

## Frontiers of the food–energy–water trilemma: Sri Lanka as a microcosm of tradeoffs

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## LETTER

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# Frontiers of the food–energy–water trilemma: Sri Lanka as a microcosm of tradeoffs

Debra Perrone<sup>1,3</sup> and George Hornberger<sup>2</sup>

<sup>1</sup> Civil and Environmental Engineering, Woods Institute for Environment, 473 Via Ortega Drive, Stanford, CA, 94305, USA

<sup>2</sup> Vanderbilt Institute for Energy and Environment, PMB 407702, 2301 Vanderbilt Place, Nashville, TN 37240, USA

<sup>3</sup> This work was initiated at Vanderbilt University as part of Dr Perrone's PhD dissertation, and it was completed during her postdoctoral position at Stanford University.

E-mail: [debra.perrone@gmail.com](mailto:debra.perrone@gmail.com)

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Supplementary material for this article is available [online](#)

## Abstract

Food, energy, and water are three critical resources for humanity. As climate variability, population growth, and lifestyle changes amplify the stress placed on each of the resources, the interrelationships among food, energy, and water systems become more pronounced. Political conflict, social and cultural norms, and spatial and temporal distribution of the resources add additional layers of complexity. It is in this context that the significance of understanding the impacts of water scarcity on the decisions around food and energy productions has emerged. Our work establishes tradeoff frontiers (TFs) as a method useful in illustrating the system-level tradeoffs between allocating water for food and water for energy. This paper illustrates how TFs can be used to (1) show how scarcity in water resources affects the tradeoffs between food and energy and (2) explore the political and social constraints that can move production away from what is feasible technically. We use Sri Lanka, a country where water resources are variable both in space and time and a country with relatively self-contained energy and agricultural sectors, as a microcosm of the food security, energy security, and water security trilemma. Nevertheless, our application of tradeoff frontiers is applicable widely to other systems.

## Introduction

Food, energy, and water are critical for humanity. Climate variability and change bring uncertainty to human and natural systems, creating and amplifying risks for securing the three resources. Population growth and changes in lifestyle that follow development will increase competition for food, energy, and water. In addition to these stresses, political conflict, social and cultural norms, and spatial and temporal distribution of the resources can impact access to food, energy, and water. Water is vital for sustaining agricultural yields, and energy is fundamental for increasing agricultural productivity [1]. Most primary and secondary sources of energy require water [2], and the acquisition, conveyance, treatment, and end-use of water requires energy<sup>4</sup> [3]. As the demand for each

resource increases, the interrelationships among food, energy, and water become more pronounced so that a solution to address scarcity in one resource cannot be achieved without impact on the others [4]. We call this the food security, energy security, and water security trilemma [4].

Some interactions among food, energy, and water involve feedbacks among all of the resources while other interactions are driven specifically by one resource. Water is a unique resource, and we have argued previously that water scarcity is the proximate cause that often promotes the interactions and tradeoffs among food, energy, and water [4]. The spatial and temporal variability of water can create disputes even in areas where average water supply is ample to meet competing demands. Water can be a public, common, or private good [5–7], and it is undervalued often [8]. Water is valued differently as an input for food than it is valued as an input for energy: the high

<sup>4</sup> For an extensive list of food–energy–water interactions, see [4].

water requirements and low prices of many major irrigation crops can result in a lower market value for food than energy. For this reason, political pressure can be applied during periods of water scarcity to forfeit irrigation water and reallocate it to higher market value productions like energy [9]. Nevertheless, domestic water needs, local environmental needs, and micro-venture needs (e.g., livestock and aquaculture) all benefit from non-agriculture irrigation water allocations [9]. These uses are small, but non-agriculture irrigation water contributes to rural livelihoods, and thus, cultural norms influence water allocation.

Water resources management is complex, and interrelationships with food and energy add to the complexity. There is a poor understanding of how technological and infrastructural approaches can be balanced with institutional or behavioral approaches within and among food, energy, and water systems [4, 10, 11]. It is helpful to develop methods that explore the range of water allocation scenarios for food and energy constrained by the physical system, as well as the political and social system [12]. **When water is insufficient to maximize both food and energy objectives, tradeoffs are made.** A tradeoff frontier (TF) is used traditionally to show the compromise between two outputs given a set number of inputs: all else equal, production of one output cannot increase without decreasing the production of the other output. The outcome is efficient if it lies on the frontier. This indicates that the production outputs are getting the most out of the available inputs given the available production technology. This framework has been applied to food, energy, and water, usually in terms of the economic value of production [13, 14]. More recently, TFs have been extended to the ecological economic literature [15, 16] and nitrogen fertilizers [17], underscoring the usefulness of the TF beyond its conventional market valuation applications.

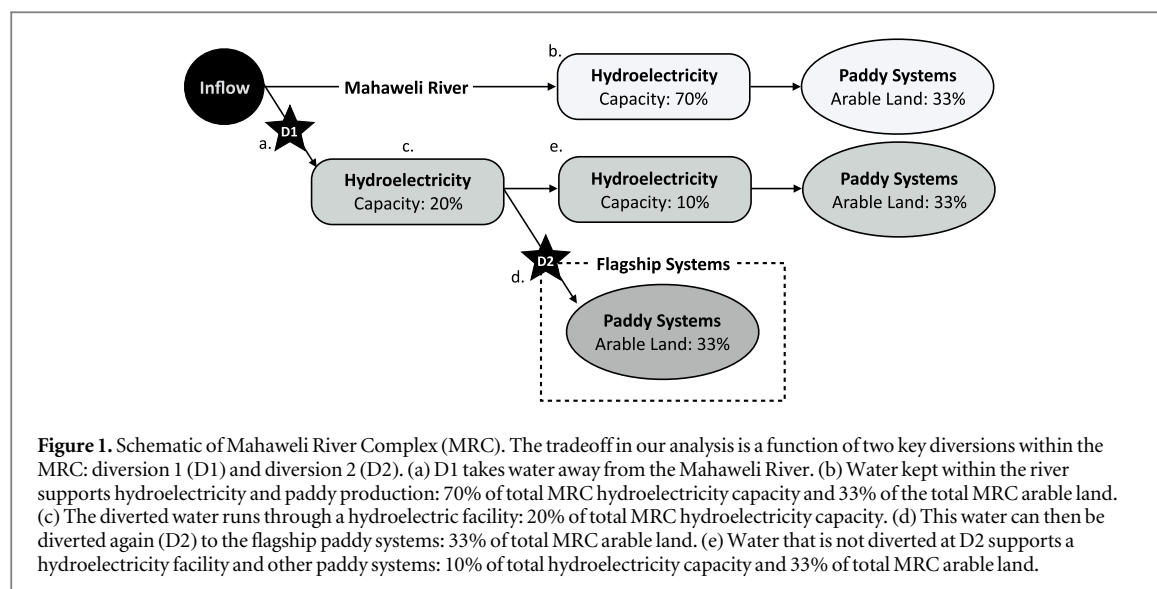
TFs provide a strategic approach to visualizing system-level tradeoffs among food, energy, and water, especially when water scarcity is driving the nexus. **In this case a TF is a plot of maximum possible production of food versus maximum possible production of energy under different water allocation scenarios.** We evaluate how water scarcity impacts the decisions surrounding the allocation of water for energy and water for food. **We focus solely on technical efficiency and do not look at allocative efficiency or the optimization of input-output price relationships.** Over the past thirty years, the literature on opportunity costs and market and non-market valuation of allocating water resources has been extensive (e.g., [13, 18–20]). During this same time period, water managers began to recognize that there are no panaceas in water institutions: in some places and at certain times, water policies focused on regulation may work, while in other places or at other times, water policies focused on collective action or markets may be more successful [21]. Although our approach is not based on economic

theory per se, the results might be of use in carrying out a comprehensive valuation project because it explores political and social constraints that have been overlooked historically in water institutions.

We use Sri Lanka, a country where water resources are variable both in space and time and a country with relatively self-contained energy and agricultural sectors, as a microcosm of the trilemma. As a small island nation, Sri Lanka's boundaries are defined clearly. As a developing country in South-central Asia, domestic food production is tied strongly to a cultural attachment to paddy irrigation [22] and a political focus on rice self-sufficiency<sup>5</sup>. Sri Lanka has a bimodal precipitation pattern, resulting in two cropping seasons: maha is the wet season, and yala is the dry season. Most of the northern part of the country is dry and vulnerable to drought especially during the yala season. Irrigation projects span the entire island, but the projects that are part of the Mahaweli River Complex (MRC) have been the centerpiece of a development plan aimed at resettling the dry zone. The dry zone within the MRC has a strong heritage in irrigation [23], and the irrigation systems in this region are the major systems of paddy (i.e., unmilled rice) production in the country.

The cornerstone of the MRC has been two diversions, labeled D1 and D2 (figure 1). There is twice the arable land area after D1 than at the tail of the Mahaweli River, but two to four times more hydroelectricity capacity on the Mahaweli River than after D1. The diversion at D2 takes water to the region that was the first to be developed in the MRC—we refer to these paddy systems as the flagship systems (figure 1(d)). When water is plentiful, the MRC can meet the needs of irrigation and hydropower, but water is not always plentiful and tradeoffs must be made. When water is scarce maximized production of one resource cannot be reached without impacting the maximized production of the other resource. The TF is a function of the technical capacity of the Sri Lankan system, but a point on the TF may not be achievable for some diversion decisions and for many cropping scenarios. Diversion decisions are influenced by Sri Lanka's heritage in paddy farming, the reliance of rural farmers on subsistence agriculture, and political dynamics. And, farmers may choose to let some fields fallow during seasons when the uncertainty surrounding diversions and precipitation is high. Depth of water is a function of total cropped area, diversion allocations, and precipitation. As a result, during times of limited water supply and low precipitation, a farmer's uncertainty about the amount of land to crop can have large impacts on paddy production.

<sup>5</sup> Sri Lanka has a flexible policy on rice imports where preference is given to domestic production, but imports are used to fill gaps in domestic demand (referred to as 'self-sufficiency on trend' in food security literature).



This paper illustrates how a TF can be used to (1) show how scarcity in water resources affects the tradeoffs between food and energy and (2) explore the political and social constraints that can move production away from what is feasible technically. We map the physical processes within MRC to identify the constraints on the system [24], and we develop production functions for hydroelectricity and paddy production as a function of water input. Inflow is used as a proxy for water scarcity, and a low inflow maha and a low inflow yala season are identified for this analysis. These two seasons have the same low inflow but different precipitation values. For each of the two seasons, we capture the sensitivity of productions to diversions and arable land cropped by varying the percent of inflow diverted at D1 and D2 and the percent of arable land cropped; precipitation values are held constant, because these values are not influenced by political and social constraints. To further explore the political and social constraints that can move production away from what is feasible technically, we identify the reported diversion and cropping decisions for both of the seasons and show these on the respective TF plots.

## Methods

### Assumptions and limitations

This analysis is concerned most with periods of water scarcity. Meetings with stakeholders indicated that during times when water is plentiful, there is little to no tradeoff between hydroelectricity and paddy production. Seasons of normal to high inflow raise additional questions not within the scope of this paper, such as flooding concerns for both hydroelectricity plants and farmers and the optimization of multi-purpose reservoirs (e.g., balancing cheap and clean hydroelectricity production, flood control, and recreation [25]).

Exploratory data analysis indicated that the MRC data were either not suitable or not available comprehensively for us to create a complex mass-balance model that accounted for storage and system losses. Although we do not dismiss the importance of storage within the MRC, we are concerned most with the diversions of water at D1 and D2 and how these diversions influenced the key tradeoff between water for a small fraction of hydroelectricity and large fraction of paddy or water for a small fraction of paddy and a large fraction of hydroelectricity. Therefore, this analysis looks only at the tradeoff of water diversions based on the inflow into the point right before D1.

Our work assumed that water is the limiting input so that we could capture the tradeoff of food and energy as a function of water resource management scenarios. Because the data indicated that arable land cropped expands readily when irrigation water is available and that heavily subsidized fertilizer is available readily to farmers, we assumed that arable land was not driving the nexus [26, 27].

Our analysis used data from MRC, which were from traditional farming techniques and not deficit irrigation techniques (e.g., System of Rice Intensification).

Our scenarios are run for the entirety of the MRC system and do not optimize within each of the paddy systems. That is, when we vary the percent of arable land cropped, we apply the same percentage across all paddy systems. When looking at individual systems, this approach indicated that the marginal value in terms of production of planting another unit area of paddy is positive for both of the low inflow seasons used within this analysis.

### Data collection

We collected information about the MRC to identify the: (1) number and capacity of hydroelectricity plants, (2) number of paddy systems and each system's arable

land, and (3) capacities of diversion infrastructure or regulations on diversions. This information allowed us to create a simplified schematic of the system (figure 1; SI appendix, section A). Additionally, we acquired data related to MRC hydroelectricity facilities (e.g., electricity production, water use) and irrigation systems (e.g., paddy production, water use, precipitation) for 2003–2013 (SI appendix, section B). This information was used to create seasonal production functions for hydroelectricity and paddy.

### Production functions

We analyzed hydroelectricity production data and paddy yield data to see how water availability influences electricity production and paddy yield (SI appendix, section C). Electricity production at each hydroelectricity plant in the MRC was related to the volume of water run through the plant's turbines using least-squares linear regression ( $r^2 > 0.98$  for all regressions).

Exploratory analyses of yield data were used to identify a method for creating paddy yield production curves. The first approach fit a **nonlinear model** for each system in the MRC relating its paddy yields (dependent variable) to water depths (duties, independent variable). The results of the nonlinear model suggested that the data were not represented well. To explore the data further, a **Bayesian multilevel** and an **ordinary linear regression** approach were used. Both methods produce similar results: few systems have yield slopes significantly different from zero. Consequently, all systems' data were plotted together to explore the relationship between water duties and paddy yields with a larger sample size. This plot suggested that there was a minimum duty required, and any duty under this amount lends itself to crop failure. Once past this threshold, the data were poorly correlated, suggesting only small yield benefits are added per unit of duty added. Yield data from Sri Lanka indicated that maximum yields were much smaller during the 2003–2013 period than what was suggested in the literature [28] and that there was not a clear difference in yields between the seasons. Because of the limitations associated with the data, we decided to use a yield production model from a peer-reviewed publication that was created for Indian field experimental data [29]. After identifying and removing outlier data, we fit the MRC paddy data to the yield production model ( $r^2 = 0.44$ ; SI appendix, section C).

### Identifying low inflows

In our analysis, water inflow is used as a proxy for water scarcity. Diversion 1 is the main tradeoff point in the Mahaweli system; we used low inflows into the point right before D1 to understand how water scarcity influences the MRC's food–energy–water interrelationship, and if in fact, water played a driving role. We selected a maha and a yala season of low inflow from

the 2003–2013 dataset. These seasons are used as representative seasons of when tradeoffs have to be made and are not necessarily a representation of the lowest inflow season on record.

The selected maha and yala season inflows were used as inputs into the production functions to estimate the production of hydroelectricity and paddy (SI appendix, sections D and E). Although inflows and mean precipitation for the maha season tend to be significantly higher than in the yala season, drought conditions plague both the maha and yala season. Both selected seasons had the same inflow (410 million m<sup>3</sup>), and precipitation differed by only five centimeters (e.g., over each six-month season, the maha and yala cumulative precipitation inputs were 310 mm and 260 mm, respectively).

### Tradeoff frontiers

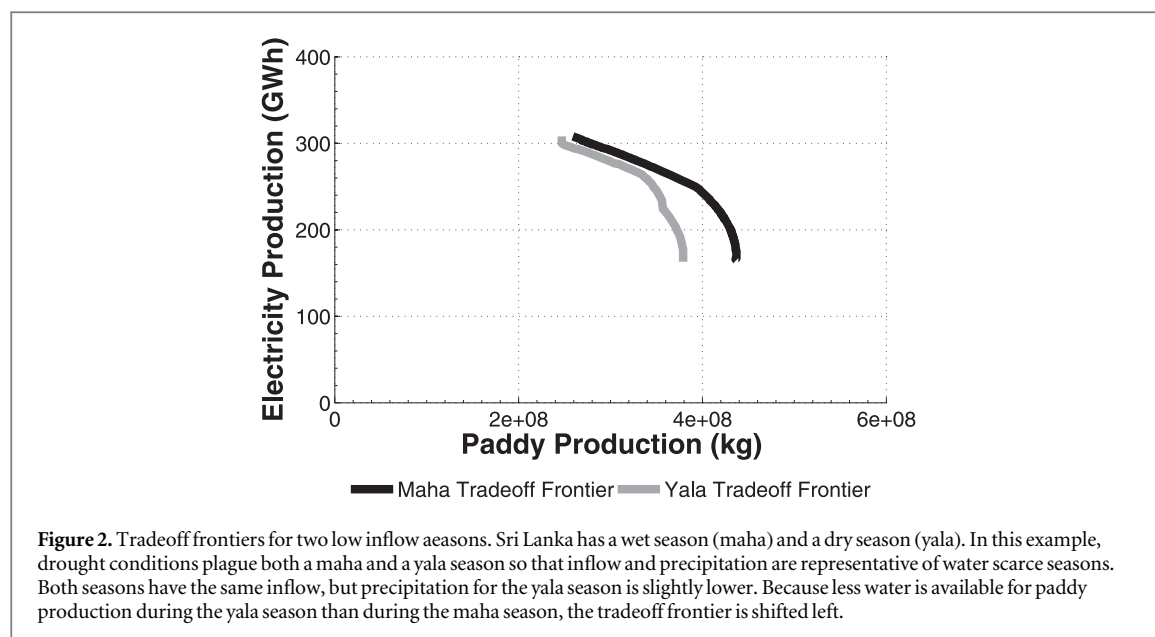
We ran a range of scenarios varying the percent of inflow diverted at D1 and D2, as well as the percent of arable land cropped within the entirety of the system. We kept rainfall constant so that it matched reported values from each system during the two seasons (SI appendix, section E). **We defined the TF by finding the optimal productions within each season's scenarios for D1, D2, and land cropped** (SI appendix, section F). Finally, we identified the reported MRC diversion decisions and the total land cropped by farmers during the two low inflow seasons; we plotted these points on each season's TF to show where the MRC and farmers operated when water was scarce (SI appendix, sections G).

### Key potential uncertainties

Two components of our analysis can influence our results: water inputs (i.e., inflows and precipitation) and production functions. Our analysis focuses on the tradeoff of inflow water at the first diversion (D1). We do not account for storage release decisions within the MRC so the production possibilities we calculate are slight underestimates. Also, we use two dry seasons selected from our ten-year record. If data were available, a statistically-based analysis could be done to elucidate the variability in low-flow responses. This would be an approach needed for detailed water resources planning.

**The main source of uncertainty in our analyses is the scatter within the empirical data for paddy production.** (The data for electricity production are quite precise.) If the technical efficiency of rice production were underestimated, the calculated TF would also be underestimated in terms of rice produced and the converse would be true if technical efficiency were overestimated. For our analyses, the main technical efficiency parameter for rice is the maximum level of the production function, which we take as 5 000 kg ha<sup>-1</sup>. This parameter was informed by a





combination of Sri Lankan yield data and literature reports (SI appendix, section C).

## Results

### Water scarcity and the TF

We use two seasons of low inflow to illustrate the tradeoffs within the MRC when water is scarce. The tradeoffs are a function of the MRC system layout: there is twice the arable land after D1 than at the tail of the Mahaweli River, but two to four times more hydroelectricity capacity on the Mahaweli River than after D1. When water is scarce maximized production of one resource cannot be reached without impacting the maximized production of the other resource (figure 2). Paddy and hydroelectricity productions are efficient technically if reported productions lie on the frontier; this indicates that the production outputs are getting the most out of the available inputs given the available production technology.

### Political and social constraints

Not only is the TF useful for identifying the diversions and cropping scenarios that can lead to the maximization of food and energy outputs that are feasible technically, but also the TF is useful for exploring the political and social constraints that can move production away from what is feasible technically. The decomposition of the TFs into subplots with scenarios for D1, D2, and land cropped illustrates the sensitivity of hydroelectricity and paddy production under different diversion and cropping scenarios (figures 3(a) and (b)).

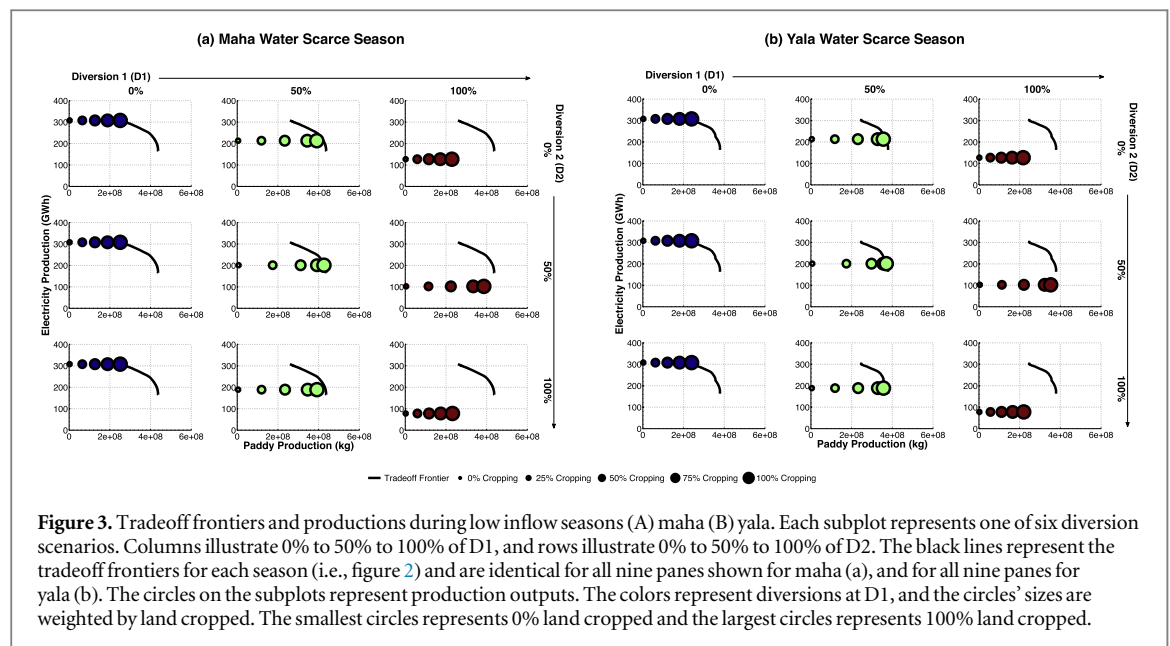
Hydroelectricity production is most sensitive to D1, the diversion that takes water from the main stem of the Mahaweli River. Maximum hydroelectricity is realized with 0% D1 diversions (figures 3(a) and (b),

left column of subplots with blue circles). Because 0% of water is diverted, all hydroelectricity production and paddy production occurs within the main stem of the Mahaweli River where approximately 70% of the hydroelectricity capacity is located (figure 1). So, as D1 increases, more water is diverted, and less water is available for the larger hydroelectricity facilities on the main stem; this results in a reduction in hydroelectricity (figures 3(a) and (b), compare left (blue circles) and right (red circles) columns of subplots). D2 does not have a significant impact on hydroelectricity production; only 10% of the system's hydroelectricity capacity is conceded by diversions at D2 (figures 3(a) and (b), compare top and bottom rows).

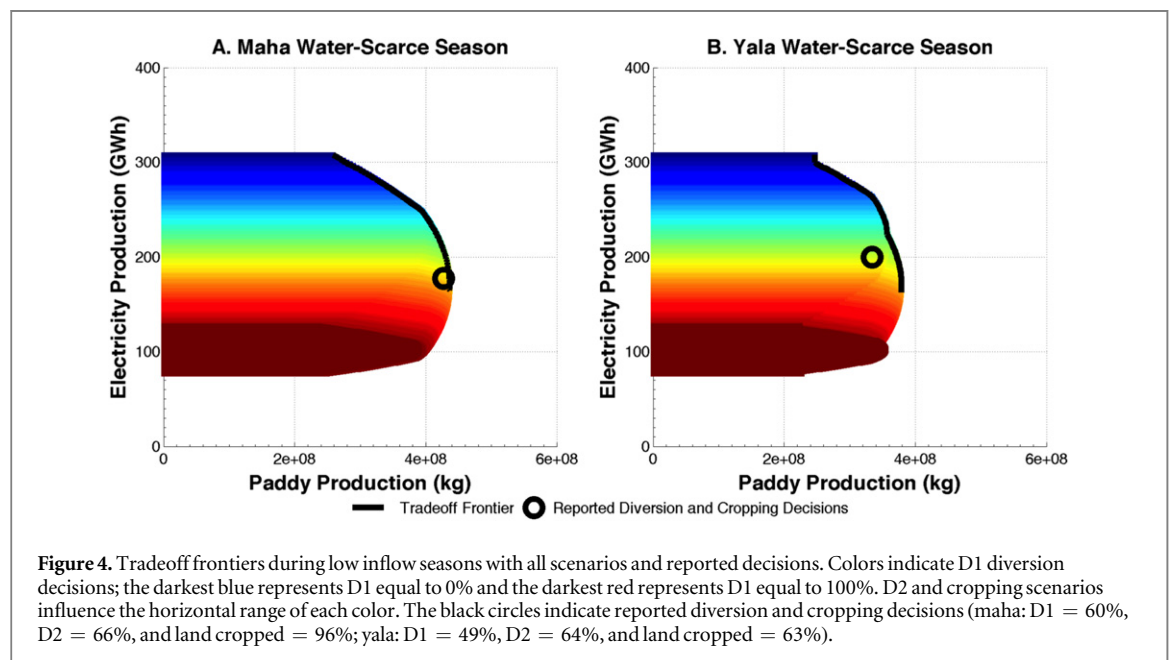
Paddy production is sensitive to both D1 and D2, as well as to land cropped. Sensitivity to the diversions is a factor of the MRC system layout, with equal amounts of arable land at the tail of the Mahaweli River and on either side of D2. Sensitivity to land cropped is more nuanced, because paddy production and paddy yield are interrelated and dependent upon cropping decisions (figures 3(a) and (b), compare small and large circles). When water is scarce, there is a balance between increasing yields by increasing water depth and decreasing area and decreasing yields by decreasing water depth and increasing area. This tradeoff is most obvious in the yala season when there is less water available (figure 3(b), middle subplot showing 50% D1 and 50% D2).

### Reported management

For the maha season, data indicate that D1 was 60%, D2 was 66%, and land cropped was 96%. For the yala season, data indicate that D1 was 49%, D2 was 64%, and land cropped was 63% (figure 4). Any diversion greater than 0% at D1 concedes the ability to maximize hydroelectricity within the MRC. When D2 is greater than 50%, more water is allocated to the flagship



**Figure 3.** Tradeoff frontiers and productions during low inflow seasons (A) maha (B) yala. Each subplot represents one of six diversion scenarios. Columns illustrate 0% to 50% to 100% of D1, and rows illustrate 0% to 50% to 100% of D2. The black lines represent the tradeoff frontiers for each season (i.e., figure 2) and are identical for all nine panes shown for maha (a), and for all nine panes for yala (b). The circles on the subplots represent production outputs. The colors represent diversions at D1, and the circles' sizes are weighted by land cropped. The smallest circles represents 0% land cropped and the largest circles represents 100% land cropped.



**Figure 4.** Tradeoff frontiers during low inflow seasons with all scenarios and reported decisions. Colors indicate D1 diversion decisions; the darkest blue represents D1 equal to 0% and the darkest red represents D1 equal to 100%. D2 and cropping scenarios influence the horizontal range of each color. The black circles indicate reported diversion and cropping decisions (maha: D1 = 60%, D2 = 66%, and land cropped = 96%; yala: D1 = 49%, D2 = 64%, and land cropped = 63%).

systems even though there are equal amounts of arable land on either side of D2. During the maha and yala season, the decision to operate D1 greater than 0% and D2 greater than 50% indicates that the flagship systems are preferred.

## Discussion

### Water scarcity and the TF

When water is plentiful, the MRC can produce maximum paddy and maximum hydroelectricity. Water scarcity is the proximate cause that promotes the interactions and tradeoffs among food, energy, and water in the MRC. It is when water is limited that decisions between diverting water toward the flagship paddy systems and keeping it in the main stem of the

Mahaweli River for hydroelectricity creates competition between food and energy resources. The plot of the TFs shows that when water is scarce, maximizing one resource cannot be achieved without compromising the other, forcing a tradeoff between food and energy.

Extending the TF upward and outward during low inflows and seasons with low precipitation would require gains in technical efficiency. Given a fixed inflow, installing more efficient turbines can increase the production of hydroelectric power and shift the TF upward. Improving the water efficiency of paddy farming can be increased too, shifting the TF to the right. One option is to transfer money from the energy sector to farmers to allow farmers to invest in and use water-saving technology. Nevertheless, Sri Lanka's

current laws do not have the flexibility needed to transfer water voluntarily among users [30]. Moreover, any movement towards transferable water rights has not been accepted well by the public [30, 31]. Other options to improve water efficiency of paddy farming include switching farmers to more water efficient paddy cultivation methods (e.g., System of Rice Intensification), and creating a seasonal forecasting program to help farmers better gauge the amount of land they crop, the paddy variety they cultivate, and the date they start cultivation [32–34]. Outputs are significantly higher, while inputs such as water are lower, when farmers adopt the System of Rice Intensification [32] and advancing the planting date during dry seasons increases average yield [35].

### Political and social constraints

The diversion and cropping scenarios during water scarce seasons show how diversion and cropping decisions can move production away from what is achievable technically. The MRC may make diversion decisions based on many factors and farmers may make cropping decisions for a variety of reasons. We interpret this as imposing political and social constraints on the TF. Only certain diversion and cropping decisions can result in productions that lie on the TF. Thus, the detailed analysis of the TF allows us to explore how diversions and the amount of land cropped can move productions from the TF to productions constrained by political and social forces.

Decisions to vary D1 and D2 not only are a factor of technical efficiency, but *also* a factor of Sri Lanka's political focus on paddy self-sufficiency. Following Sri Lanka's independence from British rule in the mid-twentieth century, irrigation projects and self-sufficiency in paddy were a major component of the country's political platform. Historically during drought years, decision makers have given priority to the flagship paddy systems—the first systems to be developed in the MRC. Water allocation decisions represented by D1 and D2 are rooted in a formal, centrally controlled, yet stakeholder supported, governance structure [25, 36]. A central authority brings together stakeholders from all interest groups to discuss seasonal water resource management plans [25, 37, 38]. Currently, Sri Lanka does not have specific water resource legislation and water rights are not defined clearly [30]; this type of management system provides only limited security for users because there is little opportunity for compensation when water is allocated for other uses [36].

Paddy production and paddy yield are interrelated and dependent upon cropping decisions: paddy production is a product of paddy yield and land area, and paddy yield is a function of the depth of water applied to the land cropped. Under certain D1 and D2 scenarios there may not be enough water to maximize yield and land cropped. Given a set volume of water,

farmers must decide how much land they want to crop—this determines the depth of water, and thus, the yield. To get the highest paddy production under during water scarce seasons, farmers are faced with balancing between (a) increasing yields by increasing water depth and decreasing area and (b) decreasing yields by decreasing water depth and increasing area. For our low inflow seasons, paddy productions can only lie on the TF when farmers use 100% of their arable land. This indicates that farmers are getting the most they can from the water resources available given the production technology available. This also indicates that farmers would have had to elect for option (b)—decrease per area yield because they reduced water depth to increase area—to lie on the TF, and this does not conform to traditional paddy practices of flooding fields for optimal depth.

### Reported management

The TF is useful to illustrate the system level tradeoffs between allocating water for food and water for energy. Mapping the physical processes within MRC helps to recognize the constraints on the system [24] and understand how each decision shifts the efficiency of water allocation across diverse settings. The TF explicitly reveals the management decisions that can lead to technical efficiency; when productions do not lie on the TF, water is being allocated inefficiently. In the case of this work, this implies that either D1 or D2 need to be altered or land cropped needs to be expanded. Thus, the scenarios that are nested under the TF help reveal some of the political (i.e., diversion decisions) or social (i.e., behavioral decisions around land cropped) forces behind specific allocation decisions.

As indicated by reported diversion decisions, in times of low inflow priority to water resources is given to paddy production. This preference also has been documented in other literature [25]. Sri Lanka aims to be self-sufficient in rice, and for the most part, Sri Lanka has been able to meet domestic demands in the past decade [39, 40]. Sri Lanka's agricultural policies help promote self-sufficiency of rice, which may be a political strategy rather than a poverty strategy [41]. Sri Lanka is a small player in the world's rice market, but the limited stocks available for export (SI appendix, section I) require a country that is importing a significant portion of their rice to have trust in the stability of the market, assume unilateral rationality, and to adopt risk mitigation techniques such as storage. Politics and market psychology have a strong influence on the global rice market [42]; as we saw during the 2008 rice crisis, there is no stable or organized futures market for rice. Sri Lanka's rice policies discourage imports through a variety of taxes [39]; it is easier to stabilize domestic rice prices by keeping domestic prices higher than the world market price [41]. On the domestic side of paddy production, fertilizer is

↑  
interesting



subsidized, and the government guarantees a minimum price to farmers and a maximum retail price for consumers. Furthermore, Sri Lanka's legislation mandates farmers to grow paddy on MRC paddy lands, discouraging diversification to other field crops with higher water efficiency [39].

For many scenarios, a point on the TF may remain accessible if farmers act rationally to get the largest production per unit water. In reality, farmers' decisions are affected by a range of factors, such as the uncertainty surrounding irrigation allocations, the uncertainty surrounding precipitation and the farmers' judgment about how to allocate water resources under uncertainty. Perceptions about weather and risk aversion have been found to affect farmers' decisions elsewhere [43] so this may be an explanation for our observations. That is, one possible reason why the percent of land cropped was significantly lower during the yala season (e.g., 96% land cropped in maha versus 63% land cropped during yala) could be linked to the uncertainty farmers face during dry seasons. Although the selected maha season experienced similar conditions to the selected yala season, under normal circumstances, farmers can expect relatively high precipitation in maha. Uncertainty is heightened when water is scarce even if irrigation entitlements are set at the beginning of the season through the MRC's stakeholder-supported governance structure. It is not unprecedented in the MRC to see changes in planned diversions mid-season, especially when faced with unprecedented weather conditions [38]. Any lack of transparency in drought management decisions can have implications on future seasons, too. Survey results looking at how Sri Lankan farmers link information about climatic changes to their farming suggest that farmers in the MRC are using past perceptions to inform their upcoming cultivations plans, and these perceptions could influence their cropping decisions [44].

#### Food and energy and the global market

Opponents to MRC's preference for allocating water to paddy argue that there are direct economic benefits to favoring water for hydropower over water for paddy production, especially because rice has a lower market price than hydroelectricity and lower water use efficiency than other field crops. In recent years, Sri Lanka has imported significantly more thermal energy resources than in the previous twenty years. During the analysis period (2003–2013), hydroelectricity generation provided between 30% and 50% of Sri Lanka's total electricity generation [45] (SI appendix, section H). Most of the remaining electricity was generated with thermal energy resources such as coal and diesel that were imported from the world market (SI appendix, section H), and imported thermal energy resources are more costly than domestic hydroelectricity.

Proponents to MRC's preference for allocating water to paddy argue that there is evidence that irrigation can reduce chronic poverty in the rural sector by improving the access to food or improving the purchasing power to buy food [46], and these positive externalities are not captured by the direct economic valuation of hydropower and paddy. Furthermore, unlike thermal energy resources, most of the global rice production is consumed in the country within which it is produced. Sri Lanka aims to be self-sufficient<sup>1</sup> in rice. The country discourages imports through a variety of taxes [39]. Fertilizer and water are subsidized, and the government guarantees a minimum price to farmers and a maximum retail price for consumers. Furthermore, the Agricultural Lands Act of 1973 mandates farmers to grow paddy on paddy lands [39]. The limited rice stocks available for export on the world market requires a country that is importing a significant portion of their rice demand to have trust in the stability of the market, assume unilateral rationality, and to adopt risk mitigation techniques such as storage [42]—all of which are difficult in particular for countries with developing economies.

#### Water and the trilemma

There are no specific rules for managing water resources successfully—the insights gained by looking at Sri Lanka's TFs will be different than the insights gleaned from other system's TFs. Thus, the TF is a useful model to understand the physical constraints of specific systems, as well as the political and social dynamics that influence decisions. Before we can take bureaucratic or market based approaches to manage water, we need this basic understanding of physical, political, and social constraints; without it, we are not capturing the comprehensive value of a critical input—water.

Decisions surrounding water resources are 'at the nexus of ethics, public policies, nature, values, beliefs, and rationality' [47], so framing the food–energy–water trilemma around water allows stakeholders to account better for elements that are often left out of tradeoff analyses. Although society is making progress incorporating social desirability with technical feasibility and profitability of water allocation, there is much work to be done. Before water can be valued economically, accounting adequately for the social externalities that arise when looking at the trilemma, it is important to identify the network connections among food, energy, and water. We think that TFs and the embedded political and social constraints on productions can illuminate these connections.

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Vanderbilt University, Nashville, TN p 102

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