European Journal of Agronomy 156 (2024) 127103

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Long-term evaluation of pasture production, seasonality, and variability: An application of the DairyMod pasture model for three tropical species

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ARTICLE INFO

Keywords:
DairyMod
Mulato II
Gatton panic
Rhodes grass
Pasture variability
Tropical pasture modelling

ABSTRACT

Adoption of improved pastures coupled with intensified management provide quality pastures in adequate quantities and thus improve livestock productivity. While pasture modelling is imperative for exploring the performance of newer pastures, models are little used for long-term simulations of multiple tropical pastures (genotype), under varying soil, climate (environment) and pasture production systems (management). We applied the DairyMod, a biophysical model to simulate the long-term pasture production of *Brachiaria ruziziensis* x *B. decumbens* x *B. brizantha* '*Brachiaria* Mulato II' (BM), *Megathyrsus maximus* 'Gatton Panic' (GP), and *Chloris gayana* 'Rhodes grass cv. Reclaimer' (RR) across major dairying regions of Sri Lanka under different management scenarios and characterize the long-term pasture growth, seasonality and spatial variability, and possible implications for dairying in Sri Lanka. Simulations of three pasture species were carried out for 16 locations (8 dry (DZ), 5 intermediate (IZ), and 3 wet zone (WZ)) over 30 years (1980–2010). Three pasture management scenarios simulated were; 1) potential pasture production system under non-limiting N and irrigation (Yp) 2) rainfed pasture production system under non-limiting N fertilizer (Yw), and 3) rainfed pasture production system under current nitrogen (N) fertilizer rate (Ya). Statistical techniques were used to identify the long-term growth rates, variability, and trends in pasture production. The long-term pasture production varied greatly among climate, species, and management scenarios. Overall, the Ya showed a seasonal cycle following the rainfall pattern, with a reduction in growth rates in dry seasons (May–September). Pasture growth rates were greater in GP at Ya, and BM at Yw and Yp while RR showed the lowest growth rate at all times. Variability of pasture growth was high in DZ (May–September) and RR has the lowest growth variability. The Yw increased the growth rate (doubled) while the Yp substantially increased (nearly tripled) the growth rate and growth pattern producing less variable pastures. Simulated growth rates suggest that GP in low-input and BM in high-input farming areas would be more suitable. Our study suggested that the BM, GP, and RR are edaphic-climatologically fit for major dairying regions in Sri Lanka and the appropriate fertilizer and irrigation management can greatly increase the herbage accumulation and availability of year-round pastures. While this study offers valuable insights, the species-specific growth pattern, growth variability, yield potential under different managements and the possible implications for herbage quality need to be sensibly considered when selecting the appropriate species.

1. Introduction

Sustainable livestock production systems are critical for ensuring food security in many tropical parts of the world. Tropical pastures constitute a key component of these systems, providing essential feed resources for livestock (Jayasinghe et al., 2022a, 2022b). The majority of tropical pasture-based systems face challenging production conditions (e.g., prolonged dry seasons, low soil fertility, pests, and diseases) which affect both the quantity and quality of feed produced, and thus limit livestock productivity (Rao et al., 2015). Adoption of improved

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https://doi.org/10.1016/j.eja.2024.127103
Received 3 August 2023; Received in revised form 17 January 2024; Accepted 18 January 2024

pastures resilient to these challenging biophysical conditions (Tubiello et al., 2007) coupled with intensified pasture management (Rao et al., 2015) is essential to improve the seasonal distribution of forage growth and its year-round production, thereby increasing livestock productivity.

Increasing livestock utilization of pastures often underpins higher profitability, because vegetative biomass is one of the cheapest sources of feed (Chapman et al., 2009; Chapman et al., 2008a; b). However, the efficient dairy cow feeding on pasture-based systems is hampered by the temporal (interannual variability) and spatial variability (between regions) of pasture growth rates associated with local climate, soil, and pasture species. Pasture growth rate data are usually reflected in the stocking rates, pasture management strategies and supplementary feeding decisions (Chapman et al., 2009). Variation in pasture supply is a significant source of business risk. Thus, the availability of accurate and timely quantitative estimates on possible pasture growth positively affects the biological efficiency and financial outcome of dairy production systems.

Crop simulation modelling is increasingly used in forage-based livestock production systems for exploring new species for environmental suitability, likely performance, growth rate variation, and trend analysis (Ahmed et al., 2022; Andrade et al., 2016; Jayasinghe et al., 2021; Silva and Giller, 2021). These models can provide a great deal of information substituting the need for labor-intensive, time-consuming, and expensive traditional agronomic experiments that often lead to season-specific and site-specific results. Further, crop modelling research on long-term time series can provide data to guide agricultural policies and the decision-making process (Ara et al., 2020; Chapman et al., 2009; Quigley et al., 2019). Consequently, the model-aided policy can promote sustainable livestock farming to cater to the growing demand for livestock products (Silva and Giller, 2021).

The dairy industry in Sri Lanka is an important livestock subsector, due to a growing demand for dairy products, and its potential influence on the rural economy for livelihood (Vyas et al., 2020). Dairying in Sri Lanka is largely forage-based and takes place in all parts of the country. The predominant practice of dairying is observed in dry and intermediate zones. Cattle are mainly reared under three different management systems, viz: extensive, intensive, and semi-intensive. Cattle are allowed to graze in free grassland under extensive systems while stall feeding is practiced under an intensive system, where pastures are cut and carried. The semi-intensive system has in between characteristics (grazing and cut and carry) (Korale-Gedara et al., 2023). Across all management systems, the inadequate supply of quality forage is the major factor limiting dairy production in Sri Lanka. Feed resources are either not available in sufficient quantities due to fluctuating weather conditions or even when available are of poor nutritive value. This can be attributed to the non-availability of quality pastures, lack of establishment and management experiences, and low awareness of improved forages (Houwers et al., 2015; Korale-Gedara, 2019; Kumari et al., 2019; MOD, 2018; Premaratne and Premalal, 2006; Vyas et al., 2020). This issue is compounded by seasonal variation in pasture conditions, with poor productivity and quality during dry seasons. Therefore, dairy cows are fed mostly local tropical forages, often harvested from along roadsides, uncultivated lands, and fallow paddy fields which have poor nutritive value (Houwers et al., 2015; Premarathne and Samarasinghe, 2020; Premaratne and Premalal, 2006). Consequently, the digestibility of these forages is low (58 to 62 %) in all systems, resulting in poor outcomes in terms of low milk yields (2.8–6.5 L day^{-1} cow^{-1}) and shorter lactation (180–300 days), longer calving interval (403–428 days), and low animal body weights (350–490 kg) (Kumara et al., 2022), high enteric methane emissions (2.3–13.8 kg CO_2 eq. kg $FPCM^{-1}$) (Rao et al., 2015; Opio et al., 2017) and low profitability for farmers (Opio et al., 2017).

In general, the climate and soils in Sri Lanka are conducive to forage production and the country has a significant capacity to produce tropical forage for greater production of milk domestically (Premaratne and Premalal, 2006). Houwers et al. (2015) estimated the biophysical potential for milk production in Sri Lanka as eight times higher than the current milk production under the increased supply of improved forages. The strategic changes for improving forage production in Sri Lanka have been broadly explored (Houwers et al., 2015; Korale-Gedara, 2019; Kumari et al., 2019; MOD, 2018; Premaratne and Premalal, 2006; Vyas et al., 2020). The key approaches are the introduction of improved grasses adapted to the local soil, and climate which are more leafy, and digestible to exploit the maximum genetic potential of the dairy herds and subsequently intensify management through appropriate defoliation in combination with improved plant nutrition through the increased use of fertilizers. While the impact of the non-availability of improved forages for dairying and the potential solutions to overcome it have been widely studied (Houwers et al., 2015; MOD, 2018; Premarathne and Samarasinghe, 2020; Prowurst, 2019), no previous studies have been undertaken to broadly evaluate the potential of improved forage species under different soil and climatic and management conditions, which are vital to expanding the productivity of dairy farming.

The use of improved tropical forage species receives significant acknowledgment in many tropical and subtropical dairying regions due to their strong adaptability to wider edapho-climatic conditions, improved nutritive value, and disease and drought susceptibility (Paul et al., 2020; Rao et al., 2015). The genera, *Brachiaria*, *Megathyrsus,* and *Chloris* are native to most of the tropical regions including Sri Lanka (CABI, 2022), however, their promising newer cultivars are yet to be introduced and tested in Sri Lanka. Given that, no studies have been undertaken to investigate the *Brachiaria ruziziensis* x *B. decumbens* x *B. brizantha* '*Brachiaria* Mulato II' (BM), *Megathyrsus maximus* 'Gatton Panic' (GP), and *Chloris gayana* 'Rhodes grass cv. Reclaimer' (RR) for the suitability and likely agronomic performances in a broader range of soil and climatic conditions.

Pasture modelling tools, while being a simplified representation of actual systems, can provide a platform and additional insights to identify the process involved in forage growth (Pedreira et al., 2011; Pequeno et al., 2014; Andrade et al., 2016; Jayasinghe et al., 2021; Silva and Giller, 2021) and explore the potential species for new areas before establishing expensive and time-consuming field experiments (Bosi et al., 2020; dos Santos et al., 2022; Ahmed et al., 2022). To date, models are little used to predict tropical pastures growth, hindering their use in decision support for dairy farmers (Andrade et al., 2016). The DairyMod, a mechanistic biophysical pasture model has shown the flexibility to simulate tropical pasture species (Johnson et al., 2008) and it has been successfully used to simulate tropical pasture growth and herbage accumulation under contrasting edapho-climatic and management conditions (Jayasinghe et al., 2024; Berger et al., 2014; Jayasinghe et al., 2021; Johnson et al., 2008; Perera et al., 2020; Svinurai et al., 2021; Wayne. et al., 2016). Despite the acceptable model behavior for tropical pastures, DairyMod has not yet been applied for long-term simulation (decadal time scale) under different pasture management conditions (i.e. different N inputs, irrigation). Moreover, no modelling studies have yet attempted to explore the tropical pasture species in Sri Lankan dairy system. Therefore, the present study aimed to apply the DairyMod pasture model for simulating the growth of three tropical pastures (BM, GP, and RR) across the key livestock production zones under three different pasture production scenarios and characterize the long-term pasture growth, seasonality and spatial variability, and possible implication for dairying in Sri Lanka.

2. Materials and methods

2.1. Study area

The scope of the study encompasses the entirety of Sri Lanka, geographically located between 5°55′ to 9°51′ North latitude and between 79°42′ to 81°53′ East longitude. The climate is characterized as tropical, hot, and humid throughout the year (Punyawardena, 2020).

The mean annual temperature varies from 27 °C in the coastal plains to 16 °C in the central highlands due to the altitudinal changes. The mean annual precipitation (MAP) ranges from under 900 mm in the driest parts of the southeast and northwest of the country to more than 5000 mm in the wet zone (Punyawardena, 2020). The country is divided into three major climatic zones; the dry zone (DZ) (MAP < 1750 mm) covers the east, northern, and south-east part of the country which has a distinct dry season from May to September, the wet zone (WZ) (MAP > 2500 mm) in the central and south-west regions which has no distinct dry periods and the intermediate zone (IZ) (1750–2500 mm MAP) separating the two with a short and less prominent dry season (Fig. 1).

Sri Lanka has a heterogeneous agro-ecological environment. A particular agro-ecological region represents fairly even agro-climate, soils, and terrain conditions and would support a particular farming system with a certain range of crops and farming practices, including forage cultivation and livestock farming. The agro-ecological zones map was used from National Spatial Data Infrastructure (NSDI) (https://catalog.nsdi.gov.lk/) to identify the homogeneous climate zones and combined it with the map of the geographical distribution of dairy herds across climate zones (Opio et al., 2017) to identify the number of locations of simulations (Fig. 1).

The number of locations was proportionately determined based on the relative land area of each climate zone, and each location within the climate zone represents highest density of cattle, and different soil, and climate conditions. Overall, sixteen locations were selected within three climatic zones; 8 locations in DZ (Anuradhapura, Puttalam, Ridiyagama, Ampara, Kantale, Mannar, Polonnaruwa, Jaffna), 5 locations in IZ (Kurunegala, Maho, Matara, Badulla, Monaragala) and 3 locations in WZ (Peradeniya, Kotadeniyawa, Galle). A large area of the wet zone (indicated by black dashed line inside the dark green area in Fig. 1) was

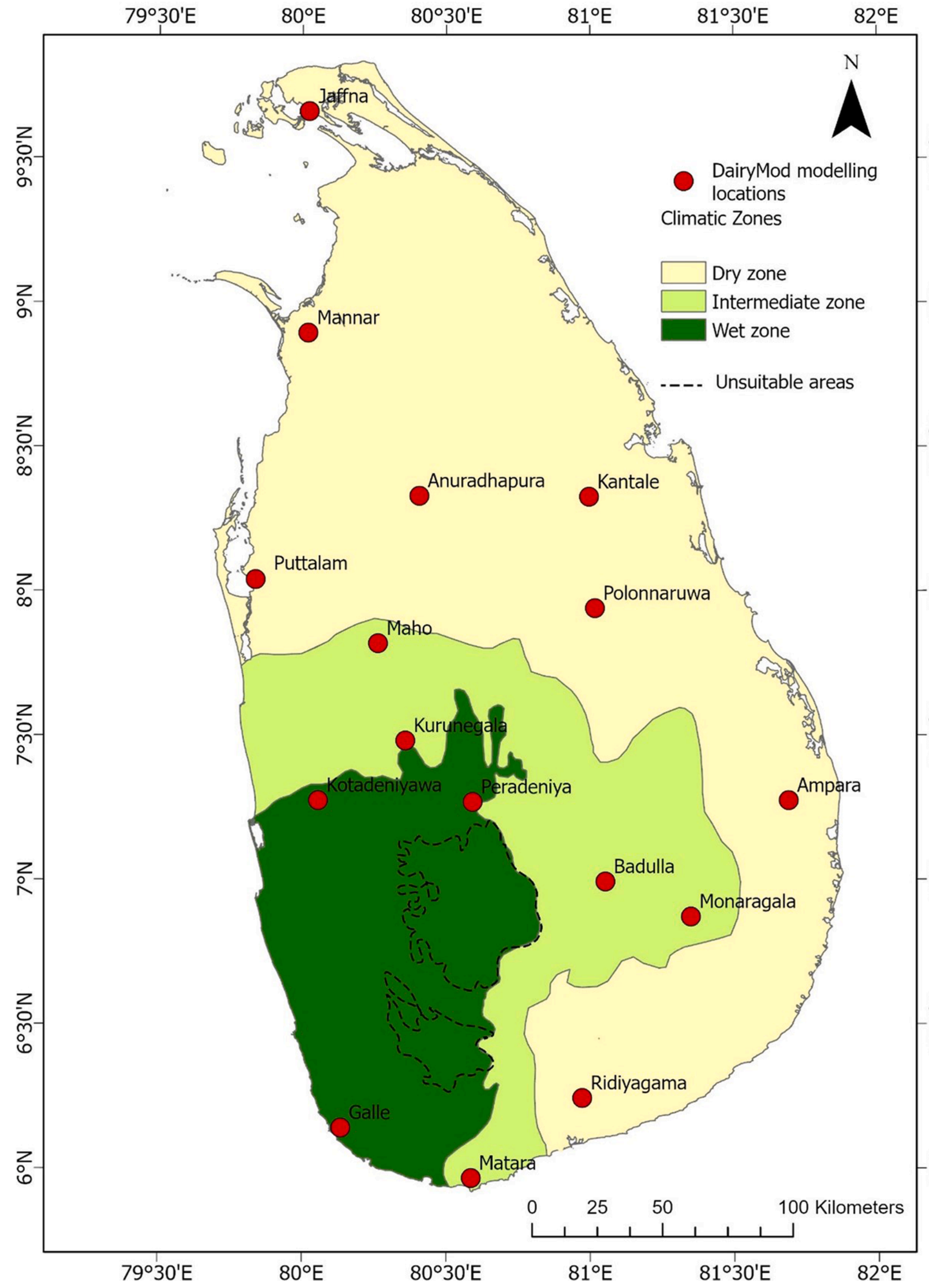

Fig. 1. Map of the DairyMod-SGS model simulation locations (red dots) in three major climatic zones of Sri Lanka.

ignored given the high elevation (up to 2400 m) and low mean daily temperature (10 °C) during most of the days in the year (Punyawardena, 2020) which makes those areas unsuitable for growing tropical pastures.

2.2. Soil and climate data

The agro-ecological zones map was overlaid on the soil map of Sri Lanka obtained from the NSDI and created a buffer with a radius of 15 km around each point in ArcGIS Pro 2.8.6 (ESRI, 2021) to determine the most representative soil series for each location. Subsequently, soil profile data for the respective soil series were extracted from the SRI-CANSOL Project database (Mapa et al., 2005; Mapa et al., 2010; Mapa et al., 1999). Observed minimum climate data required to run the long-term simulations were not available in Sri Lanka across multiple locations, therefore, the daily gridded weather data of maximum and minimum temperature, solar radiation and rainfall provided by AgMERRA (https://data.giss.nasa.gov/impacts/agmipcf/agmerra/) (Ruane et al., 2015) were used in the present study. The AgMERRA grided data have been previously used for a similar purpose in several modelling studies in Sri Lanka (Gunarathna et al., 2019; Gunarathna et al., 2020; Wimalasiri et al., 2020). Long-term weather data (30 years) were extracted for the period from 1 January 1980–31 December 2010 using the multidimensional tool in ArcGIS Pro 2.8.6 (ESRI, 2021). Supplementary Fig. 1a-c shows the long-term monthly climate variables for the 16 locations selected. The site-specific details including the climate and soil types are described in Table 1.

2.3. DairyMod pasture model

The DairyMod pasture model version 5.8.2 (Johnson, 2008) was used to run the long-term tropical pasture simulations. A comprehensive model description is given in Johnson et al. (2008). Briefly, DairyMod is a daily time-step, mechanistic, whole-farm system, a biophysical model that comprises pasture growth, soil water, soil nutrients, farm management and animal production modules. The pasture module describes the species-specific parameters for the calculation of light interception, photosynthesis and respiration, nutrient uptake, partitioning of new growth into various plant parts, and development followed by turnover and senescence (Johnson, 2008). In addition, the soil water dynamics (evaporation, runoff, and infiltration) and soil nutrient dynamics (organic matter turnover and inorganic N mineralization and immobilization, movement in the soil (leaching), absorption in the soil, and atmospheric losses) explain in the model using soil water and soil nutrients modules, respectively. The farm management module describes the different pasture management strategies including, fertilizer application, irrigation, cutting or grazing and stock management. The model has been previously parameterized and robustly validated for the pasture species, BM, GP, and RR across multiple environments by Jayasinghe (2023); Jayasinghe et al. (2024). The validated model has shown good accuracy for pasture growth and biomass accumulation under the cut-and-carry management across a broad range of edapho-climatic conditions (e.g., subtropical, tropical, Mediterranean, and desert environments), and agronomic management practices (e.g., irrigated, rainfed, nitrogen (N) fertilizer, shaded, high inputs) (Jayasinghe et al., 2024). The present study used these pasture-specific parameters (Supplementary Table 1) to simulate the likely pasture growth under the current edapho-climatic conditions in Sri Lanka.

2.4. Pasture management scenarios

Three pasture management scenarios; a representation of the current pasture production system in Sri Lanka and two hypothetical pasture production systems were built in the DairyMod pasture model (Table 2). The resulting scenarios were: 1. Potential pasture production system under non-limiting N and water (water and N unlimited yield; Yp) 2. Rainfed pasture production system under non-limiting N fertilization (water-limited potential yield; Yw), 3. Rainfed pasture production system under current N fertilizer rate (water and N limited yield; Ya),

Yp: yield under no N and water limitations.

Yw: yield under no N limitation but water limitation.

Ya: yield under water and N limitation (current practice under rainfed).

2.5. Model initialization and simulation setup

Each simulation was initialized before running the model for exporting the long-term data. By initializing, it was ensured that the soil carbon (C) and N pools reached a steady state and achieved a system equilibrium for each scenario. To set up the initializing conditions, the model was run for 30 years (1980–2010) with multiple loops (n = 5) to create more than 100 years of a long simulation until stabilizing the soil N and C pools. The stabilized soil N and C pools were determined when

Table 1

Site-specific climate, and soil types at 16 locations used for the simulation of *Brachiaria* Mulato II, Gatton panic, and Rhodes grass Reclaimer growth representing major dairying regions in Sri Lanka. (DZ = Dry zone, IZ = Intermediate zone, WZ = Wet zone).

Location	Long (E)	Lat (N)	Climate zone	Annual rainfall (mm)[1]	Altitude (m)	Great soil groups[2]	WRB (FAO) group[3]	Soil series[4]
Ampara	81.69	7.27	DZ	1606	30	Reddish Brown Earth	Luvisols	Damana series
Polonnaruwa	81.02	7.94	DZ	1542	46	Reddish Brown Earth	Luvisols	Kaduruwela series
Puttalam	79.84	8.04	DZ	1151	10	Red Yellow Latasols	Regosols	Gambura series
Jaffna	80.03	9.66	DZ	1326	11	Red Yellow Latasols	Luvisols	Chankanai Series
Kantale	81.00	8.33	DZ	1555	46	Reddish Brown Earth	Luvisols	Seruwila series
Anuradhapura	80.44	8.1	DZ	1344	115	Reddish Brown Earth	Luvisols	Mahailupplama Series
Mannar	80.02	8.89	DZ	987	10	Grumusols	Vertisols	Murunkan series
Ridiyagama	80.97	6.24	DZ	1016	39	Reddish Brown Earth	Luvisols	Ranna series
Kurunegala	80.36	7.48	IZ	1984	120	Red Yellow Podzolic	Alisols	Kurunegala series
Badulla	81.05	6.99	IZ	1737	660	Red Yellow Podzolic	Luvisols	Badulla series
Maho	80.27	7.82	IZ	1619	90	Reddish Brown Earth	Luvisols	Maho series
Matara	80.56	6.08	IZ	2090	25	Red Yellow Podzolic	Alisols	Beliatta series
Monaragala	81.35	6.87	IZ	1732	154	Reddish Brown Earth	Luvisols	Bibela series
Peradeniya	80.59	7.27	WZ	1696	480	Reddish Brown Latosolic	Nitisols	Kandy series
Galle	80.14	6.14	WZ	2307	5	Red Yellow Podzolic	Alisols	Dodangoda series
Kotadeniyawa	80.06	7.28	WZ	2253	55	Red Yellow Podzolic	Alisols	Minuwangoda series

Long = Longitude, Lat = Latitude, E = East, N = North.

[1] Nisansala et al. (2020) and Department of Meteorology, Sri Lanka (http://www.meteo.gov.lk/)

[2] Moormann and Panabokke (1961).

[3] World Reference Base for Soil Resources (WRB) Dassanayake et al. (2020)

[4] Mapa et al. (2005); Mapa et al. (2010); Mapa et al. (1999).

Table 2
Pasture production scenarios and effect of water and nitrogen fertilizer.

Pasture production scenarios	Definition	Water effect	N effect	Inorganic fertilizer
Ya	Rainfed pasture production system under current N fertilizer rate (water and N limited yield)	Yes	Yes	240 kg N ha^{-1} $year^{-1}$
Yw	Rainfed pasture production system under non-limiting N fertilization (water-limited potential yield)	Yes	No	-
Yp	Potential pasture production system under non-limiting N and water (water and N unlimited yield)	No (irrigated)[1]	No	-

[1] Irrigation (25 mm $application^{-1}$) when the cumulative rainfall deficit (rainfall–potential evapotranspiration) was 25 mm or greater.

the slope of the annualized average daily soil N mineralization rate (g N ha^{-1} day^{-1}) over 30 years was $< \pm 0.01$, along with steady soil organic C pool and C: N ratio of the fast (labile) and fast + slow turnover pools (Supplementary Fig. 2) (Christie et al., 2018; dos Santos et al., 2022). During the initialization stage, pasture swards were defoliated on the last day of each month and received 20 kg N ha^{-1} $month^{-1}$ in the form of urea to maintain a level of reasonable pasture production during the initialization phase and reflect the lowest N fertilizer rate applied during the data extraction phase. Subsequently, the endpoint of the simulation was saved for the data exporting phase.

Simulations in DairyMod were conducted as a "cut-trial" where the pasture was mechanically defoliated on the last day of each month to a residual weight of 3 t DM ha^{-1} (Jayasinghe et al. (2022a). At each defoliation, herbage was removed from the field to reflect the conditions typical in cutting trials. Three tropical pastures were separately simulated as monoculture swards at all locations and the simulations were conducted for 30 years (1980–2010). The respective N fertilizer rate (for Ya) and irrigation (for Yp) were defined in the management submodule in the DairyMod under the N fertilizer and irrigation options. Nitrogen fertilizer was applied in the form of urea at a rate of 240 N kg ha^{-1} $year^{-1}$ and the frequency of application was aligned with the rainfall pattern of each climate zone resulting in 30 N kg ha^{-1}, 24 N kg $ha^{-1}$and 20 N kg ha^{-1} rate of N fertilizer in 8, 10 and 12 times (months) per year for the DZ, IZ, and WZ, respectively. Consequently, the fertilizer application windows were set as 15 September to 15 April, 15 August to 15 May, and after each defoliation for the DZ, IZ and WZ, respectively. All locations were irrigated for the Yp scenario during the dry months to maintain the soil moisture at or near field capacity reflecting the non-limiting soil water conditions. Irrigation was applied (25 mm $application^{-1}$) when the cumulative rainfall deficit (rainfall–potential evapotranspiration) was 25 m or greater in each location.

Average annual herbage accumulation and long-term monthly average herbage accumulation rates over 30 years were compiled for each site across three major climate zones. Similarly, long-term pasture production data for the three simulated pasture management systems were summarized. The variability in herbage accumulation and growth rates were characterized using the coefficient of variation (CV %). Pasture net growth rate and CV data were analyzed for the significant difference among locations, months using oneway ANOVA. In addition, pasture net growth rate data were separately analyzed using ANOVA for the significant difference among the pasture species, climate zones and management regimes and their interactions. Tukey's honestly significant difference post hoc test was used to separate significant differences. Significant effects and differences were accepted when $p \leq 0.05$. Data analyses and visualizations were undertaken using the R software (RCoreTeam, 2021).

3. Results

3.1. Characteristics of long-term pasture growth and herbage accumulation

Overall, the mean pasture growth rates were comparatively lower in DZ and comparatively higher in WZ. All three pastures recorded relatively lower mean growth rates under the Ya pasture management scenario across all the simulated locations (Table 3 and Fig. 2) (Supplementary Fig. 3). By comparison, DZ locations, namely; Jaffna, Mannar and Kantale displayed low mean pasture growth rates under Ya, Yw, and Yp pasture management scenarios. Across all locations, GP had the highest growth rate (53.4 kg DM ha^{-1} day^{-1}) for the Ya scenario compared to BM and RR which demonstrated a similar growth rate (48.0 and 46.6 kg DM ha^{-1} day^{-1}) (Table 3 and Fig. 2). The BM had a greater mean pasture growth rate (93.4 kg DM ha^{-1} day^{-1}) under water-limited potential yield (Yw) than GP and RR. Similarly, BM showed the highest mean growth rate (138.4 kg DM ha^{-1} day^{-1}) under non-limiting nutrient and irrigated conditions (Yp) (Table 3 and Fig. 2). Overall, BM had higher mean growth rates than GP and RR in all pasture management scenarios tested, except the Ya.

Long-term monthly pasture growth rates across the main three climatic zones and pasture management scenarios are summarised in Fig. 3. Overall, interannual pasture growth rates showed the same tendency of monthly rainfall distribution (see Supplementary Fig. 1a-c) in the respective climate zones, resulting in the highest pasture growth rates in WZ across all management scenarios ($p < 0.05$).

Under the existing pasture management (Ya), monthly mean pasture growth rates showed a high seasonality, especially under dry and intermediate climates. Pasture growth rates under the Ya scenario was markedly low from June to September in DZ and IZ and RR showed comparatively little growth (15.7 kg DM ha^{-1} day^{-1}) than BM (24.1 kg DM ha^{-1} day^{-1}) and GP (27.8 kg DM ha^{-1} day^{-1}). According to Fig. 3, the Yw scenario greatly improved the pasture growth rates of all three pastures across the climatic zones ($p < 0.05$), however, the application of unlimited nutrients did not change the growth patterns. In general, both simulated rainfed scenarios (Ya and Yw) showed lower growth rates in drier months regardless of the level of fertilization in the pasture system. Increased pasture growth rates in the Yw scenario were more noticeable in IZ and WZ than in the DZ. The mean monthly pasture growth rates in DZ increased from 41.7 to 81.1 kg DM ha^{-1} day^{-1}, 49.3 to 77.8 kg DM ha^{-1} day^{-1} and 44.2 to 63.1 kg DM ha^{-1} day^{-1} for BM, GP and RR, respectively. Switching the pasture production system to the unlimited nutrient application (from Ya to Yw), the long-term average monthly pasture growth rates in IZ and WZ increased by 59.4, 45.4 and 36.6 kg DM ha^{-1} day^{-1} and 62.1, 47.4, 41.0 kg DM ha^{-1} day^{-1} for BM, GP and RR, respectively. Overall, the BM greatly responded to the increased soil nutrient level showing a higher growth rate than the GP ($p < 0.05$) and RR showed the lowest growth rates across all climates and pasture management scenarios (Fig. 3).

The differences between the Yw and Yp scenarios in Fig. 3 illustrate the water-limited gap over the annual cycles of weather for different climate zones. The simulated average monthly growth rates increased greatly under the non-limiting nutrients and irrigated conditions (Yp) across the climate zones and the amount of increased pasture growth rate was considerably higher in DZ than the growth rates displayed in IZ and WZ. By comparison, the increase in growth rate was relatively higher for BM than the GP and RR under the same conditions (Fig. 3). The average monthly pasture growth rates increased by 51.0 kg DM ha^{-1} day^{-1}, 49.9 kg DM ha^{-1} day^{-1} and 31.7 kg DM ha^{-1} day^{-1}, respectively, for BM, GP and RR due to the changes in pasture management with irrigation. Simulated monthly pasture growth rates further revealed that the growth pattern greatly changed under the Yp, resulting in higher growth rates during the drier months of the year, except in WZ. This

Table 3

Long-term average monthly net pasture growth rate (95 % CI) distributions of *Brachiaria* Mulato II (BM), Gatton panic (GP), and Rhodes grass Reclaimer (RR) for the locations in three major climatic zones (DZ = dry zone, IZ = intermediate zone, WZ = wet zone) under different pasture management scenarios in Sri Lanka. (Ya = yield under water and N limitation, Yw = yield with no N limitation but water limitation, Yp = potential yield with no N and water limitation).

Characteristic	Net growth rate (kg DM ha^{-1} day^{-1})					
	BM	p value	GP	p value	RR	p value
Climate		0.030		0.028		0.126
DZ	87.7^{a} (81.2–94.2)		87.9^{a} (81.4–94.4)		71.9^{b} (65.4–78.4)	
IZ	93.8^{a} (87.3–100.3)		94.0^{a} (87.5–100.5)		78^{b} (71.5–84.5)	
WZ	111.6^{a} (105.1–118.1)		111.8^{a} (105.3–118.3)		95.8^{b} (89.3–102.3)	
Management		< 0.0001		< 0.0001		< 0.0001
Ya	48.0^{b} (49.5–63.5)		53.4^{a} (49.7–63.7)		46.6^{b} (33.8–47.7)	
Yw	93.4^{a} (91.6–105.5)		88.7^{b} (91.8–105.7)		82.7^{c} (75.8–89.7)	
Yp	138.4^{a} (131.1–145.0)		133.0^{b} (131.3–145.2)		122.3^{c} (115.3–129.2)	
Interactions						
Species × Climate		0.031		0.029		0.030
Species × Management		< 0.0001		< 0.0001		< 0.0001

$^{a-c}$Means with different superscripts, within the same row are significantly different ($p < 0.05$).

change in the growth pattern was more evident in DZ than in IZ and WZ, producing a more constant pasture production throughout the year.

3.2. *Pasture growth and herbage accumulation variability*

The long-term interannual variability (CV %) of monthly pasture growth across three major climatic zones under different pasture management scenarios is presented in Fig. 4. In many instances, the variability of pasture growth rates differed from each other within the locations. A higher variable pasture growth rates were observed from the locations in DZ and the observed average variability was 99 %. The variable pasture growth pattern was more evident during the drier months (May to late September). Between climate zones, the locations in the WZ had the characteristically lowest pasture growth variability (59.9 %) and the variable pasture growth pattern was less evident. The relationship between the long-term monthly pasture growth rates and the CV % of the BM, GP, and RR for the locations in three major climatic zones under different pasture management scenarios is presented in Fig. 5. In general, when two or more plots overlap, the respective pastures display similar annual patterns in the relationship between the mean growth and variability in the annual growth cycle. While a variable pasture growth was noticeable between species, the characteristic variable pasture growth pattern was similar across the three pasture species. The variation in the pasture growth variability between species was more pronounced during the drier months of the year (May to September). According to Fig. 5, the BM and GP plots are mostly overlapped while the RR plot is separately placed showing the similar annual pattern of GP and BM, and different patterns of RR in the relationship between the mean growth and variability. The RR has shown the lowest variability and recorded fairly resilient pasture growth during the drier months across all climatic zones and pasture management (Figs. 4 and 5). While a considerable variable pasture growth was observed between locations, climate zones and pasture species, the convergence of pasture growth between different pasture management scenarios was noted in all locations, climates and pasture species (Figs. 4 and 5). By contrast, the level of convergence was marked in DZ and IZ and had greatly improved under both the Yw and Yp pasture management scenarios. The more divergence pasture growth observed between pasture species under the Ya pasture management scenario within the typical N fertilizer (Ya) has greatly improved due to the change in pasture management. In general, RR showed the lowest pasture growth variability under all scenarios, however, the divergence pasture growth of BM has largely reduced under Yw and Yp scenarios compared to Ya which has also resulted in a lower variability between the three pasture species. Overall, the Yp scenario has greatly increased the variable drier months pasture production and produced a more consistent, and year-round pasture growth in almost all the locations.

4. Discussion

4.1. *Long-term pasture growth and herbage accumulation*

Growth rate and herbage accumulation were greater in GP at Ya, and BM at Yw and Yp while RR showed the lowest growth rate at all times. The Ya scenario showed a seasonal cycle following the rainfall pattern, with a reduction in growth rates in dry seasons (May to September). Overall, the pasture performance of the present study in terms of long-term herbage accumulation (Supplementary Table 2) outperformed the historical average annual herbage production (discussed later). In particular, Liyanage (1989) indicated that the *Megathyrus maximus* and *Brachiaria* pastures can yield up to 17 t DM ha^{-1} year^{-1} in well-fertilized WZ soils while the *Brachiaria mutica* can yield 12.4 t DM ha^{-1} year^{-1} in IZ soils in Sri Lanka. In the present simulation study, an estimate of 19 t DM ha^{-1} year^{-1} and 23 t DM ha^{-1} year^{-1} of average annual herbage mass was produced by the BM and GP, respectively in the WZ while the BM produced 17.7 t DM ha^{-1} year^{-1} in IZ. In another study, Senanayake and Pemadasa (1991) extensively studied the *Brachiaria brizantha* in a cut-trial harvested in five weeks intervals across the 12 different regions of Sri Lanka and reported a mean DM yield of 10 t DM ha^{-1} year^{-1} (range from 2.7 to 33.7 t DM ha^{-1} year^{-1}). In contrast, the present study reported a 16.4 t DM ha^{-1} year^{-1} of average annual herbage across all locations. According to Premaratne and Premalal (2006) who presented the common forages and their yield potential under different management conditions, *Megathyrus maximus* produced up to 12–15 t DM ha^{-1} year^{-1} and 12–20 t DM ha^{-1} year^{-1} at the 45 days of cutting interval under the good management at 0.60 × 0.75 m and 0.50 × 1 m spacing, respectively. In addition, the *Brachiaria brizantha* produced an average yield of 10–12 t DM ha^{-1} year^{-1} at 35 days cutting interval in the IZ, Sri Lanka. By comparison, the long-term mean annual simulated pasture production of BM and GP are greater than the average values reported in the literature (Premaratne and Premalal, 2006) for the standard cultivars of *Brachiaria* and *Megathyrus* under the current pasture management (Ya) ranging from 4–7 t DM ha^{-1} year^{-1} and 5–8 t DM ha^{-1} year^{-1}, respectively. This greater variation in pasture production could be

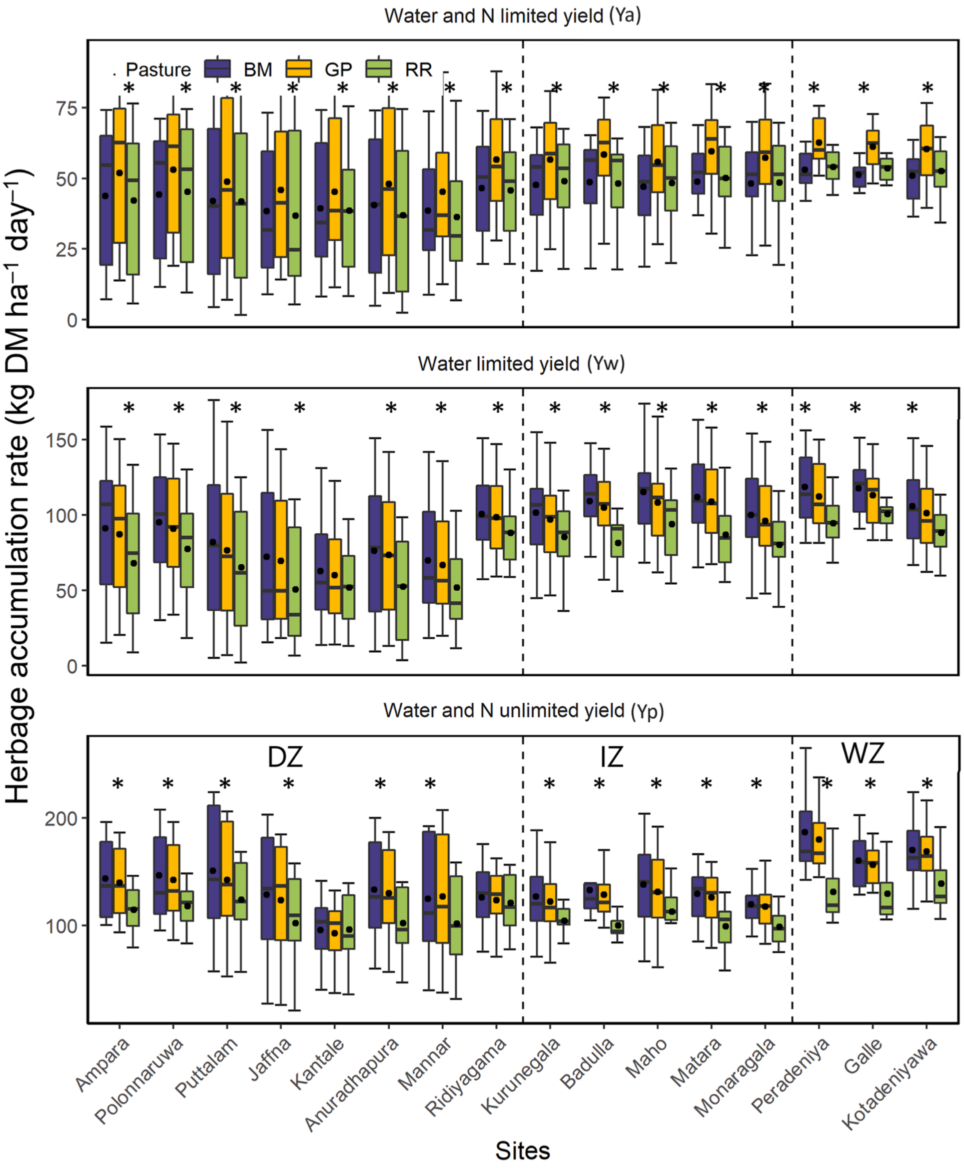

Fig. 2. Long-term monthly pasture growth rates distributions of *Brachiaria* Mulato II (BM), Gatton panic (GP), and Rhodes grass Reclaimer (RR) for the locations in three major climatic zones (separated by vertical dashed lines) (DZ = dry zone, IZ = intermediate zone, WZ = wet zone) under different pasture management scenarios in Sri Lanka. The black dots represent the mean value. *Statistically significant at $p < 0.05$ within each site.

attributed to the improved traits of the pasture species including higher yield potential, adaptability to wider edapho-climatic conditions, and improved disease and drought susceptibility. In contrast to the previously reported biomass data, the long-term average simulated herbage accumulation of BM and GP has doubled and nearly tripled under the Yw and Yp scenarios, respectively suggesting the likely yield performance of these tropical pastures under the edapho-climatic conditions in Sri Lanka.

While classical validation of the models was not performed in the present study due to the lack of data as a result of BM, GP and RR not being previously tested in Sri Lanka, it was assumed that the validated DairyMod pasture model by Jayasinghe (2023); Jayasinghe et al. (2024) maintains similar consistency in accurately simulating the long-term forage production given the broader model validation across a range of edapho-climatic and management conditions similar to Sri Lanka. The mean herbage accumulation of standard cultivars reported in the previous studies in Sri Lanka was compared (previously discussed) with the long-term simulated growth data of the present study to observe the confidence of the model predictions. Even though the results of the previously reported studies about pasture yields are not entirely comparable with the simulated yields of the present study due to possible unaccounted factors (e.g., species, cutting intervals, cutting heights, planting spaces) between studies, those studies provide a better insight into the confidence of the model predicted pasture yield. Further, both the simulated and previously observed pasture data followed similarities in terms of the trends of pasture production within the species, and under different climatic zones. Comparison of the pasture production of RR was not possible as no studies have previously been undertaken to study the RR or its standard cultivars in Sri Lanka.

4.2. Pasture growth characteristics

In general, the greater pasture growth of GP under the existing management in the present simulation study is comparable with the results observed by Jayasinghe et al. (2022a). The higher pasture growth rate and associated forage yield of GP are attributed to the forage-yielding potential of the genus *Megathyrus* explained elsewhere (Sollenberger et al., 2020), and also the characteristically higher plant

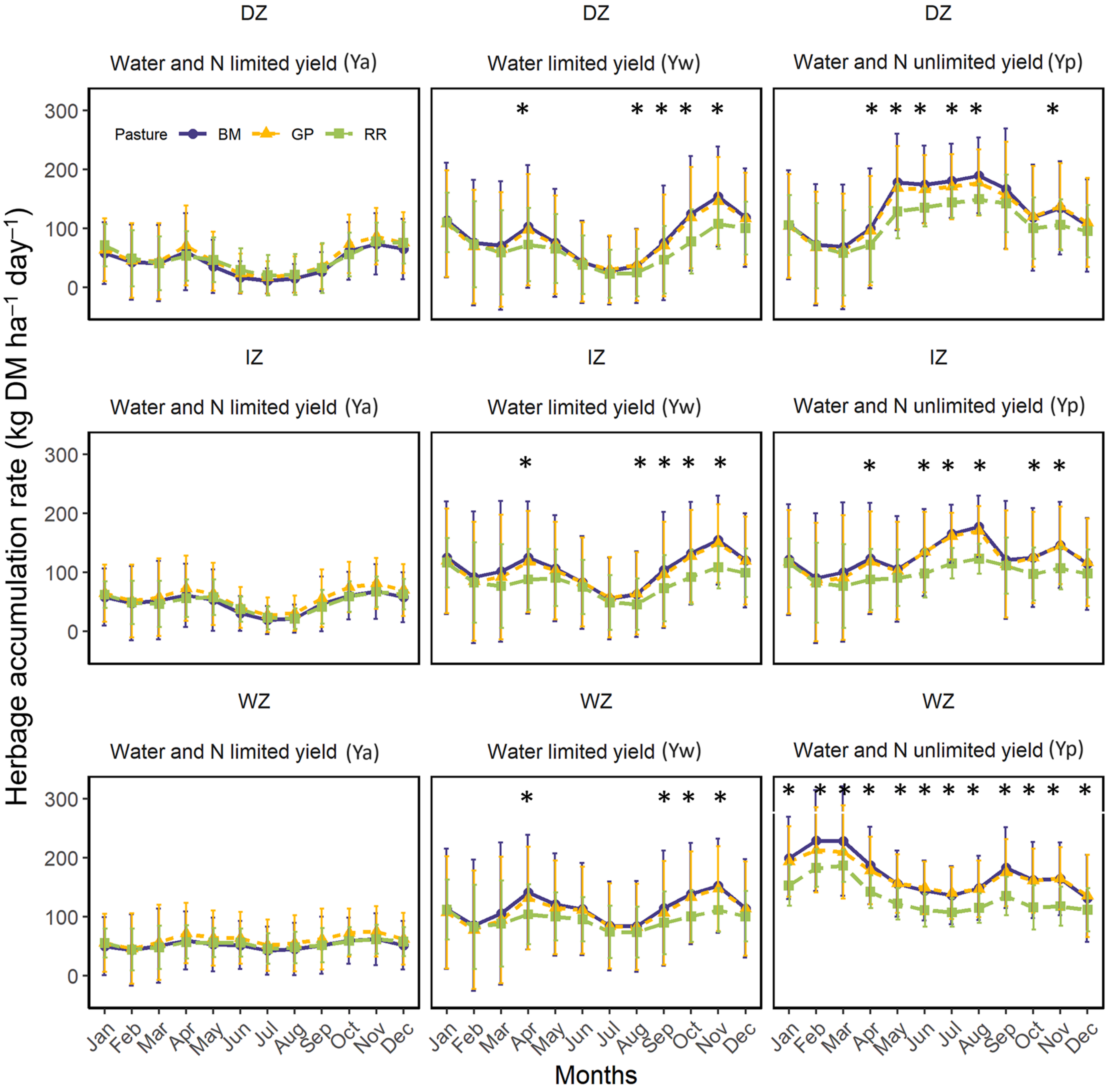

Fig. 3. Long-term monthly pasture growth rates distributions of *Brachiaria* Mulato II (BM), Gatton panic (GP), and Rhodes grass Reclaimer (RR) for the locations in three major climatic zones (DZ = dry zone, IZ = intermediate zone, WZ = wet zone) under different pasture management scenarios in Sri Lanka. Error bars represent the mean ± standard deviations. *Statistically significant at $p < 0.05$ within each month.

height, stem proportion and number of leaves (Jayasinghe et al., 2022a). Conversely, BM showed higher pasture growth rates under the Yw and Yp pasture management scenarios compared to GP and RR, highlighting the potential of BM for responding to fertilizer, particularly to the application of N at the optimum plant available water in the soil. According to Argel et al. (2007), the application of N has increased DM yields of BM from 2.2 t harvest^{-1} with one application of N to 3.1 t harvest^{-1} with three applications of N. Generally, the distribution of the rainfall largely determines the growth rates and pasture yield between different climatic zones. This reflects the similar pasture growth rate and herbage accumulation across the locations within the same climatic zone showing higher growth rates and yields in WZ than IZ and DZ.

4.3. *Seasonality and spatial variability of the pasture growth*

Pasture growth in tropical areas can experience significant variability due to a range of abiotic (e.g., climate, soil, altitude), biotic (e.g., pasture genotypic, soil microbiota) and pasture management (fertilizer, irrigation, harvesting) factors (Ara et al., 2020). The spatial and temporal variability of the monthly pasture growth observed in the present study (Figs. 4 and 5) is mainly driven by the main abiotic drivers of pasture growth like the interannual variability of the rainfall, plant available water in the soil, and possibly the solar radiation influenced by both the day length and cloud patterns. The temperature is less likely to have an impact on the temporal variability of the pasture production

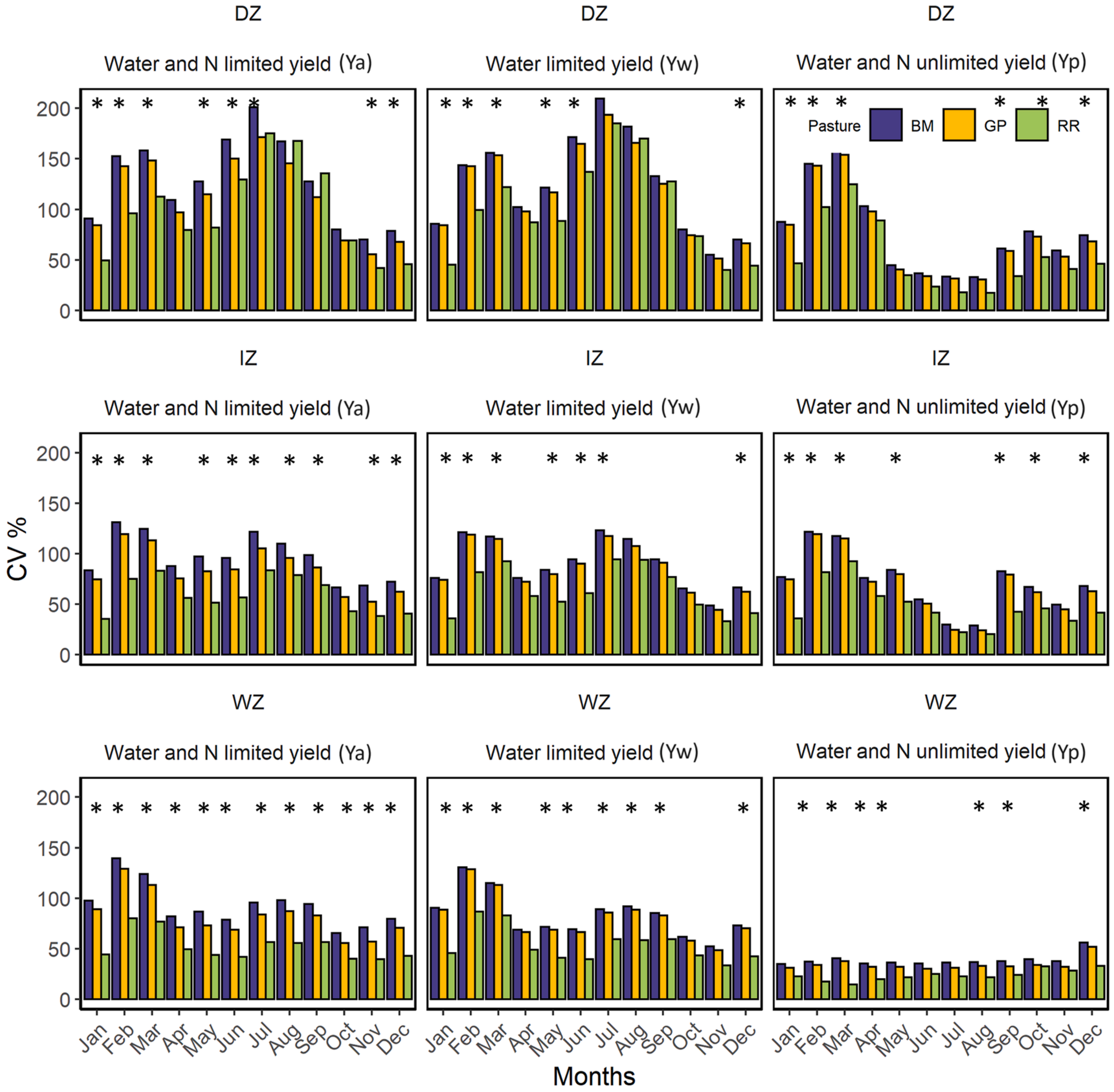

Fig. 4. Long-term interannual variability (CV %) of monthly pasture growth of *Brachiaria* Mulato II (BM), Gatton panic (GP), and Rhodes grass Reclaimer (RR) for the locations in three major climatic zones (DZ = dry zone, IZ = intermediate zone, WZ = wet zone) under different pasture management scenarios in Sri Lanka. *Statistically significant at $p < 0.05$ within each month.

(Premaratne and Premalal, 2006), given the less deviation of the daily minimum and maximum temperature of a given site due to the lack of distinct seasonal changes in Sri Lanka (Punyawardena, 2020). However, the long-term pasture production between climate zones can be considerably affected by the temperature due to the clear regional differences in altitude, the seasonal movement of the sun and some modifications influenced by rainfall (Punyawardena, 2020). Overall, the higher pasture growth rate and herbage accumulation observed in the WZ, followed by IZ and DZ in the present study reflect the characteristic combination of optimum temperature (30–35 °C) (Ivory and Whiteman, 1978) and rainfall (plant available water in the soil) for C_4 pasture growth in each climate zone. In addition, the pasture production peaks in DZ and IZ during January–April and late September–December due to increasing rainfall and soil moisture conditions, and troughs in May–early September (Fig. 3 and Fig. 4) as a result of low rainfall and soil moisture due to the inherent monsoon rainfall patterns in the area. Apart from the environmental factors, pasture species differ in their suitability to grow in different environments and it is largely determined by the morphological and physiological traits they possess (Simeao et al., 2021). These traits determine the fitness of the pasture species to grow, reproduce and survive under different environmental conditions. Overall, the RR had the least variable pasture growth rate across all scenarios and climates having increased plant productivity under drought conditions (Lowe et al., 2016), which may be attributed to its

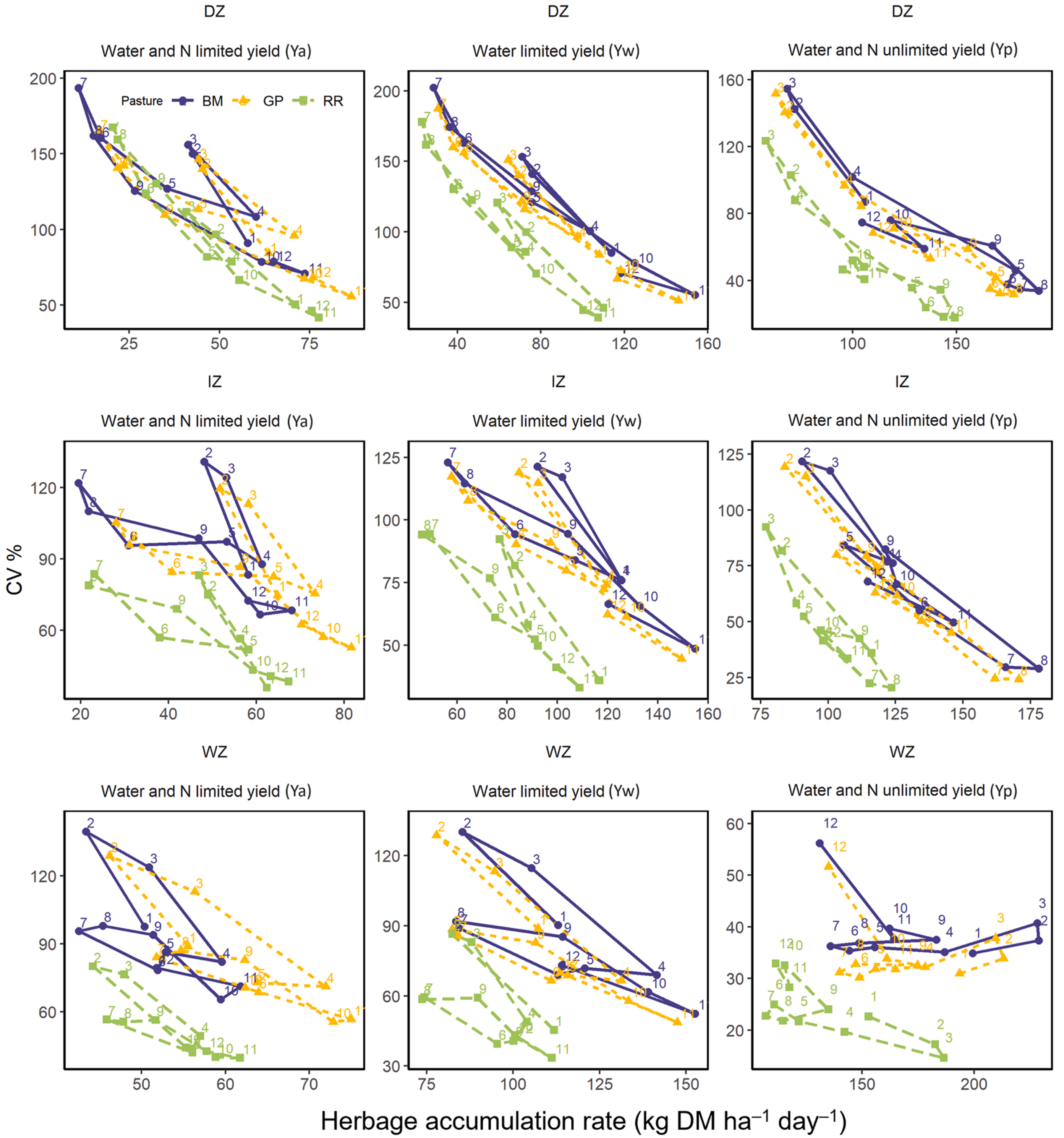

Fig. 5. Long-term monthly pasture growth rates and interannual variability (CV %) of *Brachiaria* Mulato II (BM), Gatton panic (GP), and Rhodes grass Reclaimer (RR) for the locations in three major climatic zones (DZ = dry zone, IZ = intermediate zone, WZ = wet zone) under different pasture management scenarios in Sri Lanka. The 1 to 12 numbers represent the months from January to December. Both the X and Y axes are adjusted to differentiate the plots.

deep root system (~140 cm), higher carbon partitioning to roots providing more plant available water (White and Snow, 2012) and the reduced leaf area (small leaves) which potentially reduces the transpiration. In contrast, the higher variable pasture growth observed in BM is attributed to the quick growth response of the species determined by the higher photosynthetic rate, and high leaf area index to capture the solar radiation (Jayasinghe et al., 2022a). While pasture management factors can greatly influence pasture growth and variability, the defoliation interval, N fertilizer, and irrigation can be discounted in the present study as such variables were kept constant across years and locations. However, between different scenarios, N fertilizer and irrigation largely affected the average monthly growth rate, herbage accumulation and pasture variability. This well-reflected effect of N fertilizer and irrigation in the long-term herbage results in the present study is mainly explained by the combined effect of soil, climate and species-specific responses to the N fertilizer and irrigation in the field.

4.4. Possible implications for dairying in Sri Lanka

The present study distinguishes the pasture growth and variability among species, climate zones, and different pasture management scenarios. However, to comprehend the potential consequences thoroughly, it is crucial to extend these results to the entire farm system. The productivity of pasture-based dairy systems can be influenced by the implications of pasture growth and variability, which generally depend on the balance between feed supply and demand. In addition to inadequate pasture supply, the variability of pasture growth can significantly impact its nutritive value due to the deterioration in sward structure and composition (Chapman et al., 2013). The annual forage supply is driven by the average pasture growth rate. Given the higher variability in growth rate during the drier months of the year, pastures do not produce enough biomass to meet the feed requirement of lactating cows resulting in poor milk production and reproduction. The year-round calving pattern currently observed in Sri Lanka, in particular among the low-input dairy farms, is likely to be more affected by the higher variability in pasture growth (Ibrahim et al., 1999). Therefore, supplying nutritionally balanced pastures during the peak of lactation is a considerable challenge under the current pasture management practice due to the limited supply of year-round pastures. While the superior pasture growth rate of BM and GP produced more herbage than their standard cultivars currently growing, the forage supply remains low during drier months due to a poor growth rate. However, the average accumulated annual pasture yields under the Yw and Yp management scenarios were more than double and nearly triple compared to Ya for all pastures, and BM has relatively outperformed in yields. While the pasture growth patterns remained unchanged at Ya and Yw, and Yw produced greater biomass during rainy seasons producing a surplus of feed to be used in the drier months after properly conserved (e.g., hay, silage). In addition, pasture management Yp further helped to substantially increase the pasture yield by changing the growth rate and also the growth pattern making a more consistent pasture supply during the drier months. Given the long-term average cut yield of BM, GP and RR in multiple locations tested, these pastures would be suitable to grow across the country which has similar edapho-climatic conditions. Further, the observed potential of GP producing relatively more biomass under the Ya and BM under the Yw and Yp suggests that growing GP in low-input farming areas and the BM in high-input areas would be more suitable.

Tropical pastures can grow fast during favourable weather conditions (warm and high rainfall) (Jayasinghe 2022b; Sollenberger et al., 2020). The unconstrained growth during the peaked rainfall can produce taller pasture swards structured with more stems (low leaf: stem) and accumulated dead materials (due to light competition) (Da Silva et al., 2015), resulting in poor-quality herbage (Pembleton et al., 2009). This could be further deteriorated by the sward structure determined by the pasture morphology (Lemaire et al., 2009; Simeao et al., 2021). In particular, GP at a higher growth rate produces more stem (higher ratio of carbon partitioning to stem) than BM and RR resulting in a higher trade-off between quantity and quality (Jayasinghe et al., 2022a). The present simulation used the monthly defoliation frequency (pasture harvested on the last date of each month), however, the accumulated high pasture yield indicates that the frequent defoliation of pastures (subjected to the potential herd size) during rainy months (January–April and September–December) would be more appropriate in practice to avoid excessive forage accumulation and maintain the herbage quality, particular in the IZ and WZ under the Yw and Yp scenarios. Further, the reduced pasture growth during the drier and hotter months can limit the uptake of soil-available nutrients and also induce physiological (e.g., stem lignification, reduced leaf area) and phenological changes in plants (e.g., delay or hastened anthesis) leading to accumulation of poor quality herbage (Jégo et al., 2013). These quality changes are likely to be more evident in the pastures growing in either DZ or IZ under existing pasture management (Ya).

The simulated growth rate and herbage accumulation in the modelling studies are often higher than the typically measured pasture biomass under field conditions (White and Snow, 2012). This is primarily due to the model not being able to incorporate the possible effects of the pest, weed and disease pressure. In addition, all resources required to achieve high pasture growth are rarely simultaneously available at the same time, however, exploring the resources that can be controlled (e.g., N fertilizer, irrigation) provides important insights into the possible intensification of pastures for improving dairy farming in Sri Lanka. It is a fact that high-input pasture production systems can generally incur a significant cost of production apart from the possible harm to the environment, therefore, the economic and environmental viability of the Yw and Yp pasture production scenarios need to be investigated further. The present study highlights the potential use of DairyMod for the long-term simulation of tropical pastures, enabling the characterization of pasture growth and variability under different management scenarios. The practical outcomes of this analysis provide confidence in the prospective use of this information for supporting pasture species selection, identifying responses to different pasture management practices, and making informed feed budgeting and feeding decisions.

5. Conclusions

The present simulation study demonstrated that the DairyMod pasture model can successfully simulate long-term tropical pasture production. In addition, the model successfully captured the species-specific physiological adaptation and yield potential during the pasture growth simulation. The rainfall, climate zone, pasture species and management were the key drivers for the annual average herbage accumulation and variability of the pasture growth over the locations evaluated. The growth rates were high in GP under Ya, while the growth rate of BM was superior under both Yw and Yp and RR recorded the lowest growth rate throughout. The improved pastures tested in the present study produced considerably higher biomass than the standard cultivars available under the existing pasture management. Pasture accumulation under non-limiting nutrients (Yw) increased the growth rate while the non-limiting nutrients and water (Yp) scenario substantially increased the growth rate, in particular nearly doubled and tripled under Yw and Yp, respectively and also improved the pasture growth pattern producing more consistent pasture biomass throughout the year. Overall, the results of the present simulation study suggested that the improved pastures tested are edapho-climatologically fit for growing across major dairying regions in Sri Lanka, however, when selecting the appropriate species, the species-specific growth pattern, growth variability, and yield potential under different managements and the possible implications for herbage quality need to be carefully considered.

CRediT authorship contribution statement

Thiagarajah Ramilan: Supervision, Writing – review & editing. **David G. Barber:** Supervision, Writing – review & editing. **Keith G. Pembleton:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Daniel J. Donaghy:** Conceptualization, Supervision, Writing – review & editing. **J.M.P. Jayasinghe:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Authors greatly acknowledged Ranjith Mapa, an Emeritus Professor in Soil Science at the University of Peradeniya, Sri Lanka for generously providing the soil profile data used in the DairyMod simulations. In addition, the first author was supported by the Accelerating Higher Education Expansion and Development (AHEAD) Project launched by the Sri Lankan Government under the funds of the World Bank providing a PhD scholarship.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127103.

References

Ahmed, Z., Gui, D., Qi, Z., Liu, Y., Liu, Y., Azmat, M., 2022. Agricultural system modeling: current achievements, innovations, and future roadmap. Arab. J. Geosci. 15, 363 https://doi.org/10.1007/s12517-022-09654-7.

Andrade, A.S., Santos, P.M., Pezzopane, J.R.M., de Araujo, L.C., Pedreira, B.C., Pedreira, C.G.S., Marin, F.R., Lara, M.A.S., 2016. Simulating tropical forage growth and biomass accumulation: an overview of model development and application. Grass Forage Sci. 71, 54–65. https://doi.org/10.1111/gfs.12177.

Ara, I., Harrison, M.T., Whitehead, J., Waldner, F., Bridle, K., Gilfedder, L., Marques da Silva, J., Marques, F., Rawnsley, R., 2020. Modelling seasonal pasture growth and botanical composition at the paddock scale with satellite imagery. In Silico Plants. https://doi.org/10.1093/insilicoplants/diaa013.

Argel, M., Pedro, J., Miles, J.W., Guiot García, J.D., Cuadrado Capella, H., Lascano, C.E., 2007. Cultivar mulato II (Brachiaria híbrido CIAT 36087): Gramínea de alta qualidade e produçao forrageira, resistentes as cigarrinhas e adaptada a solos tropicais ácidos. CIAT.

Berger, H., Machado, C.F., Agnusdei, M., Cullen, B.R., 2014. Use of a biophysical simulation model (Dairy Mod) to represent tall fescue pasture growth in Argentina. Grass Forage Sci. 69, 441–453. https://doi.org/10.1111/gfs.12064.

Bosi, C., Sentelhas, P.C., Huth, N.I., Pezzopane, J.R.M., Andreucci, M.P., Santos, P.M., 2020. APSIM-Tropical Pasture: A model for simulating perennial tropical grass growth and its parameterisation for palisade grass (*Brachiaria brizantha*). Agric. Syst. 184, 102917 https://doi.org/10.1016/j.agsy.2020.102917.

CABI, 2022. Invasive Species Compendium. CAB International. www.cabi.org/isc., Wallingford, UK.

Chapman, D.F., Kenny, S.N., Beca, D., Johnson, I.R., 2008a. Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. Agric. Syst. 97, 108–125. https://doi.org/10.1016/j.agsy.2008.02.001.

Chapman, D.F., Kenny, S.N., Beca, D., Johnson, I.R., 2008b. Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 2. Inter-annual variation in forage supply, and business risk. Agric. Syst. 97, 126–138. https://doi.org/10.1016/j.agsy.2008.02.002.

Chapman, D.F., Cullen, B.R., Johnson, I.R., Beca, D., 2009. Interannual variation in pasture growth rate in Australian and New Zealand dairy regions and its consequences for system management. Anim. Prod. Sci. 49, 1071–1079. https://doi.org/10.1071/AN09054.

Chapman, D.F., Rawnsley, R.P., Cullen, B.R., Clark, D.A., 2013. Inter-annual variability in pasture herbage accumulation in temperate dairy regions: causes, consequences, and management tools, 22nd International Grassland Congress. Syd.: N. South Wales Dep. Prim. Ind. 798–805.

Christie, K.M., Smith, A.P., Rawnsley, R.P., Harrison, M.T., Eckard, R.J., 2018. Simulated seasonal responses of grazed dairy pastures to nitrogen fertilizer in SE Australia: Pasture production. Agric. Syst. 166, 36–47. https://doi.org/10.1016/j.agsy.2018.07.010.

Da Silva, S.C., Sbrissia, A.F., Pereira, L.E.T., 2015. Ecophysiology of C4 forage grasses—understanding plant growth for optimising their use and management. Agriculture 5, 598–625. https://doi.org/10.3390/agriculture5030598.

MOD (Market Orientated Dairy), 2018. Market-oriented dairy assessment report of Sri Lanka's dairy sector, University of Florida-Dairy Sector Assessment. Proj., Colombo, Sri Lanka https://www.market-oriented-dairy.org/dairy-management (accessed 23 March 2022).

Dassanayake, A.R., Somasiri, L.L.W., Mapa, R.B., 2020. Major Soils of the Intermediate Soils and Their Classification. In: Mapa, R.B. (Ed.), The Soils of Sri Lanka. Springer International Publishing, Cham, pp. 69–82.

dos Santos, M.L., Santos, P.M., Boote, K.J., Pequeno, D.N.L., Barioni, L.G., Cuadra, S.V., Hoogenboom, G., 2022. Applying the CROPGRO Perennial Forage Model for long-term estimates of Marandu palisadegrass production in livestock management scenarios in Brazil. Field Crops Res 286, 108629. https://doi.org/10.1016/j.fcr.2022.108629.

ESRI, 2021. ArcGIS Pro 2.8.6; Environmental Systems Research Institute: ESRI Redlands. CA, USA.

Gunarathna, M.H.J.P., Kazuhito, S., Tamotsu, N., Kazuro, M., Kumaria, M.K.N., 2019. Sensitivity analysis of plant- and cultivar-specific parameters of APSIM-Sugar Model: Variation between climates and management conditions. Agronomy 10 242. https://doi.org/10.3390/agronomy9050242.

Gunarathna, M.H.J.P., Sakai, K., Kumari, M.K.N., Ranagalage, M., 2020. A functional analysis of pedotransfer functions developed for Sri Lankan soils: Applicability for process-based crop models. Agronomy 10, 285. https://doi.org/10.3390/agronomy10020285.

Houwers, W., Wouters, B. and Vernooij, A., 2015. Sri Lanka fodder study; An overview of potential, bottlenecks and improvements to meet the rising demand for quality fodder in Sri Lanka. Wageningen UR Livestock Research, Lelystad. https://research.wur.nl/en/publications/sri-lanka-fodder-study-an-overview-of-potential-bottlenecks-and-i (accessed 15 January 2022).

Ibrahim, M., Staal, S., Daniel, S., Thorpe, W., 1999. Appraisal of the Sri Lanka dairy sector. Synthesis report. Department of Animal Science, University of Peradeniya.

Ivory, D., Whiteman, P., 1978. Effect of temperature on growth of five subtropical grasses. I. Effect of day and night temperature on growth and morphological development. Funct. Plant Biol. 5, 131–148. https://doi.org/10.1071/PP9780131.

Jayasinghe, J., Donaghy, D.J., Pembleton, K., Barber, D.G., Ramilan, T., 2021. Preliminary results of parameterisation of DairyMod pasture model for tropical pasture; Brachiaria, In: Proceedings of the 24th International Congress on Modelling and Simulation MODSIM2021. Sydney, Australia. 99–105.

Jayasinghe, J.M.P., 2023. Investigation of Tropical Pasture Spcies to Improve Dairying in the Tropics. Ph.D. Thesis. Massey University, New Zealand. Available at: https://mro.massey.ac.nz/items/dd0e2ee3-4924-4b3f-98bf-d46f8d4a6947.

Jayasinghe, P., Donaghy, D.J., Barber, D.G., Pembleton, K.G., Ramilan, T., 2022a. Suitability evaluation of three tropical pasture species (Mulato II, Gatton Panic, and Rhodes Grass) for cultivation under a subtropical climate of Australia. Agronomy 12, 2032. https://doi.org/10.3390/agronomy12092032.

Jayasinghe, J.M.P., Pembleton, K.G., Barber, D.G., Donaghy, D.J., Ramilan, T., 2024. Modelling of tropical pasture growth using DairyMod: Model parameterisation and validation across multiple environments. European Journal of Agronomy 156, 127146. https://doi.org/10.1016/j.eja.2024.127146.

Jayasinghe, P., Ramilan, T., Donaghy, D.J., Pembleton, K.G., Barber, D.G., 2022b. Comparison of nutritive values of tropical pasture species grown in different environments, and implications for livestock methane production: A meta-analysis. Animals 12, 1806. https://doi.org/10.3390/ani12141806.

Jégo, G., Bélanger, G., Tremblay, G.F., Jing, Q., Baron, V.S., 2013. Calibration and performance evaluation of the STICS crop model for simulating timothy growth and nutritive value. Field Crops Res 151, 65–77. https://doi.org/10.1016/j.fcr.2013.07.003.

Johnson, I., 2008. Biophysical pasture model documentation: model documentation for DairyMod. EcoMod and the SGS Pasture Model. IMJ Consultants: Armidale, NSW) Available at www. imj. com. au/gmdocs [Verified 14 March 2008].

Johnson, I., Chapman, D., Snow, V., Eckard, R., Parsons, A., Lambert, M., Cullen, B., 2008. DairyMod and EcoMod: biophysical pasture-simulation models for Australia and New Zealand. Aust. J. Exp. Agric. 48, 621–631. https://doi.org/10.1071/EA07133.

Korale-Gedara, P., Weerahewa, J., Roy, D., 2023. Food safety in milk: Adoption of food safety practices by small-scale dairy farmers in Sri Lanka and their determinants. Food Control 143, 109274. https://doi.org/10.1016/j.foodcont.2022.109274.

Korale-Gedara, P.K., 2019. Analyzing opportunities for commercial fodder cultivation in Sri Lanka. Market Orientated Dairy (MOD) Project, Colombo, Sri Lanka. https://www.market-oriented-dairy.org/fodder-cultivation (Accessed 23 March 2022).

Kumara, S.N., Parkinson, T.J., Laven, R.A., Waghorn, G.C., Pushpakumara, A., Donaghy, D.J., 2022. A nutritional investigation of major feed types and feed rations used in medium-scale dairy production systems in Sri Lanka. Animals 12, 2391. https://doi.org/10.3390/ani12182391.

Kumari, K., Jayawardana, J., Jayasinghe, J., 2019. Identifications of the major factors that influence milk production: The case of dairy farmers in Badulla district, Sri Lanka. Int. J. Livest. Prod. 10, 182–187. https://doi.org/10.5897/IJLP2018.0566.

Lemaire, G., Da Silva, S.C., Agnusdei, M., Wade, M., Hodgson, J., 2009. Interactions between leaf lifespan and defoliation frequency in temperate and tropical pastures: a review. Grass Forage Sci. 64, 341–353.

Liyanage, L.,1989 Pasture and fodder production in Sri lanka-present staus and future trends. In: Pasture research in Southeast Asia: Current status, problems and resources available: A consultation meeting, Los Baños, Laguna, Philippines, 11–12. Centro Internacional de Agricultura Tropical (CIAT), Cali.

Lowe, K.F., Hume, D.E., Fulkerson, W.J., 2016. Perennial Forage and Pasture Crops-species and Varieties, Reference Module in Food Science. Elsevier,. https://doi.org/10.1016/B978-0-08-100596-5.00789-7.

Mapa, R.B., Somasiri, S., Nagarajah, S., 1999. Soils of the wet zone of Sri Lanka: morphology, characterization and classification. Soil Sci. Soc. Sri Lanka.

Mapa, R.B., Dassanayake, A., Nayakekorale, H., 2005. Soils of the intermediate zone of Sri Lanka: morphology, characterization and classification. Soil Sci. Soc. Sri Lanka.

Mapa, R.B., Somasiri, S., Dassanayake, A., 2010. Soils of dry zone of Sri Lanka: morphology, charecterization, and classification. Soil Sci. Soc. Sri Lanka.

Moormann, F.R., Panabokke, C.R., 1961. Soils of Ceylon: a new approach to the identification and classification of the most important soil groups of ceylon. Natl. Mus. Sri Lanka Publ.

Nisansala, W.D.S., Abeysingha, N.S., Islam, A., Bandara, A.M.K.R., 2020. Recent rainfall trend over Sri Lanka (1987–2017). Int. J. Climatol. 40, 3417–3435. https://doi.org/10.1002/joc.6405.

Opio, C., Clark, H., Gerber, P., Steinfeld, H., 2017. Options for Low-emission Development in the Sri Lanka Dairy Sector: Reducing Enteric Methane for Food Security and Livelihoods. FAO, Rome.

Paul, B.K., Koge, J., Maass, B.L., Notenbaert, A., Peters, M., Groot, J.C.J., Tittonell, P., 2020. Tropical forage technologies can deliver multiple benefits in Sub-Saharan Africa. A meta-analysis. Agron. Sustain. Dev. 40, 22 https://doi.org/10.1007/s13593-020-00626-3.

Pedreira, B.C., Pedreira, C.G.S., Boote, K.J., Lara, M.A.S., Alderman, P.D., 2011. Adapting the CROPGRO perennial forage model to predict growth of *Brachiaria brizantha*. Field Crop. Res. 120, 370–379. https://doi.org/10.1016/j.fcr.2010.11.010.

Pembleton, K.G., Lowe, K.F., Bahnisch, L.M., 2009. Utilising leaf number as an indicator for defoliation to restrict stem growth in rhodes grass (*Chloris gayana*) cv. Callide. Trop. Grassl. - Forrajes Trop. 43, 79–85.

Pequeno, D.N.L., Pedreira, C.G.S., Boote, K.J., 2014. Simulating forage production of Marandu palisade grass (*Brachiaria brizantha*) with the CROPGRO-Perennial Forage model. Crop Pasture Sci. 65, 1335–1348. https://doi.org/10.1071/CP14058.

Perera, R.S., Cullen, B.R., Eckard, R.J., 2020. Changing patterns of pasture production in south-eastern Australia from 1960 to 2015. Crop Pasture Sci. 71, 70–81. https://doi.org/10.1071/CP19112.

Premarathne, S., Samarasinghe, K., 2020. Animal feed production in Sri Lanka: past present and future. In: Marambe, B., Weerahewa, J., Dandeniya, W.S. (Eds.), Agricultural Research for Sustainable Food Systems in Sri Lanka, Volume 1. A historical perspective. Springer Singapore, Singapore, pp. 277–301.

Premaratne, S., Premalal, G.G.C., 2006. Country Pasture/forage Resource Profiles in Sri Lanka. FAO, Rome.

Prowurst, B., 2019. Technical assistance to the modernization of agricultural programme in Sri Lanka (TAMAP). Value chain Anal. Study Dairy Sri Lanka. Netherland.

Punyawardena, B.V.R., 2020. Climate. In: Mapa, R.B. (Ed.), The Soils of Sri Lanka. Springer International Publishing, Cham, pp. 13–22.

Quigley, M.C., Bennetts, L.G., Durance, P., Kuhnert, P.M., Lindsay, M.D., Pembleton, K. G., Roberts, M.E., White, C.J., 2019. The provision and utility of science and uncertainty to decision-makers: earth science case studies. Environ. Syst. Decis. 39, 307–348. https://doi.org/10.1007/s10669-019-09728-0.

Rao, I.M., Peters, M., Castro, A., Schultze-Kraft, R., White, D., Fisher, M., Miles, J.W., Lascano, C.E., Blummel, M., Bungenstab, D., 2015. LivestockPlus: The Sustainable Intensification of Forage-based Agricultural Systems to Improve Livelihoods and Ecosystem Services in the Tropics. CIAT Publication. https://doi.org/10.17138/tgft(3)59-82.

RCoreTeam, 2021. R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria.

Ruane, A.C., Goldberg, R., Chryssanthacopoulos, J., 2015. Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agric. For. Meteorol. 200, 233–248. https://doi.org/10.1016/j.agrformet.2014.09.016.

Senanayake, S., Pemadasa, M., 1991. A study of the genetic variability of *Brachiaria brizantha* (Hochst ex. A. Rich) stapf. Rohana 3, 149–153.

Silva, J.V., Giller, K.E., 2021. Grand challenges for the 21st century: what crop models can and can't (yet) do. J. Agric. Sci. 1–12. https://doi.org/10.1017/S0021859621000150.

Simeao, R.M., Resende, M.D.V., Alves, R.S., Pessoa-Filho, M., Azevedo, A.L.S., Jones, C. S., Pereira, J.F., Machado, J.C., 2021. Genomic selection in tropical forage grasses: Current status and future applications. Front. Plant Sci. 12 https://doi.org/10.3389/fpls.2021.665195.

Sollenberger, L.E., Vendramini, J.M.B., Pedreira, C.G.S., Rios, E.F., 2020. Warm-season grasses for humid areas. Forages 331–345.

Svinurai, W., Hassen, A., Tesfamariam, E., Ramoelo, A., Cullen, B., 2021. Calibration and evaluation of the Sustainable Grazing Systems pasture model for predicting native grass aboveground biomass production in southern Africa. Afr. J. Range Forage Sci. 38, S28–S40. https://doi.org/10.2989/10220119.2021.1875501.

Tubiello, F.N., Soussana, J.-F., Howden, S.M., 2007. Crop and pasture response to climate change. Proc. Natl. Acad. Sci. 104, 19686–19690. https://doi.org/10.1073/pnas.0701728104.

Vyas, D., Nelson, C.D., Bromfield, J.J., Liyanamana, P., Krause, M., Dahl, G.E., 2020. Milk Symposium review: Identifying constraints, opportunities, and best practices for improving milk production in market-oriented dairy farms in Sri Lanka. J. Dairy Sci. 103, 9774–9790. https://doi.org/10.3168/jds.2020-18305.

Wayne, T., Omphile, S., Malissa, M., Melake, F., Caren, J., Mpendulo, D., E, C., 2016. Water use and crop parameters of pastures for livestock grazing management. Water Res. Comm., South Afr.

White, T.A., Snow, V.O., 2012. A modelling analysis to identify plant traits for enhanced water-use efficiency of pasture. Crop Pasture Sci. 63, 63–76. https://doi.org/10.1071/CP11250.

Wimalasiri, E.M., Jahanshiri, E., Suhairi, T.A.S.T.M., Udayangani, H., Mapa, R.B., Karunaratne, A.S., Vidhanarachchi, L.P., Azam-Ali, S.N., 2020. Basic soil data requirements for process-based crop models as a basis for crop diversification. Sustainability 12, 7781. https://doi.org/10.3390/su12187781.