RESEARCH ARTICLE

Minimizing irrigation water demand: An evaluation of shifting planting dates in Sri Lanka

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Abstract Climate change coupled with increasing demands for water necessitates an improved understanding of the water–food nexus at a scale local enough to inform farmer adaptations. Such assessments are particularly important for nations with significant small-scale farming and high spatial variability in climate, such as Sri Lanka. By comparing historical patterns of irrigation water requirements (IWRs) to rice planting records, we estimate that shifting rice planting dates to earlier in the season could yield water savings of up to 6%. Our findings demonstrate the potential of low-cost adaptation strategies to help meet crop production demands in water-scarce environments. This local-scale assessment of IWRs in Sri Lanka highlights the value of using historical data to inform agricultural management of water resources when high-skilled forecasts are not available. Given national policies prioritizing in-country production and farmers’ sensitivities to water stress, decision-makers should consider local degrees of climate variability in institutional design of irrigation management structures.

Keywords Climate change adaptation · Crop production · Food security · Irrigation water requirements · Planting dates · Water resources management

INTRODUCTION

The agriculture sector is the largest anthropogenic global consumer of water; currently, 70% of global freshwater withdrawals and 90% of global water consumption are for

agricultural production (Khan and Hanjra 2009; Hoekstra and Mekonnen 2012). Population growth, urbanization, rising incomes, and other factors are projected to increase food demand by 60% by 2050 (UNESCO 2014). To meet this increased demand, irrigated agriculture is projected to expand and increase agricultural water withdrawals by 14% by 2030 (Khan and Hanjra 2009). The amount of water available for irrigation will be impacted by increased competition for water among sectors (Perrone and Hornberger 2016). United Nations projects that constraints posed by water scarcity will have greater impacts on food production than constraints posed by arable land scarcity (Hanjra and Qureshi 2010). Improving the efficiency of water use, therefore, will be critical for maintaining agricultural production (Jägermeyr et al. 2016), especially since the sustainable water footprint may have already been surpassed at a global-scale (Jaramillo and Destouni 2015).

Various practices are currently being pursued to adapt crop production to a changing climate and increase the amount of food grown per unit of water. Adaptation measures include expansion of irrigation facilities, shifting of the planting date, cultivation of stress-resistant varieties, and changing crops (Redman et al. 2011; Iglesias and Garrote 2015; Jägermeyr et al. 2016). Increasing the irrigation capacity of a system, by constructing dams to develop storage reserves or using drip irrigation technology, aims to address water scarcity issues from a supply side, whereas the remaining measures (i.e., shifting the planting date, changing the crop types, and cultivating crops that can better withstand drought) address the demand side of water scarcity issues. Each of these measures requires different levels of financial and institutional investments, such as government support and biotechnology advancements. Generally, aligning the planting date (to coincide with rainfall patterns and minimize irrigation

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water needs) is recognized as a low-cost strategy that is especially promising for resource-strained environments since no additional resources need to be invested (e.g., purchasing different seed varieties) (Kucharik 2008; Deryng et al. 2011; Hu and Wiatrak 2011; Hoanh et al. 2016).

Improving water management for food production is particularly important for nations that prioritize in-country agricultural production. One such nation is the island of Sri Lanka, which has a self-sufficiency policy for rice, its staple food. A majority of the rice in Sri Lanka is produced by smallholder farmers (Williams and Carrico 2017); decisions by smallholder farmers influence their livelihoods as well as have important implications for global food security, since they produce 80% of the food in developing countries (Pande and Saveinje 2016). On the island, rice accounts for 40% of all crop production and 40% of consumed total freshwater resources (FAO 2014; Davis et al. 2016). Historically, increases in yields and in cropped areas have allowed rice production to keep pace with tremendous population growth. Currently, however, most of the lands suitable for rice production have already been cultivated, but current harvest frequency for rice is at 1.1 harvests per year, which is well below the maximum of 2 harvests per year (Davis et al. 2016). Although significant irrigation infrastructure is present, the country still faces high water stress, in part due to the water-intensive nature of rice production (Mekonnen and Hoekstra 2012). Some farmers have started shifting towards other food crops, but rice production is often favored for financial and cultural reasons (Gunda et al. 2017). Unfortunately, the productive capacity of rice is being threatened by climate change, notably increasing water scarcity (Bouman et al. 2007; Dharmasena 2010; Eriyagama and Smakhtin 2010; IPCC 2014). Changes in rainfall timing and variability have already begun to adversely impact rice production in Sri Lanka (Senalankadhikara and Manawadu 2010). Given the crop's sensitivity to drought (Senalankadhikara and Manawadu 2010), shifting the planting date, which requires minimal resources, is a promising demand-side management adaptation strategy for smallholder rice production in the country.

Farmers in Sri Lanka grow rice during two seasons: the major and minor growing seasons. A majority of the rice production (65%) occurs during the major growing season because production during the minor growing season is constrained by water availability. De Silva et al. (2007) estimate that future mean irrigation water requirements (IWRs) could increase by 13–23% nationwide during the major growing season. However, historical variability of IWRs in the minor growing season, when rice is produced mainly under irrigated conditions on the island (Amarasingha et al. 2014), is poorly understood. Such insights would be particularly valuable for the high-rice producing

intermediate and dry zones of the country, which are characterized by high climate variability and persistent water scarcity issues, respectively (DCS 2014; Withanachchi et al. 2014; Davis et al. 2016). Given that irrigation agriculture accounts for almost all water use in parts of the country (De Silva et al. 2007), an understanding of historical patterns of variability of IWRs (arising from local climate variability) during the minor growing season is critical for informing current adaptation practices and for contextualizing estimates of future changes in IWRs.

The aim of this study is to characterize historical patterns in IWRs during the minor growing season in the main rice growing zones of Sri Lanka over the last two decades and to quantify the impact that shifting the planting date could have on reducing irrigation water needs. Our analysis of historical data indicates that significant gains can be achieved by planting early during the minor growing season in the dry and intermediate zones. This local-scale assessment of Sri Lanka IWRs demonstrates the value of using historical data to inform agricultural management of water resources, even in regions characterized by high climate spatial variability, and the role that low-cost adaptation measures can play in mitigating detrimental impacts of climate change. This study is embedded in a larger, multidisciplinary research project investigating environmental and social drivers of and barriers to climate change adaptation in Sri Lanka; more information about the project can be found at <https://my.vanderbilt.edu/srilankaproject/>.

MATERIALS AND METHODS

Site description

Sri Lanka, located off the southeastern coast of India, has been able to meet its self-sufficiency target for rice through its large rice production sector (Davis et al. 2016); 800 000 farmers and their families as well as 30% of the land area in the nation are devoted to rice production (De Silva et al. 2007). The country is divided into three climatic zones: wet, intermediate, and dry (Fig. 1), which produce 18, 27, and 55% of the nation's rice, respectively. The wet zone is characterized by an average annual rainfall amount greater than 2500 mm, while the dry zone receives less than 1750 mm annually and the intermediate zone is a transitional region. Sri Lanka has two main growing seasons, the major growing season (occurs between Oct and Mar and locally referred to as Maha) and the minor growing season (occurs between Apr and Sep and locally referred to as Yala), which coincide with the seasonal monsoon patterns. During the major growing season, rainfall is received throughout the island. During the minor growing season,

Fig. 1 Climate zones and location of the four stations

however, significant rainfall typically is received only in the southwestern (i.e., wet zone) part of the country. This rainfall pattern leads to pronounced dry conditions from May to September in the dry zone (Gunda et al. 2016).

Sri Lankans have developed two distinct irrigation schemes to adapt to this uneven distribution of rain in the dry zone: (1) small artificial lakes and ponds (locally referred to as wewas) and (2) major irrigation systems, such as the Mahaweli system. Wewas store excess local runoff from the major rainy season to provide water during the minor growing season, while the Mahaweli system depends on interbasin transfers. Irrigation water in the intermediate zone is primarily supplied by the wewa systems while water for the dry zone is supplied by both wewas and the Mahaweli system. For this study, daily rainfall, temperature, relative humidity, wind speed, and sunshine duration data from 1991 to 2010 were obtained from the Meteorological Department of Sri Lanka for four stations (Fig. 1; Table 1). The meteorological data were reviewed for quality issues prior to calculating IWRs.

Table 1 Station profiles. Average climate data reported for minor growing season (Mar 1–Oct 13)

Station	Average daily rainfall (mm)	Average daily temperature (°C)	Nearby irrigation system
Angunakolapelessa	3.1	28.1	Mahaweli System UW
Aralaganvila	2.1	29.0	Mahaweli System C: Ulhitiya Tank
Batalagoda	4.5	27.8	Wewa: Batalagoda Tank
Maha Iluppallama	2.5	28.6	Mahaweli System H: Kalawewa Tank

Irrigation water requirements

Calculations

Approximately 40% of global irrigation water is devoted to rice production (Bouman et al. 2007). The high water demand for rice is due to two factors: rice is typically grown in flooded fields, which leads to high evaporative losses, and the crop itself consumes a lot of water, so transpiration rates are also high. In this analysis, we follow Brouwer and Heibloem (1986)'s definition of irrigation water requirements (*IWR*):

$$IWR = WD - P_{\text{eff}}, \quad (1)$$

where *WD* is the water demand, and P_{eff} is the effective rainfall (i.e., available water); all units are in mm. Water demand is defined following Chapagain and Hoekstra (2011):

$$WD = SAT + WL + PERC + ET_c, \quad (2)$$

where *SAT* is the soil saturation; *WL* is the water layer; *PERC* is the percolation and seepage; and ET_c is the crop evapotranspiration; all units are in mm.

Water is required during the land preparation stage and the growing period of rice, the latter of which is composed of the initial, development, mid-season, and late stages (Table 2). *SAT* is the amount of water used by farmers during land preparation to make it easier to till and level the field; the amount of water needed for this process is dependent on local soil characteristics. The three stations in the dry zone are predominantly underlain by reddish brown earth (RBE) soils while the intermediate zone station is predominantly underlain by low humic gley (LHG) soils (Land Use Division 1988; Wijesinghe 1979). Because the

Table 2 Stage Lengths and Crop Coefficients. Sources: Rathnayake, pers. comm and Rathnayake et al. (2013)

Stages	Length (days)	Kc
Land preparation	21	–
Initial growing stage	20	1.1
Developmental stage	25	1.1
Mid-season growing stage	30	1.25
Late season growing stage	30	1.0

RBE soils have high moisture-retaining clay content (Stone 2015), we assume that SAT is 250 mm for these stations. For LHG soils, we assume SAT is lower at 200 mm, due to their sandy loam textures (Land Use Division 1988; Wickramasinghe and Wijewardena 2003).

WL is the amount of water farmers use to flood the fields (to prevent weed growth) during the initial growing period; farmers in Sri Lanka typically maintain a depth of 10 cm (Stone 2015). PERC represents the amount of water lost due to the porosity of the soil throughout the growing period; we assume the intermediate zone station has a percolation loss rate of 6 mm day^{-1} , while the dry zone stations lose water at a rate of 8 mm day^{-1} (Weerakoon et al. 2010). ET_c is the amount of water needed by rice due to evaporation and transpiration water losses throughout the growing period and is calculated as

$$ET_c = ET_o * K_c, \quad (3)$$

where ET_o is the potential evapotranspiration (in mm) and K_c is a dimensionless crop-specific coefficient, which varies for rice depending on the growing stage (Rathnayake et al. 2013). The lengths of the growing stages for the rice variety predominantly grown during the minor growing season in Sri Lanka were provided by researchers at the Rice Research Development Institute (Rathnayake, pers. comm.; Table 2). ET_o values were calculated using the Penman–Monteith method (Allen et al. 1998). Derived from energy balance and mass transfer methods, the Penman–Monteith method uses temperature, relative humidity, wind speed, and sunshine duration data to develop estimates of potential evapotranspiration rates (Allen et al. 1998).

The effective rainfall was calculated using a daily-adjusted dependable rain method (FAO 2016):

$$P_{\text{eff}} = \begin{cases} 0.6P_{\text{daily}} - 0.3, & P_{\text{daily}} \leq 2.3 \\ 0.8P_{\text{daily}} - 0.8, & P_{\text{daily}} > 2.3 \end{cases}, \quad (4)$$

where P_{eff} is the effective rainfall and P_{daily} is the daily rainfall; all units are in mm. Effective rainfall represents the proportion of total rainfall that is actually available for crops (i.e., can be taken up by their roots) to meet their transpiration needs (Bos et al. 2008).

To quantify the amount of irrigation water required to grow rice during the minor growing season, daily IWRs were summed over the land preparation and the growing stages for a given planting date (i.e., first day of the initial growing stage) to develop a seasonal estimate at each station. We assumed that there was no water deficit prior to land preparation. Seasonal IWRs were calculated for planting dates ranging from March 22 to June 30, based on local crop calendars. We used a threshold of five consecutive days to address missing data. When there were five or fewer missing consecutive days of P_{eff} or ET_o at a given station, it was imputed using one of the other stations' information; we used correlation analysis to determine which of the remaining three stations' data would be used for imputation. Otherwise, the seasonal IWR calculation was not conducted for that planting date. IWRs can be overestimated if daily net irrigation requirements are constrained to be greater than or equal to zero (Doll and Siebert 2002). We address this issue by allowing daily IWRs to be negative, which takes into consideration the soil's ability to retain precipitation (McColl et al. 2017). The harvest and postharvest stages are not considered in the IWR calculations. The IWR calculations are specific to the cropped areas used for rice production and thus, do not address water losses arising from direct evaporation of wewas and reservoirs.

Characterization and adaptation analysis

The IWR for any growing season depends on the date that rice is planted. Variability of IWRs can be assessed using several metrics. An average IWR for each season (i.e., IWR averaged across all possible planting dates) should reflect temporal trends or other large-scale patterns related to climate. Intraseasonal variation of IWRs (i.e., IWR as a function of planting date for any given season) should reflect other changes, for example a change in the onset date of the period of high rainfall. We use both interseasonal and intraseasonal metrics to explore patterns in IWR estimates.

Interseasonal analysis at each station was conducted using average seasonal IWRs:

$$\bar{X}_j = \frac{\sum_{i=1}^N X_{i,j}}{N}, \quad (5)$$

where X is the seasonal IWR for a given planting date (i) and given year (j), $\bar{X}_j$ is the average seasonal IWR for a given year (j), and N is the number of days that can be selected for planting (maximum of 101 if IWR estimates were calculated for all of the dates between March 22 and June 30). The end of the growing season varies for each planting date since the length of the growing season is 105 days for rice. Variability in seasonal IWRs was

quantified using the coefficient of variation (CV). Interseasonal CV for each station was calculated by

$$C_v = \frac{\sigma(\bar{X}_j)}{\mu(\bar{X}_j)}, \quad (6)$$

where $\sigma(\bar{X}_j)$ and $\mu(\bar{X}_j)$ are the standard deviation and mean, respectively, of the average seasonal IWRs. The intraseasonal CV is then

$$C_{v,j} = \frac{\sigma_j(X_{ij})}{\mu_j(X_{ij})}, \quad (7)$$

where $\sigma_j(X_{ij})$ and $\mu_j(X_{ij})$ are the standard deviation and mean, respectively, of the seasonal IWR estimates for all of the planting dates (i) for a given year (j). Linear trend analysis was conducted both interseasonally (i.e., $\bar{X}_j$ as a function of j) and intraseasonally (i.e., X_{ij} as a function of i for each j); significance of linear trend analysis was evaluated using the nonparametric Mann–Kendall test. Patterns in IWRs were assessed relative to sea surface temperatures from the Niño 3.4 dataset, which has been shown to explain some of the climate variability in Sri Lanka (Gunda et al. 2016).

Intraseasonal patterns in IWRs were compared with actual planting date records from nearby agricultural communities to quantify possible gains from shifting planting dates (Table 1); we assume that planting occurred 21 days after the initial water release dates listed in government records (obtained from government offices, including MASL 2003–2010). Within each season, we identify periods of low IWRs (which we define as the lowest 25% of values) to explore patterns in optimal planting dates. Additionally, we quantify potential water savings from shifting planting dates by calculating

$$W_{S,k} = IWR_{avg,actual} - IWR_{avg,k}, \quad (8)$$

where $W_{S,k}$ is the potential water savings for a given planting week (k); $IWR_{avg,actual}$ is the average of the seasonal IWR estimates corresponding to the actual planting dates across the years; and $IWR_{avg,k}$ is the average of the seasonal IWR estimates across the years for each planting week (k); all units are in mm season^{-1} . Rice yield data are aggregated at the district level and thus, could not be used to directly compare to differences arising from IWRs. A list of planting weeks and their corresponding planting dates are provided in Table S1. All analyses were conducted in MATLAB and R.

RESULTS

The three stations in the dry zone have higher and less variable seasonal IWRs (mean: 1625–1746 mm; interseasonal CV: 0.04–0.06) than Batalagoda (mean: 1163 mm;

interseasonal CV: 0.11) (Figs. 2, 3). At some of the stations (Batalagoda and Maha Iluppallama in particular), there are a number of years when the intraseasonal CV is notably greater than the interseasonal CV (Figs. 3, S1). There are no systematic trends in either the CVs or average IWRs across the seasons (Figs. 3, 4). The lack of trends in IWRs is consistent with the general lack of trends in PET and precipitation observed over the course of the growing season at the four stations (Figs. S2 and S3). Intraseasonally, IWRs generally increase with planting date (i.e., positive trend), which is consistent with the patterns observed in PET and rainfall over the course of the minor growing season (Table 3; Figs. S4–S9). In 2000, however, all four stations exhibit a significant negative trend in IWRs as a function of planting date (Table 3). Brief El Niño periods occurred in 1992, 1995, 1998, 2002, 2005, 2010 while La Niña periods occurred in 1996, 1999–2001, and 2008 (Fig. S10).

At all stations, seasonal IWRs are generally lowest between the planting dates of March 22nd and April 15th, with notable exceptions occurring during the years of 1998 and 2000 (Figs. 5, S7–S9). The actual planting did not often coincide with the low IWR periods, especially near the dry zone stations (Figs. 5, S11–S13). Water savings calculations confirm that the potential for savings is generally greater for the dry zone stations than the intermediate zone; less irrigation water would be needed if rice were planted early in the season—before April 20th at Batalagoda and before May at the dry zone stations (Figs. 6, S14). The potential maximum water savings presented in Fig. 6 correspond to 2.8% at Batalagoda, 3.1% at Angunakolapelessa, 3.7% at Aralaganvila, and 6.4% at Maha Iluppallama of the corresponding station's average IWRs.

DISCUSSION

Our analysis characterizes historical irrigation water requirements and associated patterns for the main rice growing zones of Sri Lanka. Batalagoda has a lower IWR than the three stations in the dry zone, which is consistent with the higher rainfall received in the intermediate climatological zone. The minor growing season IWRs for Batalagoda are similar to the estimates developed by Weerasinghe et al. (2000) for the Nilwala basin (1012–1246 mm), which is also in the intermediate zone. Although De Silva et al. (2007) quantify the IWRs during the major growing season (450–500 mm) for the dry zone, our average IWR estimates of 1625–1746 mm are the first developed for the minor growing season for this region of the country. In addition to average estimates, we also consider trends in IWRs both across and within seasons. Although increases in temperature have been observed in

Fig. 2 Distribution of seasonal irrigation water requirements ($X_{i,j}$ from Eq. 5) at the four study locations

Fig. 3 Intraseasonal coefficient of variation in irrigation water requirements ($C_{v,j}$ from Eq. 7; black points) compared to interseasonal coefficient of variation at each station (C_v from Eq. 6; red-dotted lines)

Sri Lanka (Eriyagama and Smakhtin 2010), we do not observe any systematic trends in average seasonal IWRs across the study years (Fig. 4). A combination of increases in PET and decreases in rainfall over the course of the minor growing season (Fig. S8 and S9) drive increases in IWRs as a function of planting date (Table 3); the notable exception was 2000 when a significant La Niña was present. The presence of a La Niña in 2000 could have

delayed and stabilized the rainfall, causing the coefficient of variation to be relatively low during this period (Fig. 3).

Variability of seasonal IWRs is also consistent with climatic zones, with higher CV of IWRs at Batalagoda than the three dry zone stations (Fig. 3). Furthermore, during certain years, the interseasonal CVs are notably lower than intraseasonal variability (particularly at Batalagoda and Maha Iluppallama). For example, the intraseasonal CV at Batalagoda was 0.19 in 1995, which is much larger than the

Fig. 4 Average seasonal irrigation water requirements ($\bar{X}_j$, from Eq. 5; black solid lines) fitted with a linear model fit (blue-dotted lines) and corresponding 95% confidence interval (gray-shaded areas). None of the slopes is significantly different from zero ($p > 0.05$ for all)

Table 3 Theil–Sen slopes of linear models fit to seasonal irrigation water requirements as a function of planting date. Significant positive slopes in red, significant negative slopes in blue, and non-significant slopes in black; significance level = 0.05

Year	Angunakolapelessa	Aralaganvila	Batalagoda	Maha Iluppallama
1991	-	-	-	2.6
1992	-0.6	0.9	-	1.6
1993	-	-1.0	2.5	3.3
1994	-1.8	1.2	-0.2	-0.1
1995	3.1	1.5	6.0	6.0
1996	-0.2	1.0	-0.6	-0.7
1997	-0.4	2.5	2.9	2.8
1998	-0.3	0.6	0.7	0.8
1999	0.6	0.8	-	2.4
2000	-1.1	-0.4	-1.9	-1.3
2001	1.7	2.8	3.0	3.8
2002	2.1	2.5	5.3	4.9
2003	2.4	2.5	2.0	1.4
2004	2.2	0.4	-3.8	3.1
2005	-	1.8	3.1	3.9
2006	-	-	0.2	4.1
2007	-	-	-0.5	0.9
2008	-	0.9	2.6	3.2
2009	-	2.4	0.7	0.1
2010	-	1.7	3.0	1.5

0.11 interseasonal CV observed at the station across the 20 years. This indicates that day-to-day decisions could have had measurable impact on seasonal IWRs in 1995 at the intermediate zone. Therefore, intraseasonal fluctuations should be considered alongside expected long-term changes (e.g., De Silva et al. 2007) during planning to minimize irrigation water demand and generally, improve management of water resources for agriculture. Specifically, decisions regarding the planting date of rice in a given season should be considered more carefully at stations with high variations in IWRs within a season (e.g., Batalagoda) than at stations with relatively stable IWR needs (e.g., Angunakolapelessa).

Currently, planting dates vary between March 22 and June 30 (Figs. 5, S11–S13). If irrigation water is available, shifting planting dates to mid-April or earlier could improve irrigation water use efficiencies in Sri Lanka while delaying the planting date to June could result in losses (Fig. 6). These dates coincide with the periods of high and low rainfall observed at the stations in the early April months and July months, respectively (Fig. S9). These findings are consistent with those of Weerasinghe et al. (2000) and Dharmarathna et al. (2014), who identify early April as the optimal planting period for the minor growing season in the intermediate zone based on historical data and future climate scenarios, respectively. However, in years where rainfall is scarce (e.g., in 2000), there may be little or no savings realized from the shifting of planting dates

Fig. 5 Seasonal irrigation water requirements as a function of planting date ($X_{i,j}$ from Eq. 5) at Maha Iluppallama (points in gray are lower than that season's 25th percentile while points in black are greater than or equal to the 25th percentile). Vertical green line indicates actual date rice was planted; rice was not planted in the irrigation area near the Kalawewa tank during 2006

Fig. 6 Potential average water savings in irrigation water requirements as a function of planting date ($W_{S,k}$ from Eq. 8)

(Fig. 3). Spatial variations between zones are also important to recognize; more water savings can be achieved in the dry zone if planting occurs in late March (up to 6.4%) while intermediate zone water savings are highest during the first week of April (up to 2.8%) (Fig. 6). Generally, the stations with the highest potential savings coincide with regions with the lowest water availabilities (Figs. 6, S3). There are also differences among the dry zone stations; PET trends at Angunakolapelessa, which generally decrease over the course of the minor growing season, are

more comparable to trends observed at Batalagoda in the intermediate zone than to the other two stations in the dry zone. Due to lack of access to historical data, this analysis was limited to a 20-year period at four stations. Gunda et al. (2016) show, however, that patterns observed from sparse station coverage in Sri Lanka are good approximations of general patterns in the country.

Climate change projections indicate that IWRs will likely be higher in the future on the island nation (De Silva et al. 2007), with increasing temperatures expected to

adversely impact rice yields (Zhao et al. 2017). These estimates are based on PET analyses that account only for temperature changes and they tend to overestimate drying trends because they do not account for plants' stomatal conductance behaviors or impacts of CO₂ fertilization (Milly and Dunne 2016). Nevertheless, the total amount of water available for irrigation may be impacted in the future due to precipitation variability and elevated temperatures, the latter of which would increase evaporation losses from storage reservoirs (Jaramillo and Destouni, 2015). Given the high sensitivity of rice to water stress throughout its growth, lowering IWRs could potentially improve rice yields (Bouman et al. 2007). Any excess water in the reservoirs at the end of the season could be used to meet future seasons' IWR needs or increase environmental flows (Poff and Zimmerman 2010).

Sri Lankan farmers have begun to adopt a range of adaptation practices (Williams and Carrico 2017), but some options (e.g., changing crops) may only be available to farmers with high financial resources (Gunda et al. 2017). Changing the planting date is a promising strategy for smallholder farmers who have limited resources. Ideally, planting dates would coincide with rainfall patterns to maximize crop yields (Amarasingha et al. 2014). However, current seasonal weather forecasts in Sri Lanka provide only general insights into the water availability for the upcoming season (Warnasooriya, pers. comm.). In the absence of high-skilled forecasts, we demonstrate how an understanding of historical patterns could help inform agricultural practices. Our analysis highlights the adverse impacts of delaying the planting date on IWRs and subsequently, the benefits of shifting the planting date, a practice in which farmers have already begun to engage during the major growing season (Senalankadhikara and Manawadu 2010). Assuming water releases are timely in the minor growing season, farmers should be able to shift to planting earlier in the season when IWRs are relatively low, especially given that these dates are within the period when planting typically occurs.

Rice production during the minor growing season is heavily dependent on irrigation releases, the timing of which significantly influences farmer planting decisions. So although our analysis focuses on the irrigation water requirements of the minor growing season, it is worthwhile to note that this irrigation water is obtained through management of excess water from the preceding major growing season. Water releases in the dry zone are based on available stored water across basins in the Mahaweli system. Given the relatively low interseasonal CVs at the dry zone stations, it would be beneficial to systematically shift the planting date of rice earlier in these areas. The locally managed wewa systems, however, could potentially respond more rapidly to local rainfall patterns, thereby

addressing the management challenge associated with high variability of IWRs in the intermediate region. In fact, the relatively low potential water savings from shifting the planting date in this region likely reflects this local adaptive management (Fig. 6). In addition to influencing crop yields, water stress can also influence farmer behaviors by shifting them away from rice production (Williams and Carrico 2017), which would impact the nation's ability to maintain self-sufficiency for its staple crop.

Most of the world's rice is harvested from rain-fed or irrigated lowland rice fields in Asia, where half of all freshwater depletions are attributed to rice production (Hundertmark and Abdourahmane 2003). As an island nation, Sri Lanka has limited options to maintain self-sufficiency in its staple crop, especially since the studied regions are already equipped with irrigation facilities and most of the arable land suitable for rice production has already been cultivated. Although global assessments provide a general understanding of the water–food nexus by modeling irrigation water requirements, they lack the necessary resolution to inform local planning and subsequent adaptations (Doll and Siebert 2002). Using historical analyses of local meteorological data, we demonstrate how the low-cost strategy of shifting irrigation water releases and thus, planting dates, could address water scarcity issues and help sustain farmer livelihoods in the country. Given increased competition of water between sectors (Perrone and Hornberger 2016) and projections of less excess water being available during the major growing season in the future (De Silva et al. 2007), it is increasingly critical that water managers leverage local institutional capacity of irrigation systems to optimize planting dates for the minor growing season so that Sri Lankan farmers can continue to maintain their livelihoods and support national self-sufficiency in their staple crop even under pressures of a changing climate.

CONCLUSION

Given the changing climate and increased competition for water resources, shifting of the planting date is a promising, low-cost adaptation strategy for reducing water needs in resource-strained environments. Using the case of Sri Lanka, we present an example of characterizing patterns in irrigation water requirements and quantifying the impact that shifting the planting date could have on reducing irrigation water demands. Such analyses could provide insight into the potential for adaptation and possibly, sources of future stress. It can also allow decision-makers to consider local irrigation management structures and how they can be leveraged to offset challenges arising from high climate variabilities. Our results show that the variability

within a season was periodically higher than variability across seasons in parts of Sri Lanka, highlighting the importance of understanding intraseasonal variability in optimizing agricultural water management. In all, this study demonstrates how decision-makers can use historical data to inform agricultural management of water resources in regions characterized by spatial variability and likely reduced water availability in the future.

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