Mapping Productivity-related Spatial Characteristics in Rice-based Cropping Systems in Sri Lanka

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Abstract
Accurate and timely information on the productivity-related spatial characteristics in paddy fields will facilitate accurate decision-making to achieve food security needs. The aim of the present study was to map rice-cultivating regions in Sri Lanka based on crop productivity and related agronomic decisions made. A grid-based map coupled with a paddy land map of the country was used for the sampling protocol, and the generated data were mapped using ArcGIS software. The study revealed the spatial heterogeneity in the productivity of lowland paddy lands, rice varieties cultivated according to their age classes and breeding stations, water sources used for cultivation, and crops grown in lowlands during the water-limited cropping seasons. The constructed maps carrying the productivity-related spatial characteristics of rice across the country could facilitate agricultural decision support systems. The maps could be used to develop novel approaches for the management of rice productivity in rice-based cropping systems in the country.

Keywords Agro-climatic zones · Crop productivity · GIS · Spatial diversity · Water availability

Introduction
Rice (Oryza sativa L.) is the staple food crop for about 50% of the world population and one of the most important tropical cereals providing most of the daily energy for mankind, mainly in developing countries (Fageria 2015). Apart from dietary carbohydrates, rice also contains proteins, lipids, minerals, and vitamins (Fageria 2015). The annual per capita consumption of rice in Sri Lanka is 105 kg indicating the major contribution of rice to the Sri Lankan diet (Jayatissa et al. 2014; Liyanaarachchi et al. 2020). Moreover, the daily rice consumption is 300.6 g/capita/day in Sri Lanka, ranking at the 9th highest in the world. The rice consumption in the country is two times greater than that of the world’s daily consumption (Xu et al. 2020). Rice is being cultivated in two seasons at an approximate total of 1.3 million hectares and has become a vital part of the rural livelihood of over 1.8 million families (Senanayake and Premaratne 2016).

Sri Lanka is divided into seven agro-climatic zones (ACZs) based on the mean annual rainfall and elevation. Areas receiving the mean annual rainfall of less than 1750 mm with a relatively dry season from March to September are identified as the dry zone. The wet zone receives a mean annual rainfall greater than 2500 mm, while the intermediate zone has characteristics in between (Punyawardena 2020). Considering the elevation, areas located in less than 300 m, between 300 and 900 m, and more than 900 m above sea level are termed as low, mid, and up country regions, respectively (Punyawardena 2020). Accordingly, the seven ACZs are dry zone low country (DL), intermediate zone low country (IL), wet zone low country (WL), intermediate zone mid country (IM), wet zone mid country (WM), intermediate zone up country (IU), and wet zone up country (WU). Rice is cultivated in all ACZs in the country; however, the majority of the cultivated areas are distributed in DL (AgStat 2019). Despite rice being cultivated in all ACZs, variation in the productivity of rice crops in different ACZs is not known.
The DL has a well-distributed cascade irrigation network developed due to the uneven rainfall distribution within the year. The irrigation network allows dry zone farmers to cultivate rice in both wet and dry seasons either as a rainfed or an irrigated crop. However, rice cultivation in other ACZs is largely practiced as a rainfed crop with a lesser dependency on irrigation water (Amarasingha et al. 2018; Nanayakkara et al. 2020). Depending on the seasonal water availability, lowland rice-based cropping systems operate either as intensive rice-rice, rice-vegetable, or rice-other field crops (OFC; such as maize, mungbean, cowpea, millets, chili, soybean, or vegetables) or rice-fallow rotations (Ratnayake et al. 2017). Furthermore, depending on the size of the command area (irrigable area), irrigation schemes are divided into two categories. Irrigation schemes with a command area of more than 80 ha are named as major irrigation schemes, and those with less than 80 ha are called minor irrigation schemes (Imbulana et al. 2006). However, the distribution of different rice-based cropping systems in Sri Lanka as affected by the availability of water in different ACZs has not been recently studied.

Improving the productivity of rice-based cropping systems is crucial to reach national food security in rice-eating populations (Pittelkow et al. 2015). The impacts of climate change, water scarcity, and poor nutrient management have led to relatively lower yields compared to achievable yields (Davis et al. 2016). Attempts are also underway to make rice production sustainable under these significant constraints. The breeding of rice cultivars that can withstand under biotic and abiotic stresses has been one of the promising approaches adopted to enhance rice productivity. Rice breeding programs are conducted at four breeding stations located at Batalagoda (Bg), Bombuwela (Bw), Labuduwa (Ld), and Ambalantota (At) to enhance the productivity under heterogeneous soil and climatic conditions. Moreover, research programs conducted at these stations are expected to mitigate region-specific problems faced by rice crops such as heat (Bg), drought (Bw, At), flood (Bw, Ld), salinity stress (At), and iron toxicity (Bw). The main aims of those breeding programs are to develop rice varieties and/or identify promising agronomic practices (NSTC 2017). Considering the growth duration, rice varieties bred at these stations are categorized either as short (≤3 months), medium (3–4 months), or long (≥4 months) duration varieties. Even though long-duration rice varieties reach higher productivity under optimal conditions, short-duration varieties are suited to water-limited environments as they likely avoid terminal drought (Rehman et al. 2016; Suriyagoda et al. 2020).

Despite rice breeding programs being conducted at four breeding stations under three age classes, the spatial distribution of those varieties in Sri Lanka has not been studied. Moreover, the productivity of rice crops in farmer-managed field conditions may differ from the values obtained in research fields under optimal management. However, studies examining the yield attained by farmers under actual field conditions in different ACZs are limited.

Despite the recommendation by the Department of Agriculture (DoA), Sri Lanka, on conjunctive use of both inorganic and organic sources of nutrients to improve crop productivity, farmers tend to rely mainly on synthetic fertilizer sources. The most common fertilizer sources in the country are urea, triple super phosphate (TSP), and muriate of potash (MOP) that supply nitrogen (N), phosphorus (P), and potassium (K), respectively. These fertilizers were provided to the farmers at a subsidized price by the government until the year 2020. Moreover, it is not understood whether rice farmers apply adequate amounts of organic matter to rice fields if apply in which ACZs, and their sources. Therefore, it is important to understand the current practice of soil fertility management by the rice farmers in different ACZs before implementing new regulatory measures to improve the system productivity.

Productivity of rice-based cropping systems can vary due to the changes in cropping intensity, crop rotation, input availability, climatic hazards, and off-farm activities (Emran et al. 2021) and their interactions with agro-climatic conditions. However, spatial variation in the productivity-related characteristics of rice-based cropping systems in Sri Lanka in relation to ACZs has not been explored. Therefore, geo-visualization of the productivity of rice-based cropping systems is crucial for a wide range of stakeholders including policy-makers, crop breeders, agronomists, researchers, input suppliers, and farmer organizations. This includes the type of rice varieties grown (i.e., age classes), crops incorporated to lowlands other than rice during water-limited seasons, types of inputs including fertilizers and/or manures applied, and water availability for rice cultivation. This information will be useful to implement novel agricultural technologies, supply and distribute inputs, disseminate knowledge, and avoid risks in rice-based cropping systems in different ACZs. Therefore, the aim of this study was to construct detailed maps of rice-cultivating regions in Sri Lanka across the seven ACZ to represent productivity levels, age classes of rice varieties cultivated, crops incorporated to lowlands other than rice during water-limited seasons, fertilizer and/or manure applications, and water sources used for rice cultivation. The constructed maps will help in understanding the current level of complexity of the rice-based cropping systems and making region-specific decisions/recommendations to improve paddy productivity.

**Materials and Methods**

**Study Site**

Sri Lanka is a tropical island located in the Indian Ocean in South Asia with a land area of about 65,610 km$^2$ and an
Selection and Identification of Sampling Locations

Sampling locations were selected using a grid-based system combined with a paddy land map of Sri Lanka. Location tracking was performed following the approach by Kadupitiya et al. (2021). Briefly, the whole land area of the country was divided into a 1 km² grid using ArcGIS (10.3) software. A unique grid identification number (Grid-ID) was given to each grid by combining longitudes (X) and latitudes (Y), generated using Universal Transverse Mercator (UTM) projected distance coordinates (km). Paddy land extent in each grid was calculated after combining the grid map and the paddy land map (1:50,000) by union operation using the ArcGIS overlay toolbox. Out of the total number of grids (65,610) in the country, only 35,537 grids are occupied with paddy lands. After calculating the % of paddy land area of each grid, 9000 grids with the highest paddy land extent were selected (i.e., more than 30% of the grid area occupied with paddy lands) using the attribute ranking approach in ArcGIS. Stratification was done at the administrative district, divisional secretariat division (DSD), and the village levels to facilitate field data collection.

Converting the ArcGIS location point (shape file) map, a Keyhole Markup Language Zipped (KMZ) file was developed. The KMZ file was used as a guide for sampling location tracking with smartphone map browser apps using Google Maps as the base map. Topographic map sheets scale 1:50,000 and 1:10,000 by the Survey Department of Sri Lanka were used as a guide for areas with weak mobile coverage. Since each location point was tagged with Grid-ID, which is coded with distance (km) coordinate X–Y, the same ID was maintained from field data collection to laboratory analysis and data analysis. This procedure allowed easy spatial reference for data set development and facilitated user-friendly GIS map production.

Data Collection

Field data collection was done by the agriculture instructors (AIs) that operate at the village level with the close collaboration of the subject matter officers for paddy (SMO-Paddy) attached to the DoA, Sri Lanka. Before the data collection, AIs were given the guidelines for data collection to make the sampling procedure uniform across all ACZs. Moreover, prior to the survey, selected farmers were contacted personally to obtain their consent for participation in the survey and to confirm that once the information is published, the names and contacts of the respondents will be kept confidential. A questionnaire was developed and pre-tested with randomly selected 35 farmers prior to the survey. Required ethical clearance was obtained from the Ethical Review Committee, Faculty of Agriculture, University of Peradeniya, Sri Lanka (ECC/2021/E/005).

The field survey covered all ACZs and was completed at the end of the Maha season, i.e., February 2020. The collected data includes the main water source used for paddy cultivation (i.e., major irrigation, minor irrigation, or rainfed), age class of the rice variety cultivated during the Maha season (i.e., short duration, ≤3 months; medium duration, 3–4 months; or long duration, 4 ≤), cropping pattern (i.e., rice-rice, rice-fallow, rice-OFC, rice-vegetables, and rice-perennials), and types of fertilizers applied (inorganic and/or organic). Out of the 9000 questionnaires distributed, only 5182 filled questionnaires (57.6%) were received by the research team at the end of the data collection period and those were used for this study.

Results and Discussion

Out of the total area in the country (65,610 km²), the highest percentage of land was distributed in DL (58.9%) whereas the lowest in WU (2.2%). Moreover, low country (i.e., DL, IL, and WL) covered 85.7% of the total land area, while only 9.7% and 4.6% were covered by mid and up country, respectively (Fig. 1, Table 1). Out of the lands distributed in low country climatic zones (i.e., DL, IL, and WL), 14.4–14.9% of lands in each ACZ were used for lowland paddy cultivation (Table 1). Moreover, 6.3–7.2% of lands in the mid country climatic zones and only 0.5–4.7% of lands in the up country climatic zones were used for lowland paddy cultivation. This declined abundance of rice cultivation from low to up country climatic zones is due to the changes in topography and water availability. Because many streams that originate from the hilly mid and up country regions bring water to the low country, and in particular to the valley bottoms in the flat or undulating terrain, in which rice crop is largely cultivated.

Over 57% of the response rate could be reached in this study due to the involvement of AIs and SMOs attached to the Department of Agriculture who visited the farmer fields and collected the data. However, missing responses would be due to the lack of coordination between AIs and SMOs, harvesting of paddy fields by the farmers without informing the AIs in that region, and transport problems that prevailed due to the lockdown of the country as a result of COVID-19 outbreak. Despite these limitations and restrictions, the response rate of the questionnaire was equally distributed...
Fig. 1 Distribution of lowland paddy lands (A) and sampling points of this study (B) in the seven agro-climatic zones (ACZ) in the country: dry zone low country (DL), intermediate zone low country (IL), wet zone low country (WL), intermediate zone mid country (IM), wet zone mid country (WM), intermediate zone up country (IU), and wet zone up country (WU).

Table 1 Land area allocated for rice cultivation in the seven agro-climatic zones (ACZs) in Sri Lanka

| ACZ   | Land area (km²) | % Land area in each ACZ out of the total land area | Rice land extent (km²) | % Rice lands in each ACZ out of the total rice land extent | % Rice lands out of the land area in each ACZ |
|-------|-----------------|--------------------------------------------------|------------------------|----------------------------------------------------------|---------------------------------------------|
| DL    | 38,610          | 58.9                                             | 5656                   | 65                                                       | 14.6                                        |
| IL    | 9210            | 14.0                                             | 1367                   | 16                                                       | 14.8                                        |
| IM    | 3460            | 5.3                                              | 217                    | 2                                                        | 6.2                                         |
| IU    | 1570            | 2.4                                              | 74                     | 1                                                        | 4.7                                         |
| WL    | 8470            | 12.9                                             | 1220                   | 14                                                       | 14.4                                        |
| WM    | 2870            | 4.4                                              | 208                    | 2                                                        | 7.2                                         |
| WU    | 1420            | 2.2                                              | 7                      | 0                                                        | 0.5                                         |
| Total | 65,610          | 100.0                                            | 8749                   | 100                                                      |                                             |

DL, dry zone low country; IL, intermediate zone low country; IM, intermediate zone mid country; IU, intermediate zone up country; WL, wet zone low country; WM, wet zone mid country; WU, wet zone up country.
among ACZs (43–67%). Therefore, equal validity of the survey results across the country is expected.

Out of the rice fields surveyed, 65% were in DL, 16% in IL, and 14% in WL (Table 1). Only 5% of the surveyed rice fields were distributed in the other four ACZs. These percentages are proportional to the distribution of paddy lands in the seven ACZs in the county due to the proportional allocation of sampling sites (Table 1). Most of the surveyed rice fields received water from major irrigation systems (50%), while the rest operated either as minor irrigation (30%) or rainfed (20%) systems (Fig. 2).

The average rice yield of the farmers in the survey area during the Maha season in 2019/2020 was 4.76 t ha$^{-1}$. This yield is similar to the national average value estimated by the Department of Census and Statistics in Sri Lanka (DCS), i.e., 4.53 t ha$^{-1}$ ($P > 0.05$) (Fig. 3, DCS 2020). Sri Lankan rice farmers could reach this productivity due to the cultivation of improved varieties; soil fertility management practices adopted such as the application of inorganic sources of nutrients (i.e., N, P, and K) and crop rotation, and irrigation water availability. When ACZs are compared, the highest paddy yield was observed in DL (5.2 t ha$^{-1}$), followed by IL (4.4 t ha$^{-1}$) and IU (3.0 t ha$^{-1}$). Moreover, the four districts in the dry zone, namely Anuradhapura, Ampara, Hambantota, and Mannar, produced paddy yields over 6 t ha$^{-1}$, which could have been attained due to favorable weather, soil, and crop management (DOA 2010).

Irrespective of the ACZ, the majority (87%) of the rice farmers cultivated medium-duration rice varieties (3.5 months), followed by short (8%) and long duration (5%) varieties (Fig. 4). The majority of rice farmers in the northern peninsular preferred cultivating long duration rice varieties, while the farmers in the western part of the country preferred short-duration varieties (Fig. 5). This cultivation pattern is explainable by the distribution of rainfall within the country. For example, the north-east monsoon, which brings rain to cultivated lands during this season, provides abundant rainwater to northern and eastern parts of the country while making the western region of the country moisture-stressed (DOA 2010). Furthermore, the presence of major irrigation networks in the central and eastern parts of the country ensures access to supplementary irrigation water (Figs. 1 and 3). In addition, farmers in the western parts of the country tend to select short-duration rice varieties due to the higher risk associated with the lack of irrigation schemes, flash floods, and scarcity of labor in that region.

Rice varieties bred at four breeding stations were cultivated in the country at varying levels (Fig. 5). The majority of farmers (65%) cultivated rice varieties bred at Batalagoda (Bg), while 20%, 10%, and 3% of surveyed farmers used rice varieties bred at Ambalantota (At), Bombuwela (Bw), Labuduwa (Ld), respectively. The remaining 2% cultivated traditional rice varieties including Hangimuthaan, Kalu heenati, Kuruluthuda, Pachchaperumal, and Maa-wee (Fig. 4). There was a clear spatial segregation among rice varieties breed at different breeding stations. For example, rice varieties bred at Bw and Ld dominated the paddy lands in the southwestern region of the DL, where those breeding stations are located (Fig. 5). Moreover, rice varieties bred at At were mainly cultivated in the southern and partly in the eastern region of the DL. The Bg varieties had a large spatial distribution and dominated in the northern, central, and western parts of the country (Fig. 4). Traditional rice varieties, the majority of which belong to the long duration age category, were prominent in the northern peninsular of the DL. Breeding programs are aimed at submergence and iron toxicity tolerance at Bw, acidity and salinity tolerance at At, submergence and soil fertility at Ld, and general cultivation at Bg (NSTC 2017). The observed spatial patterns provide clear evidence of

![Fig. 2 Distribution of major water sources used for paddy cultivation in Sri Lanka under the seven agro-climatic zones (ACZ); dry zone low country (DL), intermediate zone low country (IL), wet zone low country (WL), intermediate zone mid country (IM), wet zone mid country (WM), intermediate zone up country (IU), and wet zone up country (WU)](image-url)
the fact that rice varieties bred at those breeding stations have successfully withstood under local- and/or region-specific problems.

Over 65% of the surveyed farmers cultivated rice in the previous minor cultivation season, Yala 2019 while the rest had other land uses. Among the other land uses, 79% were...
left fallow, while 11%, 8%, and 2% were utilized for the growth of OFC, vegetables, and perennials such as bananas, respectively. The fallowing of paddy fields during the *Yala* season has increased from the eastern to the western part of the country (Fig. 6). It was due to the lack of water available for rice cultivation during the north-east monsoon in the western parts of the low country. Moreover, the cultivation of OFC was observed in the central part of the DL and IM, while vegetable cultivation occupied the central part of DL and IU. The results indicate a region-specific diversity in the land-use pattern in rice-based cropping systems. As 27% of the lowlands (out of total paddy lands) undergo fallow during *Yala* season, particularly in the western part of the country, careful selection of agronomic practices and administrative interventions are needed to improve the productivity of those areas. For example, under situations where water availability is inadequate for rice cultivation, lands could be cultivated with vegetables or OFC that have higher water-use efficiency to increase the net return per unit of irrigation water used. This will lead to overall productivity enhancement in rice-based cropping systems (Amarasingha et al. 2015, 2017; Bouman et al. 2007).

Over 99% of the farmers applied the main three synthetic fertilizers Urea, TSP, and MOP (data not shown). Around 8% of the farmers applied micronutrients in liquid form, commercial organic fertilizers, ZnSO₄, cattle manure, poultry manure, goat manure, or compost as supplementary fertilizers (Figs. 4, 6). Most of the farmers who applied organic forms of fertilizers were located in the eastern part of the DL, while only a few farmers were distributed in other ACZs. Moreover, these farmers have reached grain yield of 4–6 t ha⁻¹, which is close to the average rice crop productivity in the country (Fig. 3). Even though the farmers from the southern and central regions of DL reached higher crop productivity (6–8 t ha⁻¹) than other regions in the country, most of them have not applied organic matter. Therefore,
the higher productivity reached by these farmers would be due to the favorable climatic and soil conditions that prevail in those regions.

The present survey revealed that the farmers have largely ignored the recommendation of the DoA to amend organic matter in combination with the application of inorganic fertilizers. This might have happened due to the lack of availability of those materials in required quantities, cost of the materials, and high labor requirement for handling and field application (Jouzi et al. 2017). One of the potential causes for the average yield of rice to be stagnant below the production potential might be the imbalanced use of plant nutrients in cultivation. Nutrient imbalances in soil could result from excessive or inappropriate use of chemical fertilizers (Cao et al. 2013; Moe et al. 2019). As observed in this survey, the majority of the farmers rely only on N, P, and K from synthetic fertilizers. An integrated nutrient management approach that combines organic and inorganic fertilizers enhance the growth and yields of rice while reducing the dose of chemical fertilizers in the cultivated lands (Moe et al. 2019; Zhang et al. 2018). Therefore, encouraging farmers to apply organic matter coupled with inorganic fertilizers as per the recommendation of the DoA is worthy to reduce the yield gap of rice in paddy growing areas, thereby improving the productivity of the rice-based cropping system in the country.

**Conclusion**

This study explored the spatial distribution of productivity-related characteristics in rice-based cropping systems in the seven ACZs of Sri Lanka, which was achieved through constructing detailed maps. Study shows that the DL carries the

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**Fig. 6** Distribution of crops grown in lowlands during the water-limited minor cropping season (Yala) (A) and whether farmers apply organic matter to rice crops or not (B) in the seven agro-climatic zones (ACZ) in the country; dry zone low country (DL), intermediate zone low country (IL), wet zone low country (WL), intermediate zone mid country (IM), wet zone mid country (WM), intermediate zone up country (IU), and wet zone up country (WU).
highest percentage of paddy lands whereas WU contains the lowest. Despite the ACZ, the majority of the rice farmers cultivate medium-duration rice varieties, followed by short and long-duration varieties. Considering the varieties cultivated by farmers, there is a clear spatial segregation of rice varieties and bread at different breeding stations. The present mapping also shows that the majority of the paddy farmers in the country cultivate varieties released from Batalagoda, which is the central breeding station in the country.

Farmers incorporated other crops (8%) or left the paddy fields fallow (27%), particularly during the water-limited seasons and regions than cultivating rice with high risk. Approximately 99% of the farmers surveyed in the present study relied solely on synthetic fertilizers for N, P, and K subsidized by the government. As such, farmers have largely ignored the recommendation of the DoA to amend organic matter coupled with inorganic sources of nutrients. Therefore, the cultivation decisions made by the farmers seem to be based on several factors including the availability of inputs for the particular cultivation season (e.g., irrigation water, organic matter) and ACZ.

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**Declarations**

**Ethics Approval** All procedures performed in this study involving human participants were in accordance with ethical standards of the institutional (Ethical Review Committee, Faculty of Agriculture, University of Peradeniya, Sri Lanka) ethical standards. Required ethical approval was obtained from the Ethical Review Committee, Faculty of Agriculture, University of Peradeniya, Sri Lanka (ECC/2021/E/005).

**Consent to Participate** Informed consent was obtained from all individual participants involved in the study. Prior to the survey, selected farmers were contacted personally to obtain their consent for participation in the survey and to confirm that once the information is published, the names and contacts of the respondents will be kept confidential.

**Conflict of Interest** The authors declare no competing interests.

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