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REPORT

Sustaining food self-sufficiency of a nation: The case of Sri Lankan rice production and related water and fertilizer demands

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Abstract Rising human demand and climatic variability have created greater uncertainty regarding global food trade and its effects on the food security of nations. To reduce reliance on imported food, many countries have focused on increasing their domestic food production in recent years. With clear goals for the complete self-sufficiency of rice production, Sri Lanka provides an ideal case study for examining the projected growth in domestic rice supply, how this compares to future national demand, and what the associated impacts from water and fertilizer demands may be. Using national rice statistics and estimates of intensification, this study finds that improvements in rice production can feed 25.3 million Sri Lankans (compared to a projected population of 23.8 million people) by 2050. However, to achieve this growth, consumptive water use and nitrogen fertilizer application may need to increase by as much as 69 and 23 %, respectively. This assessment demonstrates that targets for maintaining self-sufficiency should better incorporate avenues for improving resource use efficiency.

Keywords Self-sufficiency · Food security · Agricultural intensification · Water footprint · Nitrogen runoff · Water resources

INTRODUCTION

Global food trade plays an integral role in redistributing agricultural production. Because the resources required for food production are heterogeneously distributed across the planet, the import of food allows a country's population to exceed the number of people that the locally available resources could otherwise support. Trade dynamics, however, are susceptible to long-term demographic changes as well as short-term fluctuations in political and environmental conditions. This fact is noteworthy given that 78 % of countries are not self-sufficient in terms of domestic calorie production (Davis et al. 2014). During times of scarcity (e.g., 2007/2008 food crisis and 2010 droughts/wildfires in Russia), countries that are heavily dependent on food imports are at a distinct disadvantage in terms of food security as compared to nations who can rely on local crop production to meet dietary demands. Moreover, countries in surplus may need to reduce their food exports in the coming decades as a result of increasing domestic demand (Suweis et al. 2013). Indeed, recent work has shown that, as the global food system has become more dependent on trade, it has lost resilience and grown more susceptible to shocks and crises (Suweis et al. 2015). To minimize the vulnerability associated with dependence on food imports, national self-sufficiency policies have been implemented around the world, including in Qatar, Japan, and India (Fader et al. 2013).

With rice comprising approximately 40 % its total crop production (FAO 2014a), Sri Lanka provides an interesting example of a country with a long-standing, national self-sufficiency policy. Since gaining independence in 1948, agricultural policies in Sri Lanka have generally been aimed at improving its self-sufficiency in all food crops. Particularly, the target for rice production (the staple food of the country) was established at 100 % of domestic demand (Imbulana et al. 2006). Due to a combination of high yielding varieties, paddy expansion, and increased use of irrigation and fertilizer, rice production has steadily risen to meet this target. As a result, Sri Lanka has been

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almost entirely reliant on its own rice production since 2005 (DCS 2014; FAO 2014a). While the country is currently able to meet domestic demand for rice, it is unclear whether the country can continue to do so under projected population growth.

Sri Lanka's population is projected to increase by approximately 18 % (from 20.3 to 23.9 million people) before plateauing by mid-century due to increased economic development and decreasing fertility (DCS, 2012; UN 2012). Current rice yields are also already approaching the maximum attainable yield (i.e., the highest crop yield that a farmer can attain in a given climate using conventional technologies such as irrigation and fertilizers), leaving limited room for improving crop productivity (Mueller et al. 2012). In view of Sri Lanka's continuing efforts to maintain self-sufficiency in terms of rice production, it is important for the country to take stock of what the projected demand may be in the coming decades and whether rice production can respond to meet this demand. In addition, decision-makers must be aware of what the consequences for water resources may be, as further intensification of rice production will likely necessitate the use of greater amounts of nitrogen fertilizer and irrigation water and may contribute to increased nutrient runoff and reduced environmental flows.

With these various considerations in mind, here we examine three possible scenarios of intensification—improving rice yields, maximized crop harvest frequency, and optimized water use efficiency—to determine how many people might be fed and what the impact on water resources may be. In doing so, this study offers a simple assessment of projected rice demand in Sri Lanka, potential avenues for increasing supply to meet self-sufficiency goals, and what these options may mean for future water use and quality. Intended as an example of how to evaluate future food supply, human demand, and resource needs simultaneously, our work here focuses on changes in water demand and pollution from fertilizers. We therefore acknowledge that other factors, both biophysical (e.g., climate change, greenhouse gas emissions, and soil loss) and socioeconomic (e.g., job creation and commodity markets), may also be important to decision makers and that their inclusion in a similar analysis can help provide a more holistic perspective of the impacts and benefits of intensification. Our analysis provides a framework by which other countries may gain insight into their prospects for self-sufficiency and, in turn, identify what policy changes may be needed to improve their outlook.

MATERIALS AND METHODS

To assess Sri Lanka's ability to meet future national demand for rice, rice production statistics were collected and analyzed for trends. Literature values were then used to determine the maximum harvest frequency and attainable rice yields. Using diet projections for South Asia, the number of people that Sri Lanka can support with the increased production is determined and compared to the country's population growth estimates. We then identified the irrigation water and nitrogen fertilizer inputs necessary to increase the yield from current levels to close the yield gap (calculated as the difference between the maximum attainable yield and the current yield) by 50, 75, and 90 %. The water and nitrogen inputs were then used to compute the blue and gray water footprints for each of these yield gap closures (YGC), where blue water represents irrigation water derived from surface and groundwater sources and gray water represents changes in water quality from fertilizer runoff. The blue and gray water footprint calculations are based on the water footprint network methods and allow quantification of changes in water use and quality (Hoekstra et al. 2011). These concepts of blue and gray water—as well as the calculations used to quantify them—are described in detail below. Finally, improvements in water resource use efficiency were compared to total and renewable freshwater resources (RWR) to determine absolute changes in water use.

Site description

Due to local agro-ecologies, two distinct rice production zones can be delineated in Sri Lanka: the wet zone (WZ) and the dry zone (DZ) (Fernando et al. 2010). The WZ receives approximately 2500 mm of rain annually while the DZ receives approximately 1550 mm of rain annually. To maximize rice production in the two zones, different cultivation practices and seed varieties (such as a preference for longer duration varieties in the WZ where water is not as much of a constraint) are employed (Weerakoon et al. 2011). Nubin (2002)'s delineation of the two zones was used to determine which rice districts fall within the wet and dry zones (Fig. 1). Rice is cultivated during two seasons in both zones, with Maha being the major season and Yala the minor.

Historical production and future demand

Rice statistics (average yield, harvested extent, and total production) from 1979 to 2013 for each district were obtained from the Agriculture and Environmental Statistics Division of the Sri Lankan Department of Census and Statistics and the FAOSTAT database (DCS 2014; FAO 2014a). Average WZ and DZ yields were calculated as a production-weighted mean of the districts comprising each zone. The relative contribution of improving yields, r_y,—as

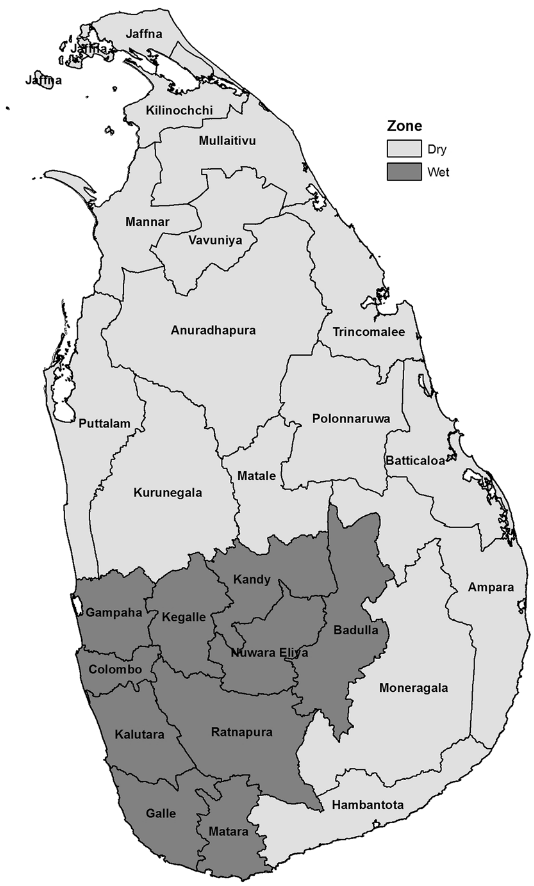

Fig. 1 Wet and dry zones of Sri Lanka

opposed to rice area expansion—to the growth in total rice production was calculated as

$$r_y = \frac{p_{2013} - (y_{1985}A_{2013})}{p_{2013} - p_{1985}},$$

where p_{1985} and p_{2013} are the total rice production in the years 1985 and 2013, y_{1985} is the rice yield in the year 1985, and A_{2013} is the harvested rice area in 2013. 1985 was selected for this analysis because it was the earliest year with no missing data.

Crop harvest frequency for temporary crops (i.e., crops that must be planted every growing cycle) was calculated for each year by dividing the harvested area for temporary crops by the arable area for temporary crops (FAO 2014a) following the methods of Ray and Foley (2013); this ratio was found to be consistent at 1.1 harvests year^{-1} over the past 30 years. Maximum potential harvest frequency for temporary crops (i.e., 2 harvests year^{-1}) was determined by Ray and Foley (2013); maximum and current harvest frequencies for temporary crops were assumed to be the same for rice because rice production comprised 82 % of temporary crop production (FAO 2014a). We also assumed a linear relationship between harvest frequency and resources for the scenarios considered here (e.g., if harvest frequency doubles for a given yield, then the amount of required resources also doubles). The distribution of arable rice area for Sri Lanka (71.5 % in DZ) used in this study was determined using Gumma et al. (2011)'s rice map (Table 1). Because much of the increase in food production is expected to occur as a result of intensification (i.e., improved crop productivity for a given area of land) and much of the lands most suitable for crops are already actively cultivated (Godfray et al. 2010; Foley et al. 2011; FAO 2014a), arable area was assumed to remain constant in the future.

Nitrogen application rates and irrigation use (i.e., the percent of arable rice area equipped for irrigation) corresponding to current yields and yields at 50, 75, and 90 % YGC were obtained from Mueller et al. (2012) for Sri Lanka under year 2000 crop resource use efficiency. The rice map from Gumma et al. (2011) combined with IIASA/FAO (2012)'s map of crop suitability index (i.e., the percent of maximum attainable rice yield possible as constrained by soil characteristics) show a homogenous rice suitability index in the rice-producing areas of Sri Lanka; therefore, we assume the maximum attainable yields and harvest frequencies are consistent across the two zones.

Future rice yields were estimated as a linear extrapolation of historical rice data. When this extrapolation reached the maximum attainable rice yield for Sri Lanka—assumed to be 5.02 tons ha^{-1} based on the value reported by Mueller et al. (2012)—rice yields were assumed to have plateaued for any subsequent years. To ensure that a linear model was the most accurate fit to historical rice yield data, we compared the root mean square error (rmse) of six different statistical models—linear, quadratic plateau, two part linear-piecewise, linear-upper plateau, linear-lower plateau, and exponential—used by Grassini et al. (2013) to describe historical crop yield trends (see details in Table S1). For all four datasets (Maha(major)-WZ, Maha(major)-DZ, Yala(minor)-WZ, and Yala(minor)-DZ), this check confirmed that a linear model was the best fit for historical rice yield data.

Information on current diet composition was obtained from FAOSTAT (2014a). Estimates for future diet compositions were based on values from Alexandratos and Bruinsma (2012) for South Asia, where the percent increases in South Asian rice demand for 2000–2030 and for 2000–2050 were then applied to the current (ca. 2000) rice demand in Sri Lanka (Table 1). This is a reasonable assumption as the daily per capita diet of South Asia in the year 2000 (2387 kcal cap^{-1} day^{-1}; 30 % from rice) is comparable to the year 2000 Sri Lankan diet (2319 kcal cap^{-1} day^{-1}; 38 % from rice) (FAO 2014a). In incorporating pre-consumer waste into the calculations, the current percentage of rice production used for food

Table 1 Variables used for calculating future supply and demand scenarios. Percent yield gap closure (YGC) is the relative improvement in crop yield—given inputs of irrigation water and fertilizer—from the current crop yield toward the maximum crop yield attainable by a farmer

Data	Value	Source(s)
Population (millions of people)		
Current (ca. 2000)	18.8	UN (2012)
2030	23.3	
2050	23.8	
Diet (kg cap^{-1} $year^{-1}$)		
Current (ca. 2000)	139.1	FAO (2014a)
2030	139.1	Alexandratos and Bruinsma (2012)
2050	136.4	
Yield (kg ha^{-1})		
Current (ca. 2000)	3.77	DCS (2014) and Mueller et al. (2012)
50 % YGC	4.40	
75 % YGC	4.86	
90 % YGC	5.00	
100 % YGC	5.02	
Crop harvest frequency (harvests per year)		
Current (ca. 2000)	1.1	FAO (2014a) and Ray and Foley (2013)
Maximum	2.0	
Area (1000 ha)		
Current (ca. 2000)	719	Gumma et al. (2011)

(95.7 %) was assumed to be constant through time (FAO 2014a). Population projections were from UN (2012). All data on current (ca. 2000) yield, area, and production are an average of values from 1997 through 2003 in order to agree with average yield gap values calculated in Mueller et al. (2012) (Table 1).

Finally, we calculated the total number of people able to be fed by rice production in the years 2000, 2030, and 2050 under three different scenarios. In the 'Yield' scenario, harvest frequency was held constant at 1.1 harvest $year^{-1}$ while rice yields were allowed to increase—based on linear extrapolations of historical rice yield data—until the maximum attainable yield. The number of people, P, able to have their dietary demand for rice met under this scenario in year x was then calculated as

$$P = \frac{a_{2000} h_{\text{hist}} r_x}{d_x},$$

where a_{2000} is the arable rice land in the year 2000, h_{hist} is the historical harvest frequency, r_x is the rice yield in year x, and d_x is the per capita annual rice demand in year x. In the 'Harvest' scenario, all conditions are the same as in the 'Yield' scenario except h_{hist} is replaced with $h_{\max}$, the maximum harvest frequency. The 'Efficiency' scenario considers the amount of rice production possible at the YGC which uses water most efficiently to produce a ton of rice. The amount of rice production at this level of YGC was then divided by d_x to determine the number of people able to have their dietary demand for rice met in year x. These estimates of supply were then compared to UN population projections to examine the rice self-sufficiency possible with each scenario.

Water footprints

The water footprint of a crop is defined as the amount of water required to produce a given amount of that crop throughout its production cycle. This concept was first introduced by Falkenmark and Rockström (2006), has been extensively studied (see Mekonnen and Hoekstra (2011) and Hoekstra et al. (2011)) and can be used to quantify the consumptive water use of a crop as well as the impact of that crop's production on water quality. Here we follow the water footprint concept and methods developed by the water footprint network and described in the manual *Water footprint assessment manual: Setting the global standard* (Hoekstra et al. 2011) and citations within. In their assessment, Hoekstra et al. (2011) separate the water use of a crop into three parts: blue, green, and gray water footprints. The consumptive water footprint of a crop—the amount of water necessary to maintain soil moisture levels above a crop's wilting point during the lifetime of that crop—is defined as the sum of the water from precipitation used during a crop's production (green) and the water from irrigation sources (e.g., rivers, groundwater) used to supplement rainfall (blue). Also, non-consumptive uses of water (e.g., nutrient loading from fertilizers, runoff) for crop production can result in changes in water quality. These changes can be quantified using the gray water footprint—the amount of water required to dilute fertilizer runoff to defined environmental or human water quality standards (Hoekstra et al. 2011). The methods employed in this study to determine all three water footprints are described below.

The value for the current green water footprint of Sri Lankan rice—1267 m^3 H_2O ton^{-1}—came from Mekonnen and Hoekstra (2011). They calculated this value as the production-weighted average of the green water footprints for each Sri Lankan district. Because the land area under cultivation was assumed to be constant and the climate change effects on precipitation were not considered, the green water footprint was also assumed to be constant for all levels of YGC.

The value for the current blue water footprint for rice in Sri Lanka—629 m^3 H_2O $year^{-1}$—also came from Mekonnen and Hoekstra (2011). The blue water footprint for each increase in yield was then calculated based on the percentage of increases both in irrigated area and in rice yield relative to current values (Mueller et al. 2012). The current blue water footprint of rice, BWF_{curr}, in Sri Lanka was therefore scaled to the increased irrigation required to close the yield gap using the following equation:

$$\mathrm{BWF_{gap}} = \mathrm{BWF_{curr}}\left(\frac{i_{\mathrm{gap}}}{i_{\mathrm{curr}}}\right)\left(\frac{y_{\mathrm{curr}}}{y_{\mathrm{gap}}}\right),$$

where i is the percentage of irrigated area, y is rice yield (ton ha^{-1}), and the subscripts curr and gap indicate the value at current yield or at some increment of YGC, respectively. In this way, we accounted for YGC both through the improvement in yield and through the increased demand for irrigation water. This value was only calculated at the national level, as our definition of wet and dry zones did not match the sub-national provinces of Sri Lanka used by Mekonnen and Hoekstra (2011).

Lastly, nitrogen was chosen to represent water pollution for estimating the gray water footprint following Chapagain et al. (2006) and Chapagain and Hoekstra (2011), and Mekonnen and Hoekstra (2011). This is because reactive nitrogen is the most widely utilized and best documented synthetic fertilizer (FAO 2014a). The gray water footprint for applied nitrogen fertilizer was based calculated using the following equation:

$$\mathrm{GWF} = \frac{0.1NA}{(C_{\mathrm{std}} - C_{\mathrm{nat}})},$$

where N is the nitrogen application rate required to achieve a given level of YGC (reported by Mueller et al. 2012), A is the harvested rice area, C_{std} is the water quality standard for nitrogen concentration, and C_{nat} is the natural nitrogen concentration (Hoekstra et al. 2011). The structure of the equation comes from Hoekstra et al. (2011). Following standard methods used by Mekonnen and Hoekstra (2011), the natural concentration and water quality standards were assumed to be 0 and 10 mg N L^{-1} for Sri Lanka. We also assume—again following standard methods by Mekonnen and Hoekstra (2011) as well as Chapagain and Hoekstra (2011)—that 10 % of the nitrogen applied will reach water bodies, represented in the equation by the factor '0.1.' Different water quality impacts associated with rice production are expected from the two zones due to varying cultivation practices. Therefore, the gray water footprint was calculated for the observed rice yield, and for 50, 75, and 90 % YGC for both the wet and dry zones in addition to the national gray WF. Our calculated value for Sri Lanka—319 m^3 H_2O ton^{-1}—agrees well with that determined by Mekonnen and Hoekstra (2011)—324 m^3 H_2O ton^{-1}.

RESULTS

Rice yields have steadily increased in Sri Lanka at both the national and sub-national levels, showing some fluctuation due to drought (e.g., in 2010) but no signs of yield plateau or stagnation (Fig. 2). Rice yields, rice production, and harvested area are all higher in DZ than WZ for both Maha (major) and Yala (minor) growing seasons for all years considered in this study (with the single exception of rice yield in the 1984 Maha (major) season). Overall when considering historical yields and rice land expansion, we find that 48 % of the increased production in Maha (major) and 50 % of the increased rice production in Yala (minor) is attributable to higher yields. In much of the country, rice yields are already approaching Mueller et al. (2012)'s estimated maximum attainable yield of 5 tons ha^{-1}. The frequency with which rice has historically been harvested in Sri Lanka has remained stable at $\sim$1.1 harvests $year^{-1}$ over the past 30 years, a value well below the maximum possible harvest frequency of 2 harvests $year^{-1}$ estimated by Ray and Foley (2013).

Based on linear extrapolations of historical rice yield data, we estimate that rice yields in WZ and DZ will reach the maximum attainable yield in the years 2053 and 2025, respectively. Because rice yields in DZ may plateau soon, this region will make up a decreasing amount of the country's rice production: 75.5 % in 2000, 74.5 % in 2030 and 71.8 % in 2050. Despite the limited improvement possible for rice yields, 24.7 million people can be fed in 2030 and 25.3 million people in 2050 if rice yields grow at current rates until reaching the maximum attainable yield (Fig. 3). As a result, domestic rice production in Sri Lanka would exceed the demands of the

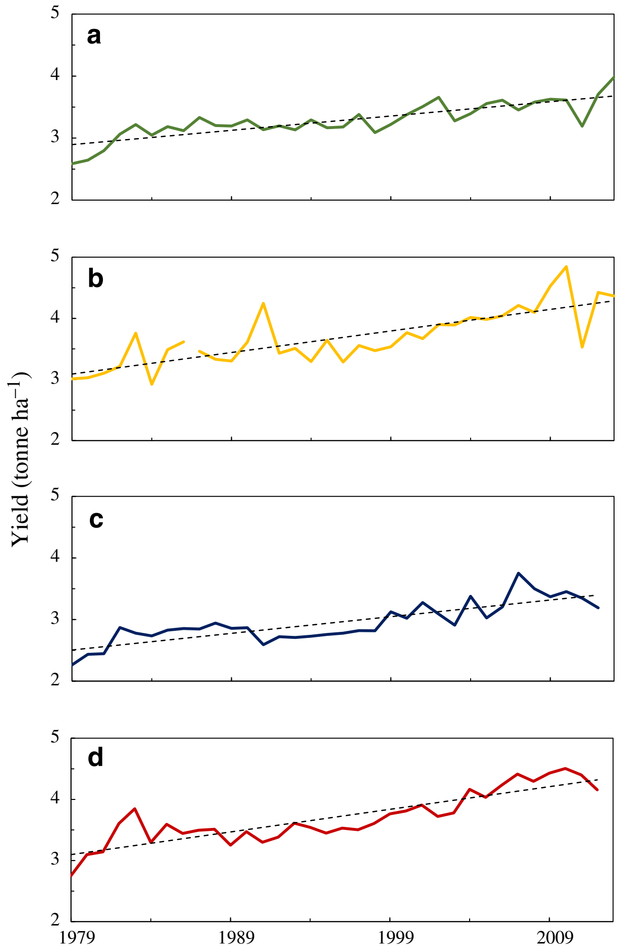

Fig. 2 Rice yields during the Maha (major) and Yala (minor) cultivation seasons in the two zones. In 2013, 68 % of rice produced in the WZ and 61 % rice produced in the DZ came from the Maha (major) season (DCS 2014). Rice yields have steadily increased in Sri Lanka at both the national and sub-national levels. Maha-WZ (**a**), Maha-DZ (**b**), Yala-WZ (**c**), and Yala-DZ (**d**) yields are best fit with an increasing linear function. For the Yala-DZ yield, an exponential fit had a lower rmse, but rmse was not significantly different from a linear fit. See Table S1 for more details on these statistics. Maha-DZ rice yield data for 1986 were not available

projected populations of 23.3 million in 2030 and 23.8 million in 2050 (UN 2012). Under current irrigation technology, increasing current rice yield to 90 % of the attainable yield would increase rice production by 0.89 million tons and would increase freshwater use to nearly 9 km^3 H_2O year^{-1} (Table 2). Alternatively, maintaining current yields but increasing the frequency of harvests from the year 2000 rate (1.1 harvests per year) to the maximum (2 harvests per year) would increase rice production by 2.22 million tons. With this increase in harvest frequency, Sri Lanka could feed 45.1 and 46 million people in 2030 and 2050, respectively (Fig. 3). In comparison, we estimate that the additional rice production required to meet domestic demand by the year 2050 is 0.62 million tons.

The 50 % YGC has the lowest water footprint (green + blue + gray) for rice production but, if maintained, would be insufficient to feed future populations (Fig. 3c). This lower WF for 50 % YGC reflects decreased values in both the blue and gray WFs. The per ton blue WF associated with YGC followed a U-shaped curve with 50 % yield gap having the smallest blue WF and the 90 % yield having by far the largest blue WF (Fig. S1). The per ton gray WFs showed a similar U-shaped behavior with 50 and 75 % YGC showing substantial reductions in nutrient loading per ton of rice and a return to current levels with further increases in yield (Fig. S2).

Current consumptive water use for rice production (i.e., blue water + green water) constitutes 39.5 % of all annual water withdrawals (agricultural or otherwise) (Table 2) and 9.7 % of Sri Lanka's total RWR (FAO 2014b). With current irrigation technology, increasing current rice yields to 90 % results in an increase to 68.9 % of total freshwater withdrawals for rice production. Conversely, maintaining current yields but increasing the frequency of harvests represents a similar increase in the share of total freshwater resource use from 40 to 72 % (Table S2). From current levels, the total gray WF increases by 33 % (to 1.15 km^3 H_2O year^{-1}) for 90 % YGC and increases 82 % (to 1.57 km^3 H_2O year^{-1}) for maximizing harvest frequency alone (Table S2).

DISCUSSION

Sri Lanka is marginally self-sufficient in terms of rice production (Fig. 3). The prospects for the long-term rice self-sufficiency of the country are promising not only because the Sri Lankan population is expected to plateau (UN 2012) before rice yields are maximized but also because per capita dietary demand for rice is expected to largely remain constant (Alexandratos and Bruinsma 2012). This potential to increase rice production through improving yields is encouraging from a food security perspective. However, pursuing this type of intensification—as will likely be the case in Sri Lanka and in all of South Asia (Bruinsma 2009)—may bear substantial impacts with as much as a 250 % increase in the required volume of irrigation (blue) water (from current yield to 90 % YGC; Table 2) and a 23 % increase in the amount of applied nitrogen under current (ca. 2000) resource use efficiency. Further, simply increasing rice yields will be a far less efficient use of freshwater resources than will closing the harvest gap. For a given increase in freshwater consumption, closing the harvest gap can increase rice production by 2.5 times more than closing yield gaps alone.

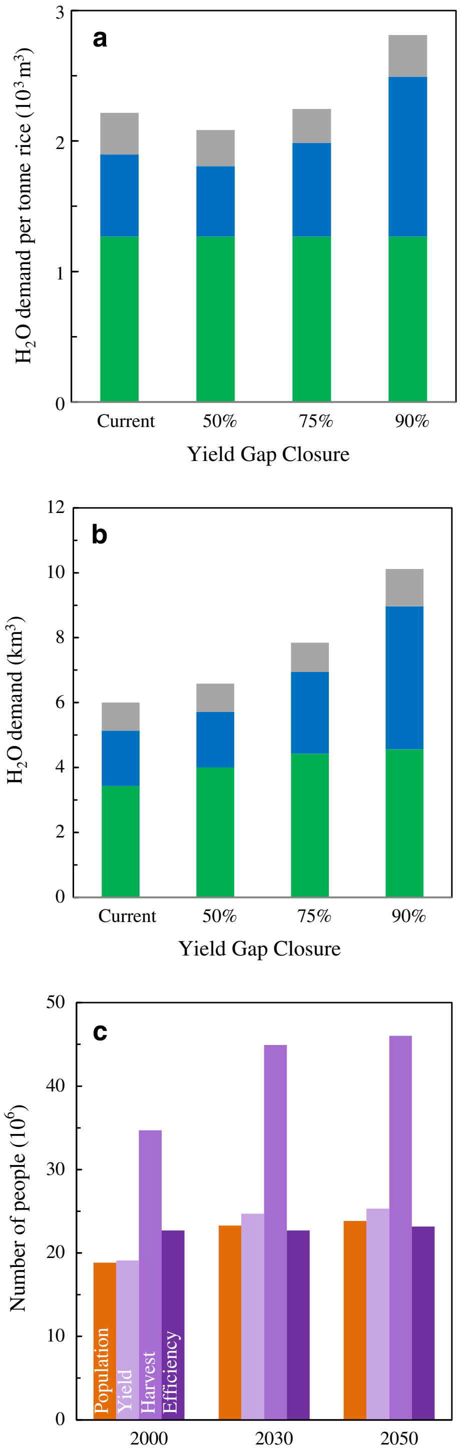

Fig. 3 Water use and human demand for rice production. Per ton (**a**) and national (**b**) water footprints of rice production are shown for different yield gap closures (YGCs). We include all three footprints together (*green*, *blue* and *gray*), but it is important to note that only *blue* and *green* water represent consumptive uses of water. **c** Current and projected populations (*orange*) are estimations from the UN (2012). These estimates of demand are compared to the number of people able to be fed under three rice supply scenarios—'Yield,' 'Harvest,' and Efficiency'—described in detail in "Materials and methods" section. The 'Efficiency' scenario utilized the water use efficiency value at 50 % YGC. Values are presented in Table S3

This would seem to indicate that closing the harvest gap is the preferred method of rice intensification, especially considering that Sri Lankan rice yields will likely plateau in the coming decades. Nevertheless, confounding socioeconomic (e.g., infrastructural maintenance and labor costs) and biophysical (e.g., climate extremes) factors likely make this option less viable (Ray and Foley 2013).

Currently, 90 % of the total water withdrawals in Sri Lanka are used for agricultural purposes (FAO 2014b) and rice comprises one-third of Sri Lankan crop production (FAO 2014a). Achieving increased rice production may have serious consequences for the country's freshwater resources with overall consumptive water use under the most intensive production scenario representing 68.9 % of national freshwater withdrawals. In addition, the most efficient levels of YGC (i.e., 'Efficiency' scenario; Figs. 3c, S1, and S2) are likely not adequate to meet future demand while buffering against climatic variability. Therefore, decision-makers may need to empower extension service agents to educate farmers on the value of improving rice water and nutrient use efficiencies. Indeed, one study found that irrigated rice production in Sri Lanka has the potential to reduce its water demand by ~50 % through efficiency improvements in irrigation infrastructure (Amarasinghe et al. 1999). Nitrogen fertilizer use efficiency can also be increased while still improving yields (Mueller et al. 2014). Further, alternative methods of cultivation are a possibility and can significantly reduce agriculture's impact if implemented on a large enough scale. One such alternative method is the system of rice intensification (SRI). Although Sri Lankan farmers cited greater labor requirements as compared to conventional rice farming methods, a 3-year study reported that SRI helped improve yields by 44 % while markedly reducing the use of synthetic fertilizers (Namara et al. 2004). In highlighting irrigation and fertilizer use in this study, we also note that additional measures and considerations related to agricultural intensification can also be incorporated to look at carbon and nitrogen footprints, soil loss, the influence of climate, and even social and economic impacts in a country.

Achieving greater rice production sustainably is already a formidable challenge because of the greater resource requirements. This task is further complicated by the various potential impacts on rice production associated with climate change. Climate change is particularly relevant to Sri Lanka's self-sufficiency because the country does not produce a large rice surplus and the vast majority of the country's rice supply is produced in DZ. Shifting precipitation patterns, elevated temperature, and more frequent extreme weather events may contribute to crop stress while longer growing seasons and the CO_2 effect may benefit rice production. Thus it remains unclear if the potential impacts of climate change on yields may offset any yield gains

Table 2 Water demand for rice production under 'Yield' and 'Harvest' scenarios. Values show the total water requirement for rice production at a given level of yield gap closure (YGC). Gray water footprints are included in the supplementary materials. Percentages represent the amount of water demand (blue + green) relative to total annual freshwater withdrawal (AFW) and to total renewable freshwater resources (RWR) in Sri Lanka (FAO 2014b). Fader et al. (2013) estimate that 40 % of RWR is accessible to humans after accounting for environmental flows

Type of intensification		Current	50 % YGC	75 % YGC	90 % YGC
Water demand (km^3 year^{-1})					
Yield	Blue	1.71	1.71	2.51	4.41
	Green	3.43	4.00	4.43	4.56
	Total	5.14	5.71	6.94	8.97
	% of AFW	39.5	43.9	53.4	68.9
	% of RWR	9.7	10.8	13.1	17.0
Harvest	Blue	3.10	3.10	4.57	8.01
	Green	6.24	7.28	8.05	8.29
	Total	9.34	10.38	12.62	16.30
	% of AFW	71.8	80.0	97.0	125.3
	% of RWR	17.7	19.7	23.9	30.9

arising from improved technology (e.g., irrigation and fertilizers). While Lobell et al. (2011) found a detectable impact on historical rice yields in nearby India and Bangladesh, a study by Knox et al. (2012) predicted that South Asian rice yields are not expected to significantly decrease despite the possible increases in rice blue water demand due to climate change. This increase in rice irrigation water requirement due to climate change has been studied by De Silva et al. (2007) and so was not quantified here. In their study, the authors showed that increases in average Sri Lankan paddy rice irrigation water requirement will be modest (+13–+23 % by 2050) under climate change but that certain areas of DZ—Batticaloa and Ampara districts in particular—will be more affected (De Silva et al. 2007). Preventing crop stress during (potentially more frequent) times of relative water scarcity may therefore mean that environmental uses of water receive a lower priority and that aquatic ecosystems will likely receive greater fertilizer pollution as a result (Meyer et al. 1999; Kundzewicz et al. 2008). Based on UN and International Water Management Institute indicators, several rice-producing areas relying on irrigation are expected to experience severe water scarcity in the next 10 years and will need to increase water withdrawals in turn (Amarasinghe et al. 1999). It may therefore be necessary for legislators in Sri Lanka to define and allocate adequate environmental flows in order to protect biodiversity and important ecosystem services.

Decisions made now regarding the intensification of rice production will have important implications for food security and the environment in Sri Lanka. Should economic growth in the agricultural sector become the primary focus for Sri Lanka, the country holds a large potential to increase and export rice production through increased cropping intensity. With many Asian countries (e.g., India, Pakistan, and Indonesia) expected to see rapid population growth in the coming decades (UN 2012) and with climate change contributing to elevated food prices and increased food price volatility (IPCC 2014), Sri Lanka could become a regional exporter of rice (Fig. 3; Table 2). While maximized rice production can increase economic development and help alleviate poverty, it also means that Sri Lanka must be willing to use more natural resources with potentially greater impact on the environment. If, on the other hand, Sri Lanka simply places emphasis on domestic food security (as has been the case with its self-sufficiency policies), increased rice production will ensure that the country is not import-reliant and is therefore less vulnerable to spikes in food prices. While maintaining the option of food imports can buffer Sri Lanka against local climatic stress in the future, this may not be a reliable option under certain climatic conditions. One recent study found that as Sri Lanka may have limited access to the global rice market due to its limited financial influence in the region—if, for instance, a large drought event impacted rice production in Asia (Puma et al. 2015). Sri Lanka's reduced dependence on food imports is also important given recent evidence that the global food system has become more vulnerable to shocks as reliance on food trade has increased (Suweis et al. 2015) and that exporting countries may reduce exports in times of food scarcity (Puma et al. 2015). Indeed, food price shocks may become more frequent, as another recent study found that global rice prices have taken on a nonlinear (and more volatile) behavior (Elser et al. 2014). However, the same departure from linear behavior is also true for fertilizer prices (Elser et al. 2014) and may affect the economics of domestic rice production in Sri Lanka given its growing reliance on fertilizer imports (FAO 2014a). How exactly Sri

Lanka may react to a high price regime—both for food and agricultural inputs—is unclear and will depend on how the country adopts new technologies for crop nutrient use efficiency and nutrient reclamation (Rittman et al. 2011). Over the past several decades, the Sri Lankan government has attempted (with mixed results) to distribute technologies to smallholder farms and rural people. In particular, Sri Lankan governments have invested heavily in irrigation projects, which helped to improve crop yields, enable rural access to water and, in turn, reduce poverty in these areas (Amarasinghe et al. 2005). However, the maintenance of this infrastructure as well as the monitoring of water use has frequently been lacking (Godaliyadda et al. 1999). Given that paddy rice cultivation employs nearly 2 million farmers, the government is under significant political pressure to continue providing a fertilizer subsidy (Weerahewa et al. 2010). Though this subsidy has helped to increase land productivity and rice yields, it continues to place a heavy burden on the Sri Lankan GDP while encouraging the over-application of fertilizers. It may therefore be necessary for decision-makers to re-evaluate such policies in the context of water footprint and resource use efficiencies in order to more holistically determine the best path forward for the country.

CONCLUSION

The case presented here is one example of how a country can examine its potential for increasing domestic crop supply, how this supply relates to projected human demand, and what the associated water and fertilizer demands may be. These analyses can provide a first insight into what the food security path of a country may be if it continues as it has and, if this is not desirable, help inform what changes may need to occur in the country's food production system in order to ensure self-sufficiency (or whatever the targeted goal may be). It can also allow decisions-makers to weigh the costs and benefits of agricultural alternatives (in this case, increasing crop harvest frequency). Sri Lanka can anticipate continued independence from rice imports, but further efforts should be made to increase the efficient use of water and nutrients and to ensure that added rice production occurs as sustainably as possible while buffering against future climatic uncertainty and stress. In all, an assessment of demand, the potential to increase supply, and possible impacts on natural resources and the environment will leave decision-makers much better equipped to address the complex issue of food security and to establish informed and concrete targets to achieve it.

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