Applied Geography 77 (2016) 92–100

Contents lists available at ScienceDirect

Applied Geography

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

Agricultural adaptation to drought in the Sri Lankan dry zone

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A R T I C L E I N F O

Article history:
Received 26 March 2016
Received in revised form
26 September 2016
Accepted 30 October 2016
Available online 9 November 2016

Keywords:
Drought
Adaptive capacity
Multi-scale
Remote sensing
Mixed methods

A B S T R A C T

Droughts affect more people than any other natural disaster. Drought severity is not merely a function of precipitation; it emerges from a web of interrelations between human and natural systems. The impacts of drought are equally complex, shifting across temporal scales, economic sectors, and regions. Even in regions with similar hydroclimatic characteristics, there is tremendous variation in the effects of drought. This study combines satellite imagery, geospatial data, and qualitative data to identify the multi-scalar factors that drive variations in agricultural responses to drought. We analyzed eleven years of remotely sensed imagery to identify agricultural areas in which cultivation occurred during an extreme drought in Sri Lanka. We visited a subset of these communities and conducted interviews with officials and farmers to identify the factors that influenced agricultural adaptation. Results suggest that though structural factors such as infrastructural capacity and physical environment significantly affect agricultural adaptation, dynamic factors such as local control of water supply, perceived risk, community cohesion, and farmer experience explain significant variation in the adaptive capacity of agricultural systems.

1. Introduction

Drought is a recurring and complex phenomena that substantially affects both human and natural systems. On average, drought affects more people and causes more economic damage than any other natural disaster (Wilhite & Vanyarkho, 2000). Recent studies suggest that in many regions of the world the spatial extent, likelihood, and duration of droughts will increase in the future (Dai, 2013; Touma, Ashfaq, Nayak, Kao, & Diffenbaugh, 2015). Drought arises from an interaction between reduced rainfall (meteorological drought), soil moisture stress (agricultural drought), reduced canal flows or reservoir storage (hydrological drought), and restricted water access caused by economic factors or political power (socioeconomic drought) (Heim, 2002). Regions with similar infrastructural, institutional, and physical characteristics may manifest markedly different responses to similar drought events (Swain et al., 2014).

Drought has particularly severe effects on agricultural systems (Lesk, Rowhani, & Ramankutty, 2016). The complex social and ecological processes that interact to generate agricultural responses to drought include management paradigms and governance, cultivation patterns, decision-making processes, information availability and access, infrastructure, and environmental factors (Meinzen-Dick, 2007; Ostrom, 2009). A system's adaptive capacity, or the ability of a system to prepare for stresses and changes in advance or adjust and respond to the effects caused by the stresses, emerges from complex interactions between these processes at multiple scales and levels (Engle, 2011; Gibson, Ostrom, & Ahn, 2000; Smit & Wandel, 2006). Adaptive systems have high adaptive capacity and exhibit the potential for structural change (Cash et al., 2006), facilitate coordination and deliberation amongst stakeholders (Lebel, Garden, & Imamura, 2005), foster social learning through critical self-reflection (Pahl-Wostl et al., 2007), and realign decision-making to natural scales (Moss & Newig, 2010). A community's adaptive capacity is a function of both local processes and the larger systems in which these processes are embedded (Cash et al., 2006; Smit & Wandel, 2006).

To capture these cross-scale interactions, we combined remotely sensed and qualitative data to identify the structural and dynamic determinants of agricultural adaptation. Structural variables are those that are slow to change such as jurisdictional boundaries, infrastructural capacity, relative location within the irrigation network, and physical environment. Dynamic factors change quickly and at smaller scales. These factors include

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http://dx.doi.org/10.1016/j.apgeog.2016.10.003
0143-6228/

community dynamics, political influence, resource control, market constraints, and perceptions of risk. Larger, slowly changing, structural factors (i.e. institutions and infrastructure) set the conditions within which the smaller, dynamic processes (i.e. political influence, resource control, market fluctuations, and perceptions of risk) operate; conversely, an aggregation of smaller dynamic processes can generate changes in structural variables (Giddens, 1984; Gunderson, 2001).

This paper focuses on the processes of agricultural adaptation that took place in rural Sri Lanka in response to a severe drought in 2014. The 2014 drought is estimated to have affected the livelihoods of over one million Sri Lankans. 58 percent of the country had completely insufficient water to cultivate during the 2014 dry season (World Food Program, 2014). We analyzed satellite imagery to measure variations in agricultural responses to drought and identify a subset of agricultural communities with similar structural characteristics (i.e. agroecological region, storage capacity, command area, number of farming families, institutional jurisdiction) but different cultivated extents. We conducted key informant interviews in eight of these communities to identify the factors, both structural and dynamic, that influenced variations in cultivated extent during the drought. By linking analyses of remotely sensed and qualitative data, we developed a rich, cross-scalar understanding of the factors that influenced agricultural adaptation to drought.

2. Background

Sri Lanka is an island nation off of the southeastern coast of India. The nation experiences two monsoon seasons annually. The northeast monsoon lasts from October to December and brings nearly two-thirds of annual rainfall to Sri Lanka; the southwest monsoon lasts from May to October and brings rain primarily to the southwestern region of the island. This rainfall pattern divides the island into a wet and dry zone (Fig. 1) and creates a distinct wet and dry cultivation season.

For over 1000 years, farmers living in the dry zone have constructed small reservoirs, locally known as *tanks,* to store wet season water for dry season cultivation. Today, the dry zone is dotted with over 11,250 "minor" tank systems (Imbulana, Wijesekera, & Neupane, 2006). Due to low tank storage capacities, variations in rainfall, and growing population, farmers in these systems frequently experience water scarcity during the dry season (Shah, Samad, Ariyaratne, & Jinapala, 2013). To address these challenges, in the 1960s the Sri Lankan government began construction of a network of massive irrigation systems that diverted the waters of nation's largest river, the Mahaweli Ganga, through a system of centrally managed reservoirs, hydropower plants, and over 10,000 km of canals (Withananachchi, Kopke, Withanachchi, Pathiranage, & Ploeger, 2014). In the 1970s, the government created the Mahaweli Authority of Sri Lanka (MASL) and charged the institution with the implementation and management of these new "major" irrigation systems (Zubair, 2005). The MASL offered perpetual leases to government-owned plots of land in the MASL systems. Farmers who resettled the land received 2.5 acres of paddy land and 0.5 acres of homestead (Takesada, Manatunge, & Herath, 2008). By the end of 2012, the MASL had resettled over 166,000 families onto 250,000 acres of irrigated land (Withananachchi et al., 2014). Today, these irrigation systems contribute significantly to the Sri Lankan economy, producing over 800,000 metric tons of paddy annually (MASL, 2014) and generating enough power to meet 40% of Sri Lanka's energy demand (Manthrithilake and Liyanagama, 2012).

Over 40 institutions and legislative acts govern water use in Sri Lanka (Manthrithilake and Liyanagama, 2012). Minor irrigation

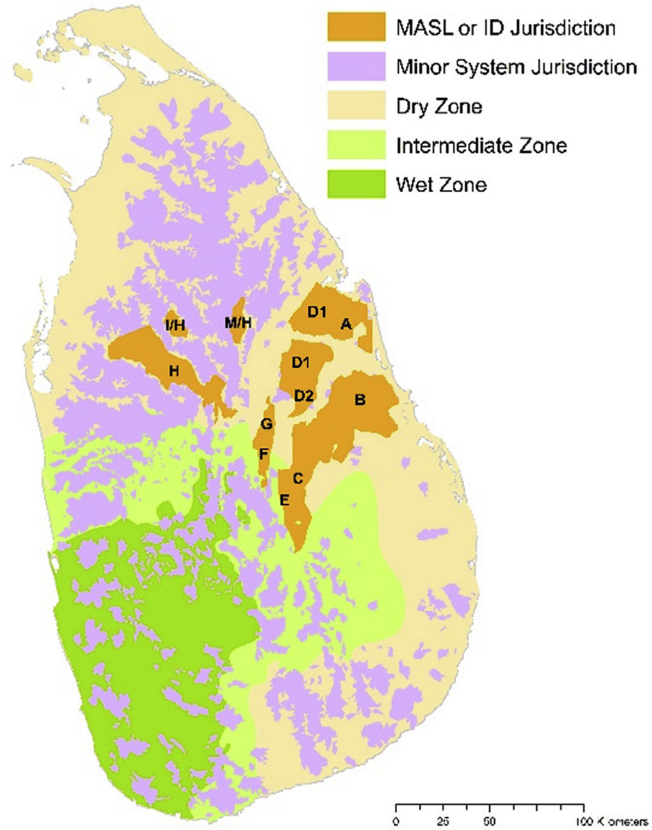

Fig. 1. Water management regimes and agroecological zones of Sri Lanka. The jurisdictional boundaries of minor irrigation systems are shown in purple below. These systems cover most of the island. Major irrigation systems managed by the MASL and ID are shown in orange. These systems are named using letters (i.e. System H, System B, System MH), which are displayed on each system in the figure. The majority of the major irrigation systems fall in the dry region of the country. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

systems fall under the jurisdiction of the Department of Agrarian Development and are primarily managed by the farmers themselves. The MASL and Irrigation Department (ID) share the management of major irrigation systems. Prior to each season, a group of national officials from the Ceylon Electricity Board, the Department of Agriculture, the ID, and the MASL meet to determine seasonal inflows to each major system reservoir. The group produces a Seasonal Operating Plan (SOP) that specifies the first and last date of water issues for each system, proposed cultivated extents, expected energy generation, and monthly diversion volumes for each major irrigation system. Within each major irrigation system, water release from reservoirs along main canals is managed by system-level MASL or ID officials. Farmers are grouped by field canal into farmer organizations (10–15 farmers) that are responsible for field-level water rotations and canal maintenance.

3. Methods

3.1. Remote sensing analysis

Many studies have used remotely sensed metrics of vegetation health to monitor agricultural responses to drought (Brown, Reed, Hayes, Wilhite, & Hubbard, 2002; Peters et al., 2002; Thenkabail, Gamage, & Smakhtin, 2004). We use the Enhanced Vegetation Index (EVI) to measure regional variations in the effects of drought on agricultural vegetation health. The EVI is a strong proxy for rice growth and is highly correlated with both leaf area and vegetation fraction estimates (Gumma, 2011; Huete et al., 2002; Sakamoto et al., 2005; Small & Milesi, 2013; Xiao et al., 2006). The EVI is measured as:

$$EVI = G\frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + C_1\ x\ \rho_{RED} - C_2\ x\ \rho_{BLUE} + L}$$

where ρ is atmospherically corrected surface reflectance, L is the canopy background adjustment, and C_1 and C_2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosols in the red band (Huete et al., 2002). EVI values approaching one indicate higher levels of photosynthetic activity.

To first identify double-cropping agricultural communities, 16-day 250 m MODIS Terra MOD13Q1.005 EVI imagery were compiled from January 2004 to June 2015 into a single spatio-temporal datacube. The EVI time series for each pixel contains information about seasonal changes in vegetation health, land cover, cropping patterns, and a stochastic component. In tropical countries like Sri Lanka, this stochastic component is strongly influenced by cloud cover. Data reduction techniques such as principal component analysis (PCA) can be used to extract phenological information from noisy datasets by separating deterministic processes in lower components and location-specific or stochastic dimensions in higher components (Eastman, 1993; Lasaponara, 2006; Small, 2012). To extract the dominant phenological signals from the noisy dataset, we applied standardized PCA to the unmasked EVI dataset, dropping data from 2014 and 2015 to remove the effects of the drought. The use of standardized PCA ensures that each temporal observation is given an equal weight in the analysis (Eklundh & Singh, 1993). The empirical orthogonal functions (EOF) from this analysis represent the data as uncorrelated temporal patterns and the principal components (PCs) represent the spatial distribution of these patterns (Anyamba & Eastman, 1996; Eastman, 1993). In our analysis, the third PC captured the contribution of surface water irrigation to variations in vegetation health and showed a strong double-cropping signal through time. To identify double-cropped pixels, we compared the third PC to a land use map created by the Sri Lankan Survey Department in 2011. Various thresholds were applied to the third PC to classify pixels as double-cropped or not and compared this classification to the land use map. A receiver operating characteristic (ROC) curve was constructed to assess the overall performance of the threshold approach and to determine the appropriate threshold (Hanley & McNeil, 1982). The total area under the ROC provides a metric for classification performance. Increasing area indicates increasing performance, with an area of one corresponding to perfect predictions. Our approach preforms well, with a value of 0.80. Using the Youden Index, we found the threshold of the third PC at which the ROC curve is furthest from the line of equity (Fluss, Faraggi, & Reiser, 2005). We masked pixels with loadings on the third PC above this value to identify regions in which farmers double-crop, i.e. they regularly cultivate their fields during both the wet and dry seasons.

Two criteria were used to identify the subset of these double-cropped pixels in which cultivation occurred during the 2014 dry season drought: total seasonal vegetation production and maximum seasonal EVI. Total seasonal vegetation production is measured as the integral of the smoothed seasonal EVI curve and is a proxy of the amount of biomass produced on a pixel (Jönsson & Eklundh, 2004; Lupo, Linderman, Bartholome, & Lambin, 2007; Rasmussem, 1992). The inclusion of a maximum seasonal EVI threshold ensures that selected pixels exhibited a greening up during the dry season. Because agricultural fields tend to have peak EVI values great than 0.5, this value was used as the maximum seasonal EVI threshold (Huete et al., 2002; Sakamoto et al., 2005).

Prior to the extraction of total seasonal vegetative production and maximum seasonal EVI, we applied the MODIS quality mask to the dataset to remove observations contaminated by cloud cover and dropped pixels missing more than 50% of their observations from the analysis. Because rapid changes in EVI are often caused by cloud contamination, observations with values exceeding a 0.15 change in EVI from the value at the previous time step were masked. Missing data were linearly interpolated and smoothed using the Savitzky-Golay filter, a low-pass filter particularly well-suited to noisy data (Chen et al., 2004; Savitzky & Golay, 1964). For each double-cropped pixel, we computed the average dry season total vegetation production from 2004 to 2013 and compared it to the 2014 value. Pixels with total seasonal vegetation production greater than one standard deviation below the 10-year pixel average and a maximum seasonal EVI above 0.5 were flagged as those in which farmers were able to cultivate during the drought.

3.2. GIS and key informant interviews

The remotely sensed analysis identified large-scale patterns of agricultural cultivation and served as the foundation for a more detailed analysis of the dynamic factors that affected agricultural adaptation to the 2014 drought. To identify the structural determinants of agricultural adaptation, we linked the results from our remote sensing analysis to a geographic information system (GIS) containing information about the characteristics of agricultural communities, such as agroecological region, storage capacity, command area, number of farming families, institutional jurisdiction, and relative location within the irrigation network. Using this information, we selected four pairs of communities with similar structural characteristics that exhibited different cultivated extents during the 2014 drought. Randomly selected locations in which our larger research project had already established institutional relationships with key government officials were prioritized in the community selection process. In August 2015, we conducted key informant interviews with local officials, system-level officials, and farmers in each community. Officials included national water managers in Colombo, system-level engineers and water managers, farmer organization officials, and agricultural extension officers. A total of 38 interviews and 4 farmer focus groups were conducted. When interviews could not be conducted in English, they were conducted through a translator. In each interview, we discussed the factors that the interviewee perceived as influencing cultivation during the 2014 drought.

4. Results

4.1. Remote sensing results

The results of the PCA analysis reveal the spatiotemporal patterns that explain most of the variance in vegetation health in Sri Lanka from 2004 to 2013 (Fig. 2). The first PC (41% of the total variance) captures the contribution of land cover to variations in vegetation health. Bodies of water and coastal regions have low loadings while areas of dense vegetation such as forests show high loadings. The second PC (4.4% of total variance) isolates the seasonal and spatial variations in vegetation health caused by the monsoon, with higher loadings in the wet zone and lower loadings in the dry zone. The third PC (3.1% of total variance) has very low loadings within the institutional boundaries of the MASL systems and the eigenvector of this PC shows a strong double-cropping signal. This PC captures the contribution of surface water irrigation systems to variations in vegetation health. To identify double-

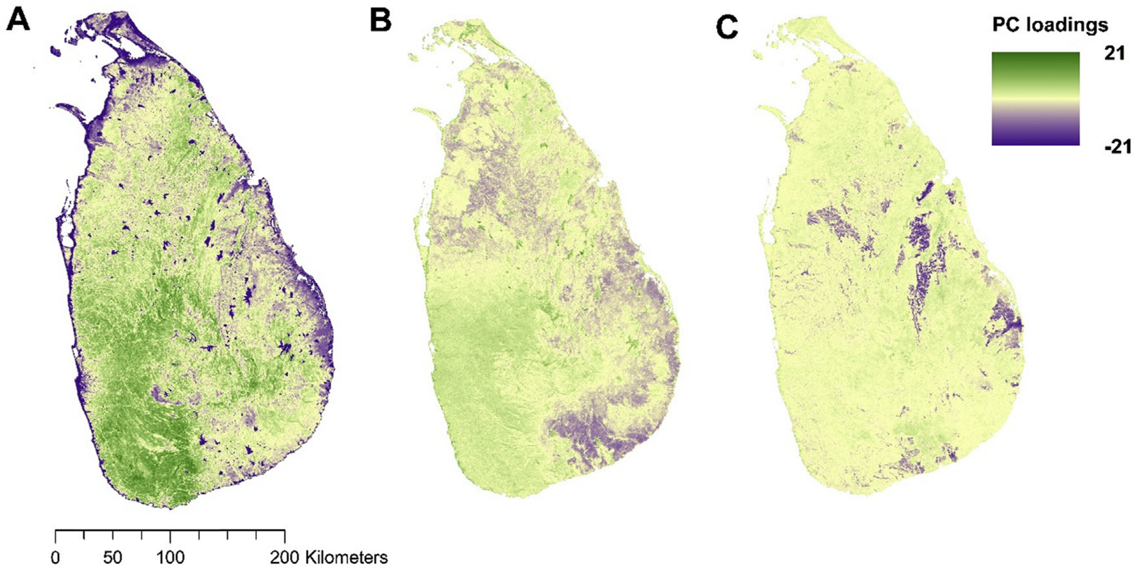

Fig. 2. Principal components analysis results. (a) The first PC captures the variations in land cover that explain most of the variance in vegetation health in Sri Lanka. (b) The second PC detects variations in vegetation health attributable to the wet, intermediate, and dry agroecological zones on the island. (c) The third PC shows strong negative loadings within the boundaries of the MASL and ID irrigation systems. This PC captures the contribution of surface water irrigation to the vegetation health variations.

cropped pixels, we applied a threshold to the third PC using the methods described in Section 3.1.

Pixels in which cultivation occurred during the drought (i.e. satisfying the total vegetation production and maximum seasonal EVI criteria) are shown in Fig. 3. 45% of these pixels are located within major system boundaries. Only 25% of cultivated pixels are located within minor system boundaries, and 65% of these pixels are located in the wet zone. The Survey Department's land use map classified 73% of the identified cultivated pixels as agricultural (slash and burn agriculture known as *chena*, gardens, plantations, or paddy). Of the remaining non-agricultural classified pixels, 16% were classified as roads, forest, or bodies of water located in close proximity to agricultural areas.

4.2. Qualitative results

The remote sensing analysis reduced agricultural adaptation to a matrix of agricultural responses to drought. To uncover the dynamic, local processes that affected agricultural adaptation, we visited eight dry zone communities (Fig. 4) to discuss the 2014 drought with local water managers and farmers. In the following section, we compare these systems to articulate processes described by community members as significantly contributing to agricultural (mal)adaptation during the 2014 drought.

4.2.1. The D1 systems: negotiation and reallocation

The reservoirs that store water for the northern D1 systems are located at the tail-end of the MASL irrigation network. These reservoirs only receive wet zone water when upstream reservoirs are sufficiently full to generate pressure required to send water north. Even with adequate pressure, transferring water to these systems creates conveyance losses. At the beginning of the 2014 dry season, the MASL determined that upstream reservoirs were too low to send irrigation water to the D1 systems. Officials warned against cultivation, urging system managers to save limited water in the D1 reservoirs for domestic use. Farmers in both systems staged multiple protests at local ID offices and MASL headquarters in Colombo demanding that officials release irrigation water for paddy cultivation. Farmers argued that they could cultivate paddy and meet

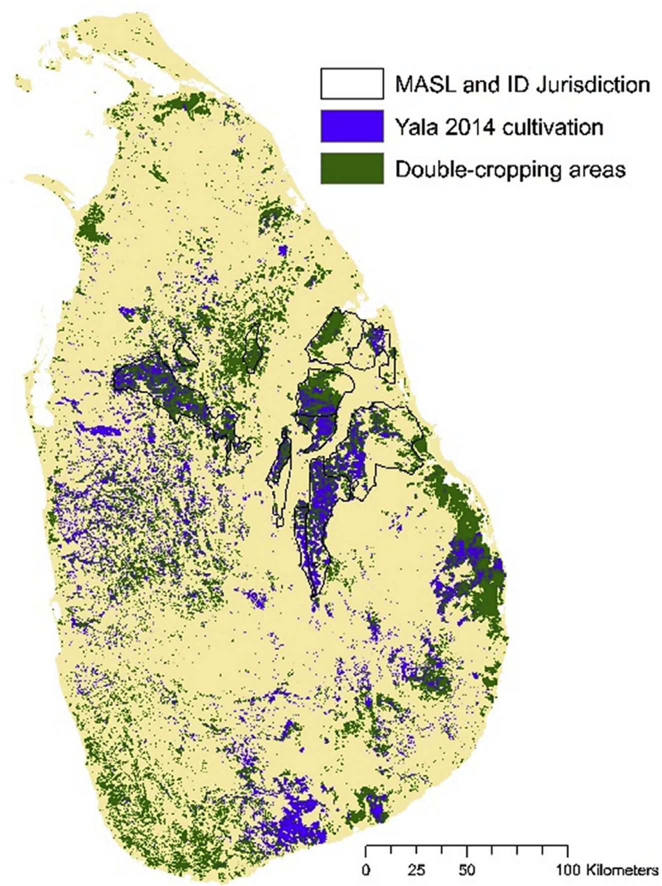

Fig. 3. Cultivation during the 2014 drought. Green pixels are the regions in which farmers typically double-crop, i.e. cultivate during both the wet and dry seasons. Purple pixels are those in which cultivation occurred during the 2014 dry season drought. Most of these cultivated pixels are located within the southeastern wet zone or are within the jurisdictional boundaries of MASL and ID systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

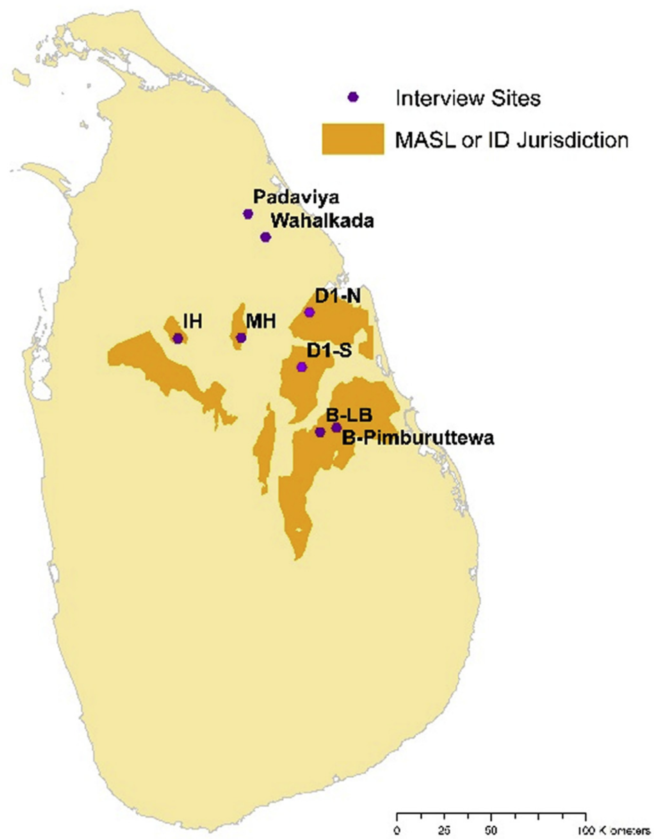

Fig. 4. Interview site locations. All sites in which interviews were conducted were located within MASL or ID jurisdiction. Padaviya and Wahalkada fall under the jurisdiction of the ID, but do not receive water from MASL irrigation infrastructure and are considered to be medium-sized rain-fed systems.

domestic water demand if they practiced *bethma*, a traditional drought mitigation technique native to the dry zone. Under *bethma,* permanent field boundaries are temporarily abolished and land is redistributed amongst all farmers who cultivate in the command area. This redistribution process is complex and varies from system to system, but in general, each family receives equal-sized parcels of land regardless of land ownership (Spiertz & de Jong, 1992; Thiruchelvam, 2010; de Jong, 1989). The total amount of land cultivated by each farmer is temporarily reduced to ensure all farmers in the community have access to limited water supplies. *Bethma* is a remarkable and relatively widespread adaptive practice; during the 2014 drought, five of the eight communities in which interviews were conducted practiced *bethma*.

In the D1 systems, farmers proposed a *bethma* in which head-end farmers would divide their original 2.5 acre fields into half-acre parcels. Each farmer cultivating at the tail-end of the command area would temporarily move to the head-end of the system to cultivate one of the remaining four parcels on each head-end farmer's land. In both D1 systems, this proposed reallocation of land would force tail-end farmers, many of whom belong to the Tamil ethnicity and speak Tamil, to travel over 40 km to cultivate head-end plots which in large part belong to Sinhalese families who speak Sinhalese. Despite these cultural, infrastructural, and physical challenges, farmers still preferred *bethma* to no cultivation. In both systems, lengthy negotiations between farmers and water managers took place, delaying cultivation by over a month. Local water managers ultimately conceded to farmers' requests to cultivate a small subset of the command area, making it clear that the farmers would bear all risks associated with cultivation. At the end of the season, 19% and 25% of the total command area was cultivated with paddy in Systems D1N and D1S respectively. Farmers attributed this success to increased involvement by local water managers and their own increased water use efficiency. In water abundant seasons, water managers rarely monitor field-level water inflows. During the 2014 dry season, officials monitored fields day and night, checking for water losses and water poaching. Farmers visited fields daily to monitor actual water demand and to close bunds and gates at the appropriate time. Despite their efforts, several farmers conceded that paddy cultivation would likely have failed if not for a chance rain at the end of the season.

Despite the serious physical and infrastructural constraints faced by D1 farmers, farmers successfully negotiated with officials to cultivate a reduced command area during the drought. Many farmers attributed this success to their political influence as potential voters in the buildup to a national election. After the negotiations were complete, farmers and water managers understood that they alone bore the risk associated with cultivation because the MASL was physically unable to send additional water north. Several farmers and officials said that the high risk increased cooperation in land and water reallocation as well as overall water use efficiency in both systems.

4.2.2. System B: control and experience

System B is the largest of the MASL systems. At the beginning of the dry season, System B's main reservoir, Maduru Oya, was filled to half-capacity and the MASL stated that the system would not receive additional inflows for the remainder of the season. To ensure adequate drinking water supplies for this large system, the MASL recommended a 50% *bethma* in which tail-end farmers would move to the head-end of the system to cultivate. The MASL also advised farmers to grow other field crops such as soy and maize that are less water intensive than paddy. We visited a community along the left bank of System B in which the cultivated area was reduced during the drought. Farmers in this community agreed to the 50% *bethma*, though few cultivated the recommended alternative crops, stating that they lacked a local market and necessary agricultural inputs to do so. At the end of the season, these farmers cultivated 59% of the command area, only 1% of which was cultivated with other field crops. Farmers generally felt that given reduced water levels in Maduru Oya, 2014 cultivation was successful.

We also visited a community in System B in which, according to the remotely sensed results, 100% of the command area was cultivated during the drought. This community, while technically located in System B, stores irrigation water in a smaller tank (Pimburuttewa tank) downstream of Maduru Oya. Most of these farmers live relatively close to the tank, making it easy for them to monitor their water supply. A group of older farmers inspected the tank's water levels at the beginning of the season and claimed that in the past they had successfully cultivated the entire command area with similar amounts of water. These farmers convinced the other farmers cultivating in the tank's command area to ignore MASL recommendations and cultivate 100% of the fields with available water. These farmers, like the D1 farmers, took a significant risk and responded by managing water with extreme efficiency. They checked fields daily, monitored water levels, and patrolled for illegal siphons. One farmer proudly stated that by the end of the season the drainage canals were too dry for fish to survive. The experience of a few farmers and the community's control of its water supply facilitated agricultural adaptation to the 2014 drought. Had the farmers listened to MASL recommendations, they would have cultivated only 50% of their command area.

4.2.3. IH and MH: institutions and culture

Much of the water delivered to System MH from the wet zone travels through a 73 km feeder canal that transfers water from an upstream reservoir in System H. Local water managers with the ID, the institution responsible for managing water in System MH, claimed that the system's main reservoir rarely received water inflows promised by the MASL because of water poaching along this feeder canal. In response to the structural water scarcity this has caused in System MH, many farmers have installed agrowells and now pump groundwater to irrigate crops. Agrowell irrigation cannot generate sufficient water to cultivate paddy, so many farmers have started cultivating other field crops such as soy, maize, and onions. During the 2014 drought, the MASL recommended that local water managers avoid releasing irrigation water from the main reservoir in System MH to ensure domestic water demands could be met. Because of this restriction, only farmers with access to an agrowell were able to cultivate during the drought, which explains the patchy appearance of cultivation in the system detected by the remote sensing analysis. Most of the farmers interviewed had not invested in agrowells and were forced to find employment outside of the agricultural sector.

System IH, a system similar to System MH in terms of command area, storage capacity, and distance from MASL headwaters, showed strong signs of cultivation during the drought. Interviews revealed that farmers in this system received 5000 acre feet of water from the MASL during the 2014 dry season. The farmers used this water to successfully practice a 50% *bethma*, 40% of which included other field crops. Like System MH, System IH receives water from a feeder canal leaving System H. Unlike MH, farmers here do not experience structural water scarcity. When asked to explain the difference in water availability in the two systems, IH officials cited two reasons. The first was institutional fragmentation. Both System MH and IH are managed by the ID, though the MH feeder canal is managed by the MASL while the IH feeder canal is managed by the ID. Officials said that the MASL had little incentive to monitor water overuse along the feeder canal that sent water to a system outside of its jurisdiction. Along the IH canal, however, ID officials actively monitor water poaching and water flow. The second reason cited by officials was the cultural importance of the IH area. System IH also surrounds the city of Anuradhapura, home to some of the most sacred Buddhist sites in Sri Lanka. During the drought “diversions were made … to address [the] cultural requirement” of the thousands of thirsty pilgrims that temporarily call Anuradhapura home during religious festivals (MASL, 2014). Despite similar infrastructural and institutional characteristics, variations in upstream water management, the cultural significance of sites located within the system, and domestic water demand generated radically different outcomes in Systems MH and IH.

4.2.4. Wahalkada and Padaviya: history and expansion

The remotely sensed analysis revealed radically different cultivated extents in two northeastern minor systems that share similar command areas and storage capacities: Padaviya and Wahalkada. In Wahalkada, farmers surprisingly cultivated 100% paddy during one of the most severe droughts in recent history. Local farmers attributed their cultivation to the system's history. Like most of the irrigated communities in the dry zone, farmers were resettled from overpopulated southern cities during the 1960s and 1970s. Today, in most of the dry zone irrigation systems, second and third generation descendants of the original settlers face land fragmentation, growing population, and increased demand for water (Azmi, 2007). Wahalkada's resettlement began relatively late in 1973. At the onset of the civil war in the 1980s, resettlement stopped. After the war ended in 2009, families moved back to the area, but today relatively few families cultivate in the Wahalkada command area. Low water demand allows farmers in the area to cultivate the entire command area even during periods of extreme drought.

Several kilometers down the road in Padaviya, only 19% of the command area was cultivated during the drought. Padaviya resettlement started in 1954, nearly 20 years earlier than in Wahalkada. Though many farmers left during the war, long-established ties to the region brought them back in the mid-2000s. While Wahalkada's 810 ha command area supports only 1185 farming families, Padaviya's 970 ha acre command area supports over 9000 families. Overpopulation in Padaviya contributed to water shortages during the 2013 dry season and the 2012 and 2013 wet seasons. These systematic water shortages have pushed many farmers to seek alternative employment. When water managers proposed a 25% *bethma* during the 2014 drought, many remaining farmers sold their *bethma* plots and abandoned agriculture for the season. The remaining farmers cultivated 19% of the command area, 100% of which with crops other than paddy. Despite water managers' efforts to manage water efficiently, at the end of the season water was so scarce that drinking water had to be delivered by truck. Several farmers cited crop damage at the end of the season due to insufficient water.

5. Discussion

5.1. Infrastructural access

The most important driver of cultivation during the 2014 drought was access to MASL irrigation infrastructure. This access facilitated a spatiotemporal transfer of water from the wet season and wet zone to their fields. Without access to this infrastructure, there was generally insufficient rainfall to cultivate during the drought. Despite widespread access to this infrastructure, many MASL farmers questioned whether exiting storage capacities were sufficient to support future population growth in the dry zone. The MASL response to these concerns is the construction of the largest reservoir in Sri Lanka, Moragahakanda, which could bring an additional 3500 acres under cultivation (SMEC Ltd., 2013). Over a thousand families will be displaced to construct this reservoir and thousands more will be resettled into the newly irrigated regions of the dry zone (Ranasinghe, 2013).

Though infrastructural development is an essential response to changing climate, the expansion of water-intensive agriculture in the dry zone should be executed with extreme caution. Systems which are located far downstream from MASL headwaters such as the D1 systems already experience severe water scarcity during periods of drought. The overexpansion of agricultural production in the dry zone may push the region past its carrying capacity and gradually erode the adaptive capacity of agrohydrological systems (Holling & Meffe, 1996).

5.2. Cross-scale interactions

More flexible, democratic, and participatory institutions have been shown to increase adaptive capacity (Cash et al., 2006; Engle & Lemos, 2010; Gupta et al., 2010). In most MASL and Irrigation Department systems, water allocation management is already fairly decentralized. Local water controllers, often farmers themselves, are responsible for opening sluice gates and monitoring water flows at the field-canal level. These water controllers are familiar with canal layouts, canal maintenance needs, and variations in field characteristics (primarily soil type and elevation). This expertise allows them to tailor allocations determined in system offices to local contexts. Farmers organization leaders liaise with water management officials regularly to discuss issues with water access and cultivation. Leveraging this existing organizational structure to increase farmer participation in *system-level* allocation decisions would integrate farmers' unique knowledge of field and canal dynamics into seasonal allocation plans. By increasing cross-scale communication between system-level officials and farmers, officials could more easily identify infrastructural and agricultural interventions to water use efficiency, such as regular canal maintenance, support for crop diversification, and monitoring of illegal water use. Similarly, by limiting institutional fragmentation, water scarcity emerging from coordination problems such as those seen in System MH could be avoided in the future.

5.3. Decentralized resource control

In System B, local control of water supply allowed farmers to apply their expertise to water release decisions. This autonomy ultimately allowed farmers to achieve 100% cultivation during the drought. Though not always feasible, increasing a community's control of its water supply could be one way of increasing local adaptive capacity. In MASL and ID systems, this may mean creating local tanks to store water as is moves through the system. It would require a reorganization of farmers around these smaller tanks rather than the current organization along field-canals. Though tank-based communities have existed in the dry zone for over a thousand years, this massive restructuring of the MASL infrastructure is not likely. An alternative is to provide farmers with additional information about water availability to increase their ability to negotiate with system-level and national officials.

5.4. Radical reallocation

Bethma is one of the most impressive responses to drought observed in the dry zone. *Bethma* temporarily disrupts the status quo to buffer against inequalities in drought exposure within a community. Despite the prevalence of *bethma*, many farmers doubted that the practice would survive in the future. Land fragmentation has reduced farmers' field size so significantly that many fields can no longer be divided under *bethma*. In addition, the introduction of agrowells has individualized water access, which has encouraged agrowell-owning farmers to opt out of *bethma* and cultivate their entire field using groundwater (Burchfield & Gilligan, 2016). At present, system-level officials are mandating that these farmers share their land. As the prevalence of agrowells increases, this mandate is becoming more and more difficult to enforce.

5.5. Diversification

Farmers at the majority of the study sites practice paddy monoculture. Though paddy is heavily subsidized, easy to store, and ideal for home consumption, its cultivation is extremely water intensive (Prasanna, Bulakulama, & Kuruppuge, 2011). At present, farmers have little incentive to cultivate less water intensive field crops such as soy, onions or chilies. There are no subsidy programs and other field crops are much more difficult to store, transport, and sell (Chandrasiri & Bamunuarachchi, 2015). The main market for vegetables is located in the center of the island in Dambulla, a significant distance from many dry zone communities. At the end of each season, the Dambula market is often flooded with a single crop, such as onions or chilies, and farmers are forced to accept extremely low prices. In addition to these market constraints, farmers face infrastructural constraints when cultivating other field crops. In surface water irrigation systems, farmers along the same field canals frequently follow the same water rotation schedule, making it difficult for a single farmer to diverge from the dominant crop planted on that field canal. Increasing support at the national level for agricultural diversification broadens the portfolio of options available to farmers during a drought (Ellis, 1998; Lin, 2011) and increases an agricultural system's potential to positively respond to a water supply shock (Holling, 2001; Liu et al., 2007).

5.6. Monitoring agrowell use

In the past, farmers used groundwater predominantly for domestic use. Today, groundwater is increasingly used as a compliment to surface water for irrigation (Villholth & Rajasooriyar, 2009). The total number of agrowells in Sri Lanka has increased in the last two decades from zero to more than 50,000 and an estimated 55 percent of farmers in the dry zone now use groundwater to irrigate agricultural fields (Kikuchi et al., 2001). The long-term sustainability of agrowell use is questionable, especially given the fact that in Sri Lanka many of these agrowells are only deep enough to collect surface water drainage (Shah, Roy, Qureshi, & Wang, 2003). This the gradual individualization of water access disincentives farmer participation in community adaptive processes such as *bethma* that increase community adaptive capacity (Burchfield & Gilligan, 2016; de Jong, 1989). The government should carefully monitor agrowell use in the dry zone and study the long-term implications of increased groundwater pumping.

5.7. Farmer perception

In systems where farmers bore the risks associated with cultivation beyond command areas proposed by the MASL, farmers engaged in extremely efficient water management practices. Farmers agreed that during normal dry seasons, they rarely monitored fields or water releases because they knew there was sufficient water. During the drought, these farmers applied existing knowledge of efficient water management techniques with rigor. This suggests that though farmers are aware and capable of engaging in efficient water management practices, they lack incentives to manage water efficiently during normal seasons. System-level officials could establish norms and incentives for the farmers to manage water efficiently and to report misuse during normal seasons.

6. Conclusion

Despite massive infrastructural and institutional investments in the dry zone over the past 50 years, water scarcity remains a serious problem. Droughts of a serious nature occur every three to four years, while severe droughts occur every ten years (Imbulana et al., 2006). Growing population has increased demand for land and water, causing land fragmentation, landlessness, encroachment, and water scarcity (Azmi, 2007). The Sri Lankan population is expected to increase by 15% in the next 30 years, further straining limited water supplies (UN, 2006). Climate scientists predict that farmers will face a decrease in wet season rainfall and an increase in dry season drought in the future (De Silva, Weatherhead, Knox, & Rodriguez-Diaz, 2007; Jayawardene, Sonnadara, & Jayewardene, 2005; Malmgren, Hulugalla, Hayashi, & Mikami, 2003). The demographic, economic, and environmental changes facing Sri Lanka challenge agrohydrological systems around the world. Research exploring how these complex resource management systems respond to water stress is of paramount importance if we are to meet growing demands in an increasingly stressed physical environment.

Our findings suggest that though structural factors such as water management regime boundaries, infrastructural capacity, relative location within the irrigation network, and physical environment significantly shape agricultural adaptation, a number of dynamic factors such as local autonomy, effective monitoring, perceived risk, diversification potential, and community cohesion, and farmer experience explained much of the variation in cultivated extent observed across communities. Unlike the structural factors, these dynamic factors are relatively easy to influence and control. In Sri Lanka, increasing institutional support for the cultivation of other field crops could reduce water use in MASL systems and diversify the portfolio of options available to farmers during drought, though this support must be balanced with increased access to markets, market information, storage facilities, and agricultural inputs required to successfully cultivate these crops. Leveraging existing institutional structures to increase cross-scale communication between national and system-level water managers and farmers could increase information flow through the system and support system-wide adaptive capacity. Carefully planning infrastructural expansion to consider future population growth and shifting water demand could decrease the probability of future generations experiencing structural water scarcity. Officials should carefully monitor groundwater use to prevent over-exploitation and to increase participation in collective cultivation activities. Finally, programs that support farmer responsibility and local resource control could be used to change farmer perceptions of risk and to increase water use efficiency.

Acknowledgements

This work was supported by the National Science Foundation [EAR-1204685] and a Dissertation Planning Grant from the American Institute for Sri Lankan Studies. Thank you to Elizabeth Stone and Katherine Nelson for comments.

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