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Water quality implications of raising crop water productivity

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ABSTRACT

Because of a growing and more affluent population, demand for agricultural products will increase rapidly over the coming decades, with serious implications for agricultural water demand. Symptoms of water scarcity are increasingly apparent, threatening ecosystem services and the sustainability of food production. Improved water productivity will reduce the additional water requirements in agriculture. However, there is a tradeoff between the quantity of water used in agriculture and the quality of return flow. Where yields are low due to limited nitrogen (N) and water supply, water productivity can be enhanced through higher fertilizer applications and improved water management. This limits the amount of additional water needed for increased food demand, thus leaving more water for environmental requirements. But it also increases the amount of nitrate (NO_3–N) leaching, thus adversely affecting the water quality of return flows.

This paper quantifies the tradeoff between enhanced water productivity and NO_3–N leaching and shows the importance of the right management of water and N applications. Using the Decision Support System for Agro-technology Transfer (DSSAT) crop model, several scenarios combining different water and N application regimes are examined for maize (*Zea mays* L.) in Gainesville, FL, USA. Without adequate water, nitrogen use efficiency (NUE) remains low, resulting in substantial NO_3–N leaching. Too much water leads to excessive NO_3–N leaching and lower water productivity. The lack of N is a cause of low water productivity but too much of it leads to lower NUE and higher losses. The paper concludes that increased NO_3–N leaching is an inevitable by-product of increased water productivity, but its adverse impacts can greatly be reduced by better management of water and N application. The paper briefly shows that leaching can be reduced and water productivity increased by split application of N-fertilizer. This implies that improved water and nutrient management at field- and scheme-level is a prerequisite to limit adverse impacts of agriculture on ecosystems, now and especially in the future.

1. Introduction

Agricultural achievements over the past 40 years have been remarkable. Global cereal production has doubled mainly due to increased yield resulting from greater inputs of fertilizer, water and pesticides, new crop varieties, and other technologies of the ‘‘Green Revolution’’ (WHO, 1990; FAO, 2001; Tilman et al., 2001). During the past 40 years, global fertilizer use increased by an estimated 700% (Matson et al., 1997; Tilman et al., 2001) and the area under irrigation expanded by an estimated 70% (Rosegrant et al., 2002; Gleick, 2003). As a result per capita food supply increased, reducing hunger and improving nutrition (Waggoner, 1995; Molden et al., 2007a). With a growing and more affluent global population, food demand is projected to nearly double over the coming 50 years (Alexandratos, 1999; Cassman, 1999; Cohan and Federoff,

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1999). Without increases in water productivity, crop water requirements may increase by 70–110% with potentially serious implications for the environment (de Fraiture et al., 2007).

Agriculture affects ecosystems downstream in two ways: (i) nutrient and pesticide loading from return flows, and (ii) change of hydrologic regime in terms of quantity and timing of flow (Falkenmark et al., 2007). Often there are tradeoffs between water quantity and quality. Wetland managers in the western United States must sometimes choose the ''lesser of two evils''—accepting irrigation drainage and risking toxic impacts, or rejecting the drainage and having insufficient water to maintain marshes (Lemly, 1994). Aquatic ecosystems provide important services such as fisheries, flow regulation, groundwater recharge and water purification (Galbraith and Huber-Lee, 2001). For instance, people in Cambodia get 60–80% of their animal protein from fisheries in the floodplains (Millennium Ecosystem Assessment, 2005). Communities that directly or indirectly depend on these services are harmed by ecosystem degradation. Poor people who typically have few alternative sources of income and food may be particularly at risk. Signs of severe ecosystem degradation due to overabstraction of water are increasingly apparent. Already, an estimated 1.2 billion people live in areas where water scarcity is an issue and increasing the output per unit of water is crucial to food security (Molden et al., 2007b). Additional water for agriculture will further strain ecosystems and intensify competition for water resources.

There is an urgent need to reduce the amount of water abstracted for agriculture by producing more food, income, livelihoods, and ecological benefits at less social and environmental costs per unit of water used. Water productivity defined in physical terms is the ratio of the mass of agricultural output to the amount of water used. In an economic sense, water productivity reflects the value derived per unit of water used. Improving physical water productivity in irrigated and rainfed agriculture reduces the need for additional water and is thus a critical response to increasing water scarcity (Molden et al., 2007b).

Fortunately, there is substantial scope to improve physical water productivity in both rainfed and irrigated agriculture, particularly in sub-Saharan Africa (SSA) and South Asia where yields are low because of sub-optimal nutrient and water supply (Bindraban et al., 1999; Rockström et al., 2003; Nangia et al., in review). In many parts of SSA, former Soviet Union and South Asia yields and fertilizer usage are less than 50% of those in the USA and the European Union (IFA, 2002). Improved fertilizer and water interaction management has beneficial impacts on biomass production and harvest index, and therefore water productivity in both irrigated and rainfed agriculture. Results of a recent study by Nangia et al. (in review) show that water productivity of maize, in terms of mass of crop yield per unit of evapotranspiration (WP_{ET}), can be improved with additions of N fertilizer. This improvement is highest at low levels of WP_{ET} associated with low to medium application rates of N. Beyond a threshold, further N application leads to little improvement in WP_{ET}.

But a higher level of N application leads to more NO_3–N leaching to groundwater, streams, and rivers. In fact, agriculture has become the largest source of N and phosphorus in waterways and coastal zones (Carpenter et al., 1998; Bennett et al., 2001). NO_3–N concentrations in major rivers of the northwestern United States have increased three- to tenfold since the early 1900s, an increase that is related to the use of inorganic fertilizers as well as other human activities (Howarth et al., 1996). Contamination of groundwater is common in agricultural regions around the world (Matson et al., 1997). High NO_3–N concentrations in drinking water are a human health hazard, causing methemoglobinemia (Frink et al., 1999). NO_3–N also affects the health of natural systems. Eutrophication of estuaries and other coastal marine environments can cause low- or zero-oxygen conditions, leading to loss of fish and shellfish and to algae blooms that are toxic to fish (Nixon, 1995; Howarth et al., 1996).

Achieving synchrony between N supply and demand, without excess or deficiency is the key to optimizing tradeoffs between enhancing water productivity to minimize water use and limiting NO_3–N leaching to reduce adverse effects on water quality. Setting the research agenda and developing effective management practices to meet this challenge requires a quantitative understanding of the current levels of nitrogen use efficiency (NUE) and NO_3–N losses. NUE is defined as the ratio of crop yield to the N fertilizer applied during the growing season (Cassman et al., 2003). Nitrogen fertilizer is the largest input of N and accounts for the largest portion of leaching losses from cereal cropping systems. Smil (1999) estimates total N input to the world's cropland at 169 million ton N $year^{-1}$. Inorganic fertilizer supplies 46% of the total, biological fixation from legumes and other N fixing organisms 20%, atmospheric deposition 12%, animal manure 11% and crop residues 7%.

Applied N that is not taken up by the crop is at risk to losses from NO_3–N leaching. The overall NUE of a cropping system can be improved by achieving greater uptake efficiency of applied N inputs. Fig. 1 shows the 5-year (1995–2000) average of inorganic N application and NUE for maize in different countries around the world. Countries on the extreme left of the *x*-axis exhibit very high NUE and low N fertilizer application (e.g. Uruguay, Azerbaijan, Nigeria and Ethiopia). Field experiments in the United States suggest that typical NUE for maize is approximately 58 kg grain/kg N applied (Dobermann and Cassman, 2002). Much higher NUE values at low N fertilizer application levels generally suggest mining of natural organic N. Such conditions are unsustainable in the long-term. Countries clustered on the right of the *x*-axis exhibit very low NUE in spite of moderate to high N fertilizer application rates (e.g. Zimbabwe, Ecuador and Egypt). This suggests that crops are not taking up the high rates of N, for example, because of unfavorable soil conditions (aeration, waterlogging), inadequate water supply in quantity or timing; or unsuitable fertilizer type for crop or soil (pH). The net effect is that the applied inorganic fertilizer is not benefitting the crop but pollutes the natural environment instead.

The objective of this paper is to explore the tradeoff between the water saving aspects of improved water productivity (i.e. more water for nature through higher water productivity) on one hand, and water quality degradation (i.e. potential adverse impacts of increased NO_3–N leaching) on the other. We use the DSSAT model to test several scenarios, comparing different fertilizer regimes in irrigated and rainfed

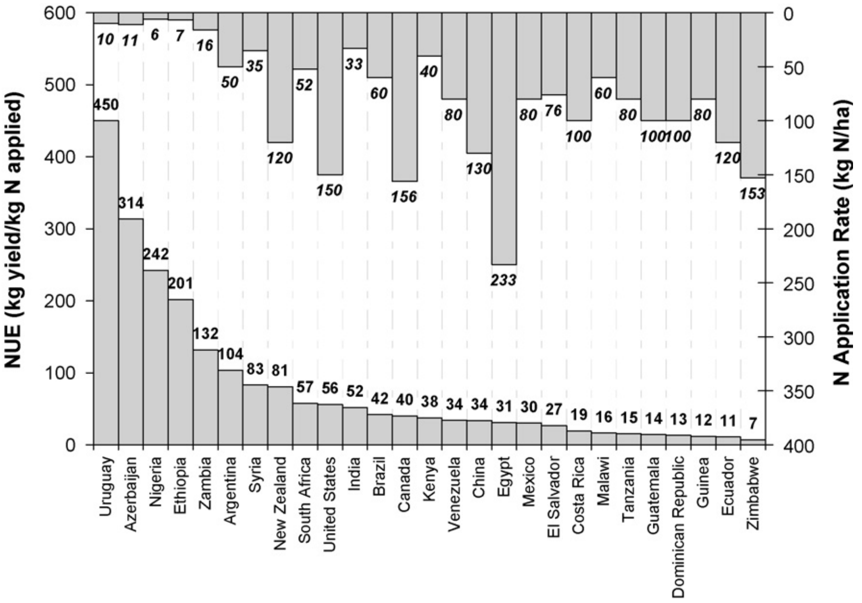

Fig. 1 – Comparison of average (1995–2000) nitrogen use efficiency (NUE) and nitrogen (N) application rate for maize crop in different countries (data sources: nitrogen application rate – International Fertilizer Association (IFA), 2002; yield – USDA-Foreign Agricultural Service, 2006).

agriculture to investigate the relationship between water productivity and NO_3–N leaching.

2. Materials and methods

2.1. DSSAT model

The Decision Support System for Agro-technology Transfer (DSSAT) incorporates CROPGRO and CERES crop growth models. The CERES-maize model is used to simulate maize cultivation. A detailed description of the CERES models can be found in Ritchie (1998). The models predict the growth duration, average growth rates and the amount of assimilate partitioned to the economic yield components of the crop. They compute crop growth stages and morphological development using temperature, day length and cultivar characteristics. Biomass accumulation is based on the radiation use efficiency method, where the biomass is partitioned among the leaves, stems, roots, ears and grains. Biomass partitioning is based on the stage of development and general growing conditions. The partitioning is based on the source-sink concept and is modified when water and nutrient deficiencies occur. Crop yields are determined as the product of grain numbers per plant and average kernel weight at physiological maturity. The number of grains is calculated from the aboveground biomass accumulation during the critical growth stage for a fixed thermal time (or growing degree-days, which is computed based on the daily maximum and minimum temperatures) before anthesis. The grain weight in all CERES models is calculated as the product of cultivar-specific optimum growth rate and the duration of the grain filling. Grain fill is reduced below the optimum if there is insufficient supply of assimilates from daily biomass accumulation or stored mobile biomass in stems and leaves. When growth is source-limited, assimilates are redirected from the shoot to the roots.

The soil water balance in DSSAT is based on Ritchie's model, where the concept of upper and lower drained limits of soil water is used as a basis for the available water in the soil (Ritchie, 1981a,b). It follows a so-called ‘‘tipping bucket’’ approach incorporating rainfall, infiltration and runoff, drainage, soil evaporation, plant transpiration, root absorption or flow to an adjacent layer. The soil-plant-atmosphere module computes potential evapotranspiration (ET) according to the Priestley–Taylor or Penman–Monteith method (Doorenbos and Pruitt, 1977). The potential ET is partitioned into potential soil evaporation (E) and potential plant transpiration (T). Potential soil evaporation is estimated from the fraction of solar energy reaching the soil surface based on a negative exponential function of leaf area index (LAI). Actual soil evaporation is simulated in a two-stage process. After the soil surface is wetted by rainfall or irrigation, soil evaporation occurs at the potential rate until a certain amount after which the rate is reduced proportional to the square root of time elapsed. If evaporation is less than potential soil evaporation, the difference is added back to potential plant transpiration to account for the increased heat load on the canopy when the soil surface is dry (Ritchie, 1972).

The nitrogen balance model simulates the processes of organic matter turnover such as mineralization and/or immobilization of nitrogen, nitrification, denitrification, hydrolysis of urea, ammonia volatilization, N plant uptake and translocation to the different organs during the crop cycle. Transport of NO_3–N occurs at the same rate as the flow of water (Booltink et al., 1996). Water and nitrogen sub-models calculate feedback effects on plant growth and development. Nitrogen uptake by the plant is determined by the potential supply and the uptake capacity or demand by the plant. Nitrogen demand has two parts. The first is the deficiency demand which represents the amount of N required to restore the minimum concentration required for optimum growth. The second and usually smaller part is required for new growth. The growth models in DSSAT estimate the potential amount of new growth before any stresses (due to water, nutrients or temperature) are applied. The potential new growth increment, together with the prevailing N concentration, determines the new growth demand. The soil water balance routine calculates the volume of water moving through each soil layer and the amount of NO_3–N lost from each layer. A simple cascading approach is used where the NO_3–N lost from one layer is added to the layer below. When the concentration of NO_3–N in the layer falls below 1 μg NO_3 (per gram soil), then no further leaching occurs.

In our simulations we use the modified Priestly–Taylor method to estimate ET. The WP_{ET} is computed from predicted yield and predicted ET.

2.2. *Site description and input data*

For our scenarios we use a calibrated DSSAT model for maize grown on a Kendrick fine sand soil (loamy, siliceous, hyperthermic Arenic Paleudult) at the Irrigation Research and Education Park located on the University of Florida Agronomy Farm at Gainesville. Fig. 2 shows the average rainfall distribution for the site. Before planting, the experimental area was moldboard ploughed and 1125 kg/ha of 0–6–25 (N–P_2O_5–K_2O) commercial fertilizer containing a mixture of trace elements was broadcast. Two seeds per hill of maize cv. McCurdy 84AA were hand-planted on 26 February 1982 in 61-m rows with 23 cm between seeds. Seedlings emerged on 8 March 1982 and plants were thinned to one plant per hill on 19 March 1982 resulting in a final plant population of 71,000 plants/ha.

Results of this and many other field experiments were used to calibrate the DSSAT model and are stored in the model database. More details on the Gainesville experimental study used for our scenarios can be found in (Bennett et al., 1986, 1989).

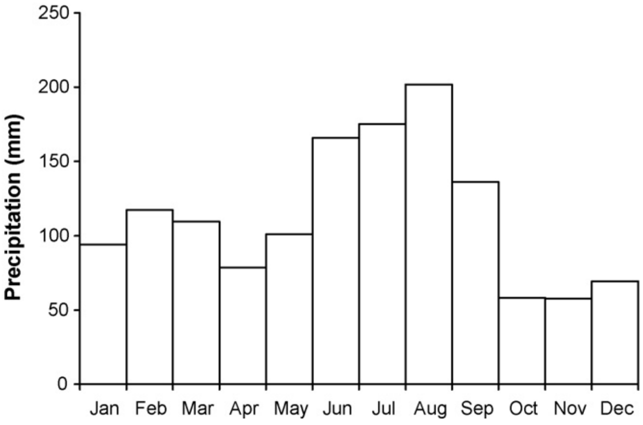

Fig. 2 – Average (1958–1987) precipitation at University of Florida, Gainesville weather station.

2.3. *Scenarios*

Long-term simulations with 30 years of weather data were conducted under rainfed and irrigated conditions. For the irrigated scenarios, the rainfall was set to zero. This was done to isolate the effects of non-uniform rainfall distribution from irrigation timing and depth. Combinations of rainfed, five irrigation depths at three different timings, six fertilizer application rates and two application timings were simulated. Table 1 gives the details on the different treatments. Under rainfed conditions a total of 529.1 mm of rain fell (30-year average) on the field (treatment 1). Under the irrigated treatments a total of 225, 450, 675, 900 and 1125 mm of water was applied (treatment no. 2, 3, 4, 5 and 6, respectively). Ammonium nitrate fertilizer at a depth of 10 cm was applied in six different dosages given on 15 March (treatment no. 7, 8, 9, 10, 11 and 12). Under the last five treatments (treatment no. 13, 14, 15, 16 and 17) the fertilizer application was divided over two dates (8 March and 29 April of each year). Although they are important factors affecting plant growth, application type and depth were kept constant to isolate the effects of water application and fertilizer amount and timing on crop growth.

Crop yield (kg yield/ha), water productivity in terms of mass of crop yield per unit of evapotranspiration (kg yield/m^3 ET), and NUE (kg yield/kg inorganic fertilizer N applied), leachate (kg NO_3–N leached/ha) were predicted by the DSSAT model.

3. Results

3.1. *Crop yield*

Crop yields are closely related to the amount of N and water applied (Fig. 3a). At low fertilizer applications (between 0 and 60 kg N/ha), additional water applied to the crop did not improve crop yields. But, additional rates of fertilizer together with more water improved crop yields dramatically. For example, yield increased from 2441 kg/ha at 60 kg N/ha and 675 mm irrigation depth to 6413 kg/ha at 250 kg N/ha and 900 mm irrigation depth. Beyond a certain level of irrigation and fertilizer rate, crop yield increments start to diminish. For this particular experimental site, a water application of 675 mm and nitrogen rate of 400 kg/ha produced the highest yield.

3.2. *Water productivity*

Improvements in water productivity are related to the interaction of water and N applications. Nitrification in DSSAT is a function of soil temperature and soil water content. Thus, good interaction of water with inorganic N helps improve plant N uptake leading to WP_{ET} improvement. For example, where only 225 mm of irrigation water was given, water productivity increased by 8% (from 0.99 to 1.07 kg/m^3 ET) when the N application rate was doubled from 60 to 120 kg N/ha, but when 675 mm of irrigation was given the same increase in fertilizer led to an increase in water productivity of 92% (from 0.36 to 0.69 kg/m^3 ET). Beyond 675 mm of irrigation, crop yields and water productivity began to decline (Fig. 3b): at 120 kg N/ha water productivity was 0.52 kg/m^3 ET and 0.24 kg/m^3 ET

Table 1 – Irrigation and fertilizer application treatments

Rainfed treatment	Date	Treatment no. 1 (average precipitation (mm))				
	–	529.1				
Irrigation treatments	Date	Treatment no. (amount water applied (mm))				
		2	3	4	5	6
Once a week	04 March	15	30	45	60	75
	11 March	15	30	45	60	75
	18 March	15	30	45	60	75
	25 March	15	30	45	60	75
	01 April	15	30	45	60	75
	08 April	15	30	45	60	75
	15 April	15	30	45	60	75
	22 April	15	30	45	60	75
	29 April	15	30	45	60	75
	06 May	15	30	45	60	75
	13 May	15	30	45	60	75
	20 May	15	30	45	60	75
	27 May	15	30	45	60	75
	03 June	15	30	45	60	75
	10 June	15	30	45	60	75
Once in 2 weeks	04 March	28	56	84	112	141
	18 March	28	56	84	112	141
	01 April	28	56	84	112	141
	15 April	28	56	84	112	141
	29 April	28	56	84	112	141
	13 May	28	56	84	112	141
	27 May	28	56	84	112	141
	10 June	28	56	84	112	141
Once in 3 weeks	04 March	45	90	135	180	225
	25 March	45	90	135	180	225
	15 April	45	90	135	180	225
	06 May	45	90	135	180	225
	27 May	45	90	135	180	225
Fertilizer treatments	Date	Treatment no. 7 (amount (kg N/ha))				
Single application	–	0				
Fertilizer treatments	Date	Treatment no. (amount (kg N/ha))				
		8	9	10	11	12
Single application	15 March	30	60	120	250	400
Fertilizer treatments	Date	Treatment no. (amount (kg N/ha) on each date)				
		13	14	15	16	17
Split application	8 March and 29 April	15	30	60	125	200

under 675 and 900 mm of irrigation, respectively. Unlike crop yield, which was highest at water application depth of 675 mm and fertilizer application rate of 400 kg N/ha, water productivity was highest at 450 mm water application depth and 400 kg N/ha fertilizer application rate. These results confirm the finding by others that the highest crop yields (land productivity) do not necessarily result in the highest water productivity (Zhang et al., 1998; Zwart and Bastiaanssen, 2004; Bessembinder et al., 2005).

3.3. Nitrogen use efficiency

NUE is highest at the lowest N fertilizer application rate of 30 kg N/ha (Fig. 3c). However, at this level of fertilizer application the yield is also at its lowest. This implies that although the bulk of the applied N is taken up, the plant does not get enough for potential growth. At higher N application rates, the NUE decreases while crop yield increases. Thus, we witness a tradeoff between trying to maximize the NUE and trying to achieve a high crop yield. At low irrigation application rates, the decline in NUE with increased N application is most pronounced.

3.4. Nitrogen leaching

Higher water and fertilizer applications lead to higher yields, improved water productivity and better NUE, but also to increased NO_3–N leaching (Fig. 3d). Leaching rates are modest

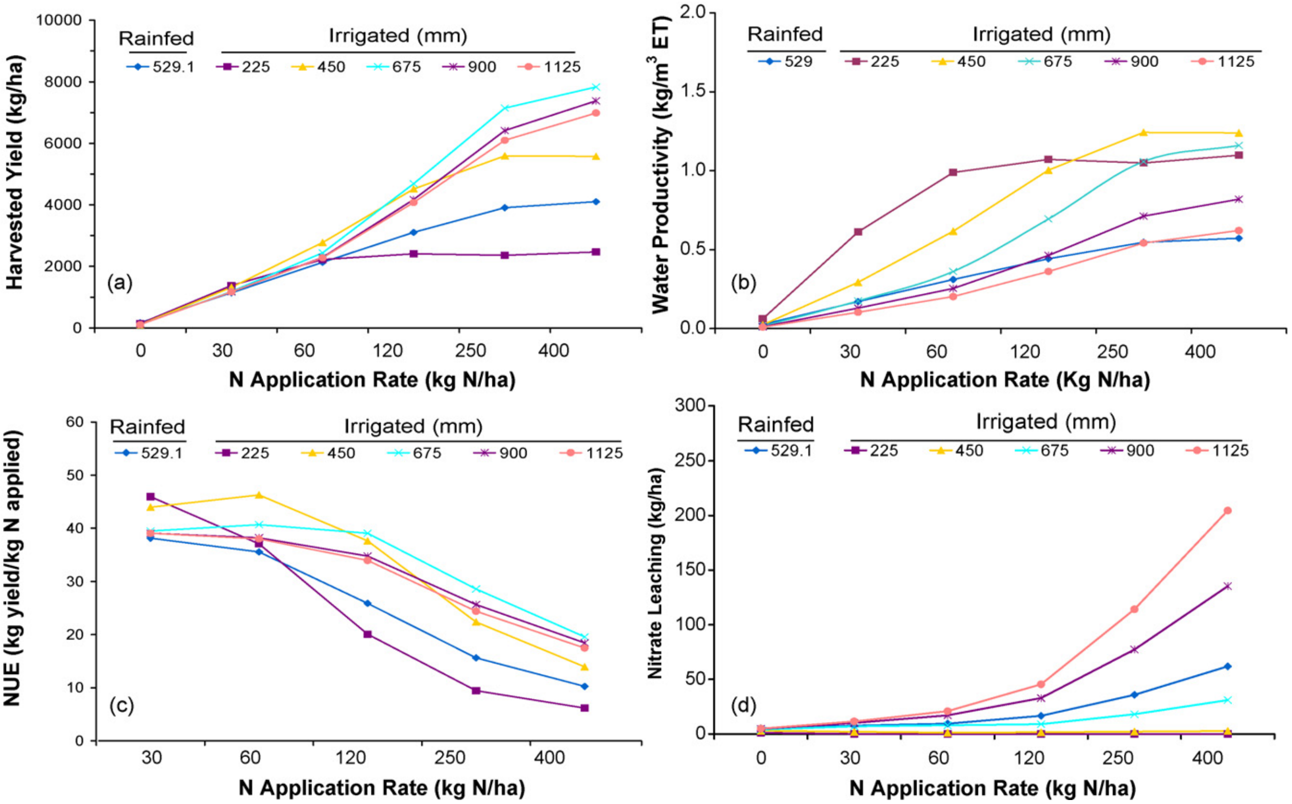

Fig. 3 – Predicted relationship between nitrogen fertilizer, water application rates, and (a) yield, (b) water productivity, (c) NUE, and (d) NO_3–N leaching for maize crop at Gainesville, Florida. Irrigation timing is held constant at once per 2 weeks.

up to an N fertilizer application rate of 120 kg N/ha, while yield and water productivity increase at a relatively higher rate. For example, NO_3–N leaching increases by 14% (from 8 to 9 kg/ha) between 60 and 120 kg N/ha at 675 mm once in a 2-week irrigation schedule but crop yield and water productivity increase by 92% (from 2441 to 4688 kg/ha) and 92% (from 0.36 to 0.69 kg/m^3 ET), respectively. But beyond the 120 kg N/ha threshold, NO_3–N leaching rates increase steeply. For example, NO_3–N leaching increases by 100% (from 9 to 18 kg/ha) between 120 and 250 kg N/ha fertilizer application at 675 mm once in a 2-week irrigation schedule, but crop yield and water productivity increase only by 52% (from 4688 to 7146 kg/ha) and 52% (from 0.69 to 1.06 kg/m^3 ET), respectively. NO_3–N leaching increases at fertilizer application rates of above 120 kg N/ha because the supply exceeds the uptake capacity or the demand by the plant. This leads to a lower NUE.

3.5. *Rainfed*

Under rainfed conditions, yields and water productivity are low. This is reflected in a low NUE. Beyond a N application rate of 30 kg N/ha, yields increase with additional applications of water suggesting that supplemental irrigation can improve yields at this site. Although water application for rainfed treatment (529.1 mm) is higher than for irrigation depths 225 and 450 mm, the water productivity under rainfed conditions is much lower than under the two irrigation treatments. The rain falls at sub-optimal times and often in large quantities. When not required by the plants and not stored in the root zone the rain runs off or percolates to deep groundwater thus leading to low water productivity.

3.6. *Irrigation timing*

The timing of water and nutrient application is an important factor governing plant growth, water productivity and NO_3–N leaching. In our simulations, irrigation once per 3 weeks with a seasonal total of 675 mm and an N fertilizer application rate of 250 kg N/ha results in a water productivity of 0.51 kg/m^3 and 32 kg/ha of NO_3–N leaching. Changing the irrigation regime to watering once per week leads to a water productivity of 0.95 kg/m^3 and NO_3–N leaching of 13 kg/ha, an improvement of 86 and 146%, respectively. However, factors such as availability and price often determine how much and at what time water and fertilizer are applied to the field. In regions where these resources are scarce, farmers tend to apply less. Where these resources are plentiful and their relative cost in overall crop production small, farmers tend to apply more than at the level where the highest productivity is obtained. Farmers optimize income and land productivity rather than water productivity, particularly where water is cheap or free. For example, Florida Cooperative Extension Service (Hochmuth and Cordasco, 2000; Wright et al., 2004) recommends application of 165–220 kg N/ha. These application rates produce highest crop yield but they

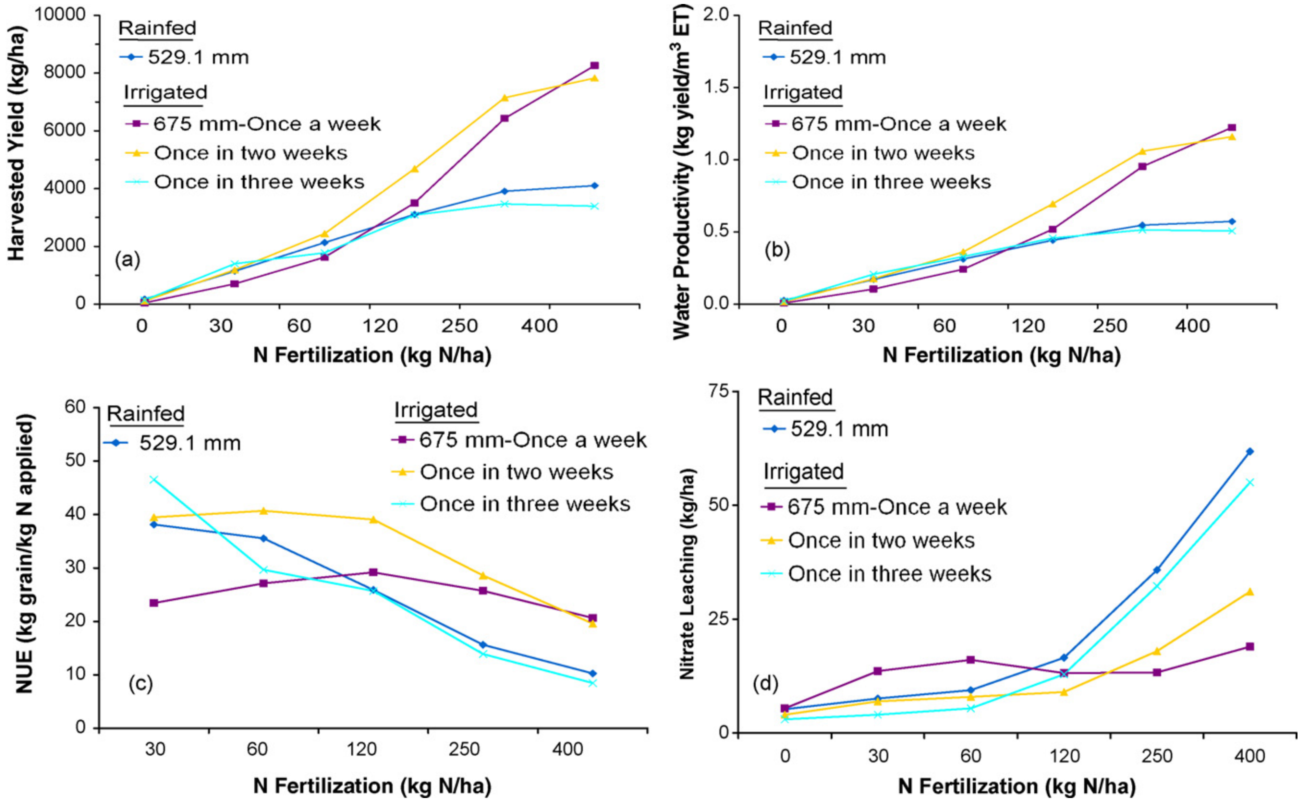

Fig. 4 – Predicted relationship between nitrogen fertilizer, water application timings, and (a) yield, (b) water productivity, (c) NUE, and (d) NO_3–N leaching for maize crop at Gainesville, Florida. Irrigation depth is held constant at 675 mm.

are below the level where the highest water productivity occurs.

Fig. 4(a–d) shows harvested yield, water productivity, NUE and NO_3–N leaching predicted for different amounts of N fertilizer application and irrigation timings. Irrigation depth is held constant at 675 mm. Irrigation intervals of 1 and 2 weeks produce high crop yields and water productivity compared to 3 weeks and rainfed conditions (Fig. 4a and b). When yield and water productivity are high, NUE is usually high as well. But an irrigation frequency may come at high operational costs in terms of energy where water has to be pumped. Fig. 4c shows that irrigating once a week and once in 2 weeks produces high NUE values whereas the other treatments produce low values. The NO_3–N leaching trend is the inverse of the NUE trend (Fig. 4d). High uptake efficiency under the high frequency irrigation scenarios exhibit lower NO_3–N losses compared to the other two treatments, i.e. low irrigation frequency and rainfed.

Fig. 5 shows the relationship between irrigation frequency and leaching, evaporation, transpiration and NUE. A high irrigation frequency leads to higher losses from soil evaporation because the soil is wet during a longer period than when irrigation is applied with a lower frequency. In our simulations 11% of 675 mm of irrigation water applied is lost by the soil evaporation when irrigation is applied once per week. Only 5% is lost to soil evaporation when irrigation is applied once in 3 weeks. However, both plant transpiration and NUE are also higher under a high irrigation frequency regime. With an irrigation frequency of once per week plant transpiration accounted for 50% of the 675 mm applied compared to 26% under a low irrigation frequency of once in 3 weeks. NUE amounted to 26 kg grain/kg N and 13 kg grain/kg N for irrigation frequencies of once per week and once in 3 weeks, respectively. The water that is not consumed by evapotranspiration (39 and 69% in case of the high and low frequency irrigation, respectively) can facilitate the leaching of applied N in the form of highly soluble and mobile NO_3–N. As a result, NO_3–N leaching is 19 kg N/ha higher under the low irrigation

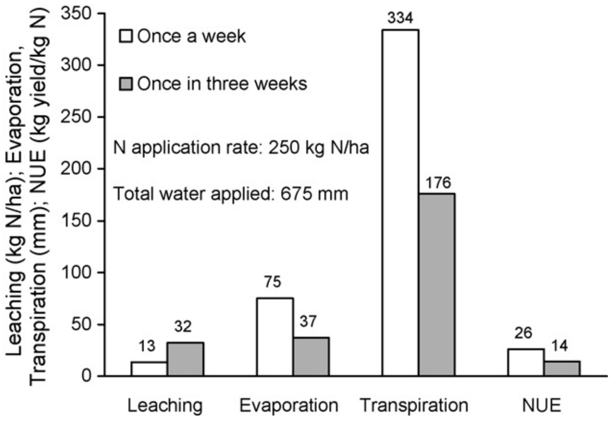

Fig. 5 – Relationship between irrigation timing and leaching, evaporation, transpiration and NUE.

Table 2 – Change in water productivity (kg yield/m^3 ET) and NO_3–N leaching (kg N/ha) as a result of change in N fertilizer application rate

Treatment	Total water applied	WP	Leachate	WP	Leachate	WP	Leachate	WP	Leachate	WP	Leachate	WP	Leachate
	N fertilizer application rate (kg N/ha)												
		0		30		60		120		250		400	
Rainfed	529.1	0.03	5.23	0.17	7.57	0.31	9.40	0.44	16.53	0.55	35.80	0.57	61.83
Irrigated: once per week													
Depth of irrigation (mm)													
15	225	0.10	0.00	0.57	0.00	0.83	0.00	0.80	0.00	0.79	0.00	0.81	0.00
30	450	0.01	3.37	0.30	1.23	0.55	1.07	0.85	1.20	1.09	1.50	1.08	1.93
45	675	0.01	5.40	0.10	13.60	0.24	16.07	0.52	13.17	0.95	13.30	1.22	18.97
60	900	0.01	6.00	0.07	20.83	0.13	36.17	0.24	62.93	0.45	107.03	0.64	152.57
75	1125	0.00	6.57	0.05	23.10	0.09	42.90	0.16	84.60	0.28	174.03	0.38	278.70
Irrigated: once per 2 weeks													
Depth of irrigation (mm)													
28	225	0.06	1.00	0.61	0.00	0.99	0.00	1.07	0.00	1.05	0.00	1.10	0.03
56	450	0.02	3.00	0.29	1.93	0.62	1.20	1.00	1.53	1.24	2.13	1.24	2.73
84	675	0.02	4.03	0.18	6.97	0.36	7.93	0.69	9.00	1.06	18.00	1.16	31.07
112	900	0.01	4.60	0.13	10.07	0.25	17.10	0.46	32.83	0.71	77.23	0.82	135.37
141	1125	0.01	4.90	0.10	11.47	0.20	20.83	0.36	45.47	0.54	114.13	0.62	204.50
Irrigated: once per 3 weeks													
Depth of irrigation (mm)													
45	225	0.06	1.00	0.56	0.03	0.85	0.03	0.78	0.03	0.78	0.17	0.80	0.20
90	450	0.36	3.00	0.31	2.20	0.49	2.97	0.77	3.57	0.77	6.17	0.75	8.50
135	675	0.02	3.00	0.21	4.03	0.33	5.42	0.46	12.87	0.51	32.27	0.51	55.03
180	900	0.02	3.03	0.16	4.87	0.25	8.17	0.34	17.97	0.38	48.97	0.38	87.00
225	1125	0.01	3.03	0.12	5.13	0.20	9.10	0.27	21.07	0.30	58.20	0.30	101.77

frequency. Despite higher soil evaporation, WP_{ET} is highest under a high irrigation frequency.

Table 2 and Fig. 6 summarize the relationship between change in N fertilizer application rate, irrigation depth, and their combined effects on water productivity and NO_3–N leaching. It is evident that there is a strong relationship between increased water productivity and an increase in NO_3–N leaching. But careful depth and timing of irrigation can mitigate NO_3–N leaching losses.

3.7. *Fertilizer application timing*

To show the impact of timing, scenarios were run with two N fertilizer application timings—single and split application. Previous research has shown that split application of fertilizer generally improves crop yield because the first application of fertilizer helps the crop during germination and early vegetative growth. The second application, as a side-dressing, helps improve growth to maturity (Baker and Melvin, 1994; Randall et al., 2003). Whenever fertilizer application benefits crop growth, the uptake of N by the crop is high, leading to less NO_3–N leaching. Table 3 compares two irrigation depths – 675 and 900 mm applied once every 2 weeks and two fertilizer application rates – 120 and 250 kg N/ha with single and split applications. It is evident that split application reduces NO_3–N leaching and improves N uptake by crop resulting in higher yield, NUE and water productivity. Therefore, an important management strategy to minimize leaching of fertilizer applied to increase water productivity will be better fertilizer management, using split applications.

Table 3 – Comparative performance of single and split N fertilizer applications on leaching and water productivity

Irrigation (total depth)	Fertilizer rate (kg N/ha)	Fertilizer timing	Yield (kg/ha)	NUE (kg grain/kg N)	NO_3–N leaching		Water productivity	
					kg NO_3–N/ha	% decrease	kg/m^3 ET	% gain
675	120	Single	4710	39.3	9.4	27	0.70	20
675	120	Split	5656	47.1	6.9		0.84	
675	250	Single	7160	28.6	18.5	44	1.06	6
675	250	Split	7615	30.5	10.4		1.13	
900	120	Single	4184	34.9	33.7	46	0.46	31
900	120	Split	5463	45.5	18.1		0.61	
900	250	Single	6413	25.7	77.2	49	0.71	11
900	250	Split	7127	28.5	39.1		0.79	

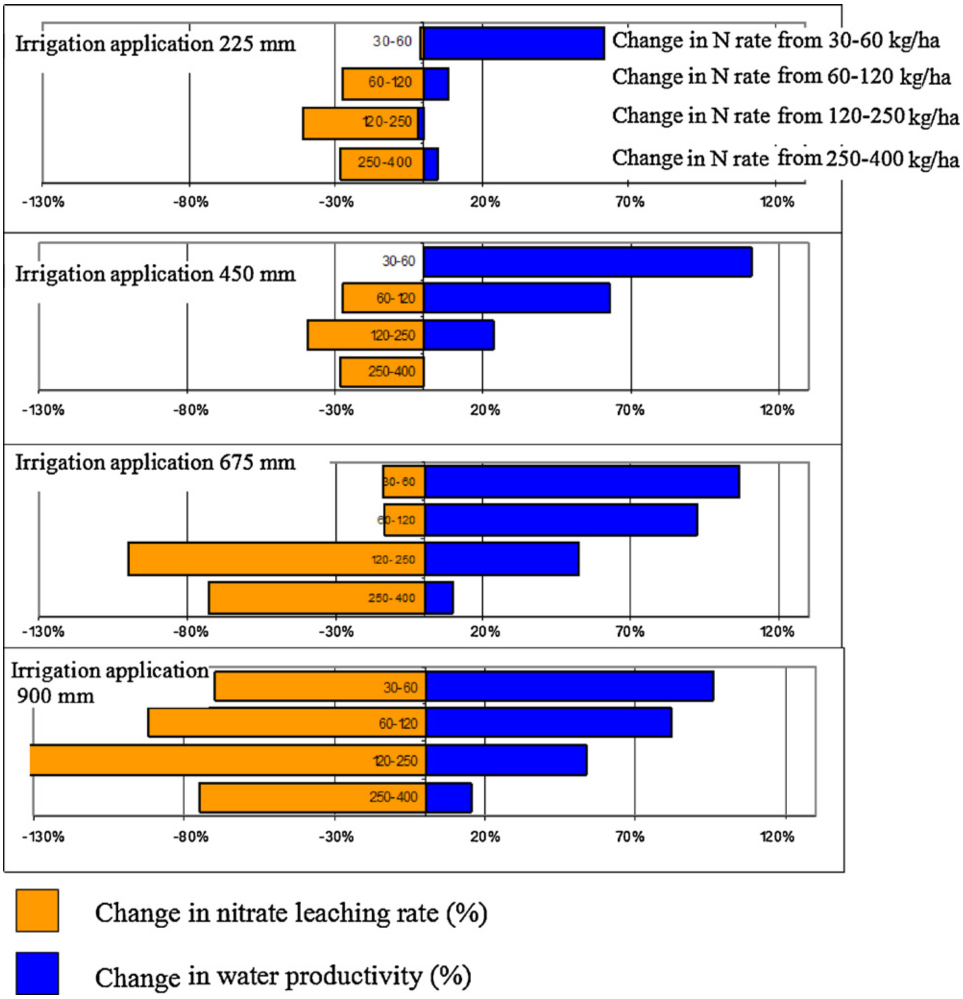

Fig. 6 – Percentage change in water productivity and NO_3–N leaching as a result of change in N fertilizer application rate.

4. Conclusions and discussion

With growing water demand and increasing signs of water scarcity, there is an urgent need to achieve higher output per unit of water consumed. Fortunately, there is ample scope to improve crop water productivity, particularly in areas where yields are currently low. Reliable water supply and improved N fertilizer application rates are prerequisites to achieve improved water productivity. But there is a tradeoff between water quantity and quality: improved water productivity may lead to less water withdrawals for irrigation, and hence more water for the environment. All other things being equal, improved water productivity often requires higher N fertilizer application rates than currently applied, inevitably leading to higher NO_3–N leaching. This may lead to deterioration of water quality affecting groundwater and downstream ecosystems.

This paper examines this tradeoff using data from an experimental site for maize at Gainesville, Florida. Yields, water productivity, NUE and NO_3–N leaching under different fertilizer and water application regimes are tested using the DSSAT model. Results show that improvements in water productivity are related to the improved management of water and N application.

While the optimal water and N application rates are site specific (depending on soil characteristics, crop type, climate and agricultural practices), the general conclusion of this paper has wider implications:

- An increase in NO_3–N leaching is an inevitable by-product of higher fertilizer application rates that are necessary for improvements in crop water productivity. This implies a tradeoff between water quantity and quality.
- Fortunately, a substantial part of NO_3–N leaching can be offset by managing the quantity and timing of N fertilizer and water application. Better inorganic N and water management lead to higher water productivity and at the same time less NO_3–N leaching. Protected or slow release fertilizers have also been developed and used in Organisation for Economic Co-operation and Development (OECD) countries, and could, in the long-term, find a place in the agricultural practices of developing countries to further mitigated NO_3–N leaching.

In this study, we apply a pre-calibrated model at field scale. The values of yields, water productivity and NUE are specific for the site in Florida. For example, the NUE is lower than average for the USA. A study by Cassman et al. (2002) reports that data obtained from 55 farm experiments conducted in Illinois, Michigan, Minnesota, Missouri, Nebraska and Wisconsin gave a NUE of 56 kg N/ha with a 30% standard deviation. Maize is not a predominant crop in Florida. Soil and climatic conditions in the Midwest US are better suited for maize than in Florida. The NUE of our simulation results is lower than the US average because it is biased towards the Midwest region where the bulk of the American maize is grown.

We define water productivity here as the economic yield per unit of water consumed. We prefer this definition over the theoretically more robust definition of biomass per unit of water transpired due to two reasons. First, farmers are primarily interested in economic yield (in terms of kilograms of produce) rather than biomass. The ratio of economic yield and biomass is defined as the harvest index. The harvest index depends mainly on crop variety and the level of water and nutrient stress during the flowering period. The DSSAT model is able to simulate this, though admittedly the lack of empirical data on the harvest index adds uncertainty to the results. The behavior of the harvest index is an important determinant of water productivity and deserves more research. Second, water managers tend to be more interested in ET rather than T, because they have little control over the separation between E and T. The DSSAT model predicts both T and E.

The aim of this paper is to examine the tradeoff between water quantity and quality. For this site the optimum scenario in terms of highest crop water productivity (1.13 kg/m^3 ET) and lowest NO_3–N leaching (10.4 kg NO_3–N/ha) occurs at 675 mm of irrigation once per 2 weeks and a split fertilizer rate of 250 kg N/ha. However, this is not necessarily the most optimal scenario from a farmer's perspective. Farmers optimize income and land productivity rather than water productivity. The Florida Extension Service recommends a fertilizer application of 165–220 kg N/ha where highest land productivity occurs. Site specific recommendations on optimal fertilizer and water rates are beyond the scope of this desk study. Further detailed farm studies are needed to provide more site specific insights.

Although a substantial amount of NO_3–N leaching can be mitigated at field scale, there nevertheless will be an increased load off-farm. Where water is scarce, it is often reused several times within irrigated areas and between sectors. Recycling of polluted return flows will lead to higher concentrations of fertilizer residuals. Consequently, higher fertilizer application at field scale requires better management of return flows at irrigation system and catchment scale. Research is required into appropriate ways of doing this—for instance, in better irrigation and drainage system management, with greater internal recycling. Buffer strips along rivers have long been mooted and implemented in countries like Australia, and have been shown to reduce non-point source loadings, but ironically will consume water in the process. The issues of scale in NPS pollution related to agricultural intensification require further elaboration and research.

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