trade-off between the blue and N-related grey WF per tonne of crop at different N-application rates, under various field management practices. As a reference, we consider the common combination of applying inorganic-N, conventional tillage and full irrigation. We study other management packages by changing the form of fertilizer (inorganic-N or organic-N), the tillage practice (conventional or no-tillage) and the irrigation strategy (full or deficit irrigation). As a case study, we consider irrigated maize over a 15-years period (1998–2012) on a loam soil in Badajoz, Spain, which is a semi-arid environment. We use the Agricultural Policy and Environmental eXtender (APEX) model, which simulates water and nutrient balances and crop growth (Williams and Izaurralde, 2006). This model is able to successfully simulate the effect of a wide array of field management practices (Wang et al., 2012; Gassman et al., 2010; Gaiser et al., 2010), and has been applied for a wide range of environments, including semi-arid conditions in Spain (Cavero et al., 2012).

This is the first study assessing the trade-off between water depletion (blue WF) and water pollution (grey WF). By fully elaborating one case study we intend to show the feasibility of quantifying the effect of relevant soil, water and nutrient management interventions on both blue and grey WF and the feasibility of identifying which measures are no-regret (reducing both blue and grey WF) and which measures imply a trade-off. In addition, we explore how putting a price to pollution can alter a farmer's decision on the amount of N fertilizer to use and thus its effect on water depletion and water pollution. We do not expect that the quantitative findings can immediately be generalized to other crops and environments, but we expect that the methodological approach introduced here for one case study can be extended for other crops and environments and thus provide a basis for further study.

2. Method and data

2.1. Research set-up

We use the APEX model to simulate the effect of seven nitrogen application rates on evapotranspiration, N load to freshwater, and crop yield, and subsequently compute the resultant blue and N-related grey water footprints. We do this for eight field management packages, which results in 56 simulations altogether (Fig. 1). Each management package constitutes of a combination of management practices: application of inorganic-N or organic-N, no-tillage or conventional tillage, and full or deficit irrigation. The combination of inorganic-N fertilizer with conventional tillage and full irrigation is assumed as a reference management package.

The rate of N application from livestock manure in EU member states is legally restricted by the EU Nitrates Directive to 170 kg N ha^{-1} y^{-1}, or in case of derogation up to 250 kg N ha^{-1} (Van Grinsven et al., 2012; Amery and Schoumans, 2014). However, surveys in Spain show that application rates of 300–350 kg N ha^{-1} y^{-1} are still common to cultivate maize in the Ebro Valley (Berenguer et al., 2009) and up to 300 kg N ha^{-1} in La Mancha (Valero et al., 2005). In our simulations, we therefore use 300 kg N ha^{-1} as an upper value for the N-application rate.

2.2. Soil water and nitrogen balances and crop growth simulation

The soil water and nitrogen balances and crop growth under different conditions are simulated with a daily time step using APEX, a dynamic, deterministic and physical-based model (Williams and Izaurralde, 2006). A brief summary of the processes simulated in the APEX model, provided in detail in the documentation of APEX (Williams et al., 2008), is given below.

In the water balance routines, the incoming rainfall or irrigation is partitioned between surface runoff and infiltration. Infiltrated water partly gets stored in the soil profile, partly gets lost via evapotranspiration (ET), partly percolates vertically to groundwater, and partly flows out laterally, eventually splitting up into quick return flow and lateral subsurface flow.