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What agronomic and environmental factors drive coffee yield in Burundi? A country-wide study.

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ABSTRACT

Arabica coffee accounts for 70 % of Burundi's trade income. However, production has been steadily declining. The objective of this study was therefore to identify the agronomic and environmental factors driving coffee yield on smallholder farms across Burundi. For this purpose, a diagnostic survey was conducted on 155 coffee plantations across three key agroecological zones: Mumirwa, the Humid Central Plateau, and the Dry Central Plateau. Data collection included plot and management characteristics, soil fertility variables, and yield. Yield surveys were conducted over two successive years to account for production cyclicity. Principal component analysis, random forest and boundary line analysis were used for data analysis. Average yields of washed merchant coffee were 887 kg ha^{-1} for Mumirwa, 1115 kg ha^{-1} for the Humid Central Plateau, and 1268 kg ha^{-1} for the Dry Central Plateau, with maximum yields reaching 1891, 2533, and 2262 kg ha^{-1}, respectively. Based on the random forest analysis, soil organic carbon, mulch thickness and soil magnesium content were the most important variables for explaining yield. On average, Burundi's coffee plantations experience a 59 % yield deficit. The most yield-limiting factors included inadequate weeding and mulching, aging plantations, soil acidity, as well as phosphorus, exchangeable bases and soil organic carbon content. These factors varied across regions. Renewal of plantations, better management practices, and addressing specific soil fertility issues are key to improve yields, for which the study proposes revised norms. The study also highlighted the importance of considering coffee yield cyclicity to avoid misidentifying yield-limiting factors.

1. Introduction

Coffee is one of the world's most traded commodities. It is grown in more than 70 countries around the world and contributes significantly to the livelihoods of millions of smallholder farmer (Pham et al., 2019). Indeed, around 25 million smallholder farmers produce 80 % of the world's coffee (Wolde, 2018). Although Africa accounts for only 11 % of the global output (ICO, 2021), it is home to the largest number of coffee-producing countries for which this commodity is generally of significant economic importance, as is the case for Burundi.

Introduced in Burundi in the early 1920's (Hatungimana, 2008), coffee is currently grown throughout much of the country. Approximately 122 million coffee trees, mostly Arabica, occupy 10 % of the cultivated land (ISTEEBU, 2010). Coffee is mostly grown by smallholder farmers whose plantations generally range in size from 0.12 to 0.5 ha (GCP, 2016). Approximately 30 % of all Burundian households are involved in coffee farming (ISTEEBU, 2019). Beyond its economic significance for Burundian households, coffee production plays a vital role in the country's foreign trade balance, serving as Burundi's primary export product (BRB, 2020). However, coffee production in Burundi has declined substantially in the last decades, with severe impacts for both the national economy and the income of the smallholder coffee producers (Lenaghan et al., 2018). Recognizing the strategic importance of coffee, the Burundian government seeks to revitalize the coffee sector. Although expanding the area under coffee cultivation might seem like a potential solution, this approach is not realistic in view of the high population pressure and the already limited average farm sizes. Instead, increasing yields therefore seems a more viable pathway.

Lenaghan et al. (2018) have shown that Burundi's coffee yield lags far behind that of other coffee producing countries in East Africa. These

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authors also argued that the difference in coffee yield across countries in the region is not related to differences in agroecological conditions, such as elevation and rainfall. Indeed, coffee-producing areas of Burundi are very similar to those of its highland African neighbours in this respect. Research in Uganda, Ethiopia and Rwanda has shown that coffee yield gaps, i.e., the difference between the yield obtained by farmers and the achievable potential coffee yield, are caused by low soil fertility, insufficient rainfall, poor cultivation practices, erosion, insufficient mulching as well as lack of organic and inorganic fertilizers (Nzeyimana et al., 2013; Melke and Ittana, 2014). Identifying these yield-limiting factors helps understand the causes of yield gaps and it may therefore help optimize production factors (Espe et al., 2016; Nehbandani et al., 2021).

Low soil fertility is of particular concern in Burundi and has been identified previously as a significant constraint to coffee cherry yield in the different coffee-growing areas (Bitoga et al., 1994). In the medium to high altitude areas of Burundi, which are favored for Arabica coffee production, approximately 1 million hectares are acidic (pH < 5) with a risk of Al toxicity and deficiencies in major macronutrients (P, Ca, Mg, K) and micronutrients (Cu, Zn) (Kaboneka, 2015). While some of these limitations stem from the inherent nature of the strongly-weathered soils in these regions, nutrient depletion and soil erosion by water have also played a significant role. According to Keringingo and Kayakayacı (2023), an average of 100 tons of soil are lost annually per hectare on the hillsides of the Mumirwa region. Other factors affecting coffee yield are low rainfall, the length of the dry season, steep slopes and coffee planting density. For example, while rainfall has been found to be optimal in Mumirwa, steep slopes limit yield (Bitoga et al., 1994). However, the political and social crisis that gripped the country from 1993 onwards prevented further research and the valorization of these results. Later, the ageing of plantations and the lack of technical support for producers to ensure proper management practices have been cited as additional causes of the decline in Burundian coffee production (Kimonyo and Ntiranyibagira, 2007).

The country's favorable coffee-growing climate, the premium Bourbon varieties and the significant involvement of households in coffee production are key assets that can drive the development of this crop to support both the national economy and household livelihoods. However, since the study of Bitoga et al. (1994), no in-depth study has been conducted to update the main constraints limiting coffee yields in Burundi. The objective of the present study was therefore to update the previous diagnosis and identify the environmental factors and cropping practices that are limiting coffee yield. For this purpose, a diagnostic survey approach was used. Such an approach has been successfully implemented in various countries to identify the constraints limiting banana yield in the Great Lakes region of central Africa (Bizimana, 2018; Delstanche, 2011) or coffee yield in Uganda (Wang et al., 2015).

2. Materials and methods

2.1. Study area

Burundi is located between latitudes 2°45' and 4°26' south and longitudes 28°50' and 30°53' east. The survey was carried out in three agroecological zones - Mumirwa, Humid Central Plateau and Dry Central Plateau - encompassing the entire coffee-growing area of Burundi (Fig. 1). These agroecological zones are defined mainly on the basis of topography, geology, climate, flora and fauna (Everaerts, 1947).

Altitude ranges from 1100 m to 2000 m (Nzigidahera, 2012). The dominant soils in the three zones are ferralsols, acrisols and nitisols (WRB, 2015). Rainfall is highest in Mumirwa (1692 mm yr^{-1}) and

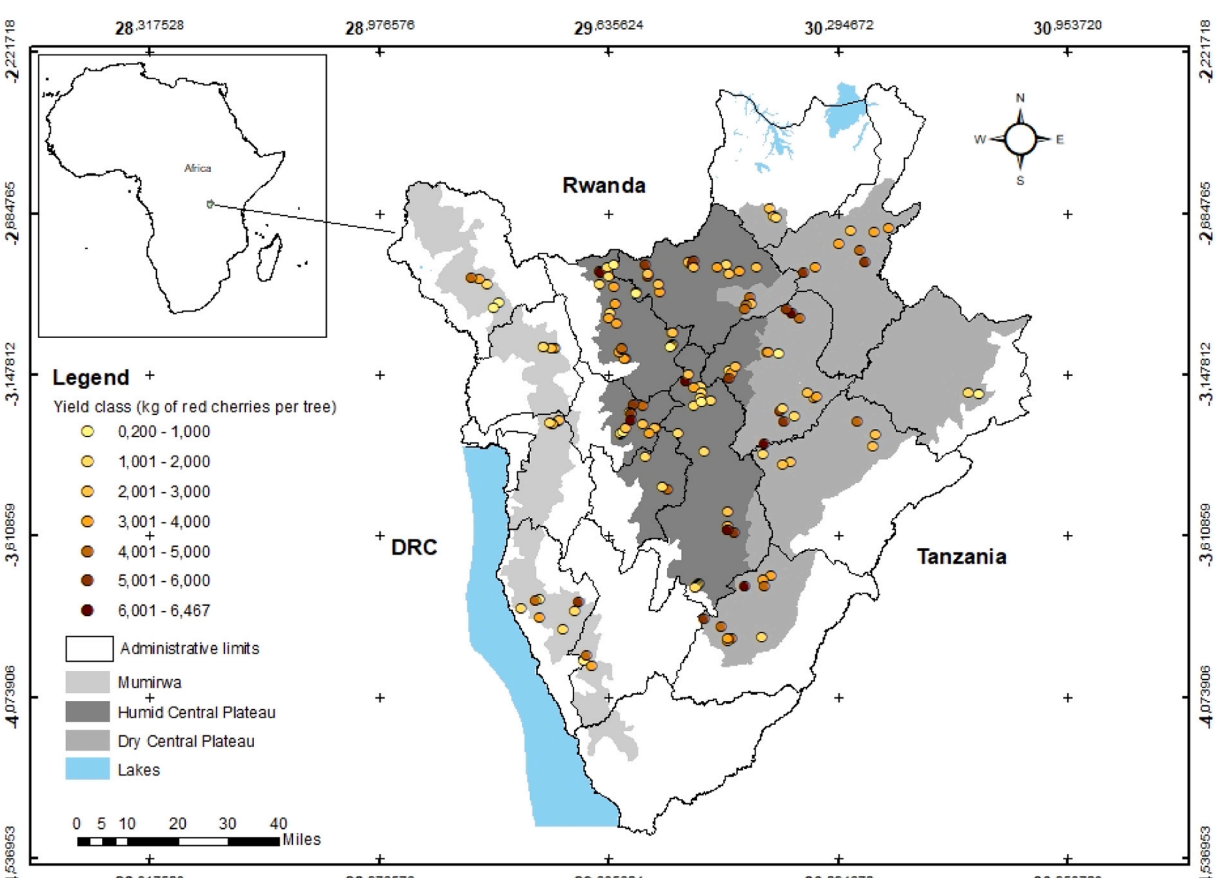

Fig. 1. Location of sampled coffee plots in the three coffee-growing agroecological zones of Burundi. The colour of each dot reflects the measured red cherry yield per tree, averaged over 2018 and 2019.

lowest in the Dry Central Plateau (1512 mm yr^{-1}; Table 1). The same seasonal rainfall and temperature trends are observed in the three agroecological zones, but the Humid Central Plateau has a lower temperature on average than the other two agroecological zones (Fig. S1 in supplementary material and Table 1).

2.2. Data collection

A diagnostic survey was carried out on 155 coffee plots in 2018 and 2019 (Fig. 1). The plots were chosen to cover the whole study area, considering their accessibility and a minimum distance of 2 km in-between two farms. Plot were selected at four levels: i) agroecological zone level, ii) province level (all provinces of each agroecological zone were covered), iii) commune (= municipality) level and iv) colline (= hill) level. A colline is an official administrative subunit of a commune. The communes and collines were selected beforehand by choosing those with a high number of coffee trees according to the most recent (2009) coffee tree survey. On each colline, coffee growers were chosen randomly but respecting a minimum distance of 2 km in-between farms. Both shaded and full sun plantations were included. As coffee production in smallholder systems presents a strong biennial cyclicity, the yield survey was carried out for two successive production years on each farm (2018 and 2019). Yield cyclicity is a widespread feature in perennial crops, also referred to as alternate bearing (Krasniqi et al., 2017; Bernardes et al., 2012).

Data were collected in two stages. First, individual interviews were carried out with the coffee growers, which allowed to collect data relating to the year of planting, the number of weeding operations per year as well as organic and mineral fertilization practices. Subsequently, data were collected in the plots. Data related to shading was not collected because several species are used for shading with very different canopies, making it difficult to obtain reliable data on shading. In each plot, ten coffee trees were selected on the diagonal of the plot, avoiding trees at the plot edges. These 10 trees were marked with paint in 2018 so that they could be identified again the following year. Plant density and mulch thickness were recorded. Data on yield components were collected in April 2018 and 2019, a period that corresponds to the peak of coffee production in Burundi (Gaie and Flémal, 1988). Average cherry yield per tree was estimated following the method developed by Cilas (1993) and also used by Nibasumba (2013) (Eq.1).

$$ACY = ANFB * ANC/FB * CW \quad (1)$$

where:

– ACY = Average cherry yield per tree [kg]
– ANFB = average number of fruiting branches per tree
– ANC/FB = average number of cherries per fruiting branch
– CW = average weight of a coffee cherry, based on 100 cherries [kg]

Measured plant density was used to convert average cherry yield per tree to cherry yield per hectare. A conversion factor of 6.29 was used to convert cherry coffee yield to washed merchant coffee yield (Sualeh and Dawid, 2014).

Soil samples were taken from each plot to a depth of 30 cm using an auger at nine different points selected in a zigzag pattern (Okalebo et al., 2002). Soil sampling was carried out in November 2017, corresponding to the start of fruiting of the coffee trees for the 2018 production year. The 9 sub-samples were mixed, and a composite sample of one kilogram per plot was dried, crushed and sieved to 2 mm. pH_H_2O and pH_KCl were measured using a pH meter, pH_H_2 O in a 1:5 suspension of distilled water and soil, and pH_KCl in 1 N potassium chloride solution. Exchangeable bases were extracted with ammonium acetate and determined by atomic absorption spectrometry. Exchangeable protons and aluminum were extracted with potassium chloride solution and assayed by titration. Cation exchange capacity was determined using

Table 1
Soil and coffee plantation characteristics (min., max., mean ± standard deviation (SD)) in the 3 surveyed agroecological zones. For a given variable, means followed by the same lower-case letter are not significantly different at P < 0.05.

	Mumirwa (n = 25)		Humid Central Plateau (n = 83)		Dry Central Plateau (n = 47)		P-value
	min-max	**mean ± SD**	**min-max**	**mean ± SD**	**min-max**	**mean ± SD**	
pH_H_2O	3.97–6.06	4.87 ± 0.61b	4.30–6.86	5.48 ± 0.61a	4.48–6.80	5.54 ± 0.64a	< 0.0001***
pH_KCl	3.40–5.4	4.07 ± 0.1b	3.50–5.9	4.53 ± 0.06a	3.70–6.1	4.63 ± 0.08a	0.0005***
Al^{+3} ($cmol_c$ kg^{-1})	0–4.69	1.30 ± 1.50a	0–3.84	0.30 ± 0.80b	0–2.25	0.30 ± 0.60b	0.0001***
H^+ ($cmol_c$ kg^{-1})	0–1.21	0.37 ± 0.2a	0.05–0.99	0.23 ± 0.2b	0.03–0.81	0.22 ± 0.2b	0.0149*
Total N (%)	0.08–0.52	0.20 ± 0.09	0.10–0.5	0.20 ± 0.07	0.08–0.68	0.24 ± 0.13	0.0744
Organic carbon (%)	0.93–5.6	2.2 ± 1.1b	0.70–5.57	2.3 ± 0.9b	0.94–7.26	2.7 ± 1.4a	0.0336*
C/N (-)	7.8–16.46	11.0 ± 2	3.5–19.72	11.3 ± 2	7.46–19.5	11.6 ± 2	0.5772
P* (mg kg^{-1})	1.4–19.7	7.0 ± 4.7	1.1–23.1	5.7 ± 4.6	1.9–20.5	6.4 ± 4.6	0.3670
CEC ($cmol_c$ kg^{-1})	5.4–30.7	12.2 ± 5.6	5.3–30.9	14.4 ± 5.2	5.6–42.8	16 ± 7.9	0.0517
Exch. K ($cmol_c$ kg^{-1})	0.04–1.18	0.6 ± 0.32b	0.04–3.42	1.04 ± 0.71a	0.06–5.33	1.22 ± 1.05a	0.0084 **
Exch. Ca ($cmol_c$ kg^{-1})	0.05–9.38	2.66 ± 2.39b	0.31–14.98	5.22 ± 3.71a	0.15–15.92	3.89 ± 3.64b	0.0037**
Exch. Mg ($cmol_c$ kg^{-1})	0.08–3.08	1.07 ± 0.95b	0.02–6.44	1.93 ± 1.37a	0.16–8.05	2.43 ± 1.78a	0.0011**
Mg/K (-)	0.22–7.42	1.96 ± 2.05	0.21–8.5	2.19 ± 1.4	0.38–7.9	2.60 ± 1.83	0.2410
Ca/Mg (-)	0.11–8	3.29 ±2a	0.42–3.8	3.08 ± 2.08a	0.2–7	1.96 ± 1.39b	0.0022**
(Ca+Mg)/K (-)	1.10–20.93	6.69 ± 4.83	0.94–51.33	9 ± 8.72	0.85–25.16	7.45 ± 5.74	0.2960
Manganese* (mg kg^{-1})	3–246	64.2 ± 65.4	3–206	49.2 ± 44	3–303	58.8 ± 74.93	0.4575
Zinc* (mg kg^{-1})	0.06–7.4	1.8 ± 2.5	0.2–4.21	1.3 ± 1.6	0.2–7.9	0.8 ± 1.5	0.6459
Cupper* (mg kg^{-1})	0.58–6.93	2.15 ± 1.4	0.91–10.4	2.9 ± 1.8	0.8–4.9	2.8 ± 2	0.1623
Iron* (mg kg^{-1})	108–327	182 ±64a	47–249	97 ±39b	19–262	108 ±61b	0.0001***
Clay (%)	12.9–72.8	44.6 ± 16.0b	21.0–89.4	57.9 ± 1.9a	18.0–88.5	51.4 ± 16.9a	0.0012**
Silt (%)	7.5–39.2	18.4 ± 7.0	3.6–46.2	16.7 ± 9.5	3.5–44.0	17.9 ± 10.3	0.6520
Sand (%)	6.3–78.1	37.0 ± 18.7a	1.8–70.18	25.2 ±15b	5–76.8	29.6 ±6ab	0.0130*
Average precipitation 2017–2019 (mm/month)	123–157	141 ±9a	121–149	135 ±7b	113–134	126 ±5c	< 0.0001***
Monthly average temperature 2017–2016 (Celsius degrees)	17.7–22.4	19.9 ± 1.3a	17.7–20.1	19.01 ± 0.89b	19.2–21.03	20.19 ± 0.84a	< 0.0001***
Mulch thickness (cm)	0–6.5	2.2 ± 1.2	0–7.9	3.3 ± 1.8	0–7.4	3.0 ± 1.7	0.0794
Age of plantation (years)	6–52 24 ± 15		7–53	30 ± 11	7–42	30 ± 10	0.0975
Altitude (m)	1366–1734 1585 ±117c		1530–1980	1754 ±115a	1454–1845	1669 ±90b	0.0001***
Yield (kg per tree)	0.28–5.03 2.36 ± 1.39b		0.44–6.47	2.85 ± 1.68b	0.20–6.40	3.59 ± 1.57a	0.0049**

p-value signifiance codes at 5 % level: P ≤ 0.001: "***"; P ≤ 0.01 "**"; P ≤ 0.05 "*"
* Mehlich-3 extraction

ammonium acetate at pH7. Soil organic carbon was determined using the Walkley and Black method (Walkley and Black, 1934). Total nitrogen was analyzed using the Kjeldahl method, and the determination was made volumetrically. The procedures for these analyses are documented in Page (1982). Available phosphorus and trace elements were extracted with a Mehlich-3 solution (Mehlich, 1984). Texture was determined using the hydrometer method (Gee and Bauder, 1986) after destroying organic matter using hydrogen peroxide and dissolving oxides with hydrochloric acid. Sodium hexametaphosphate was used to disperse clay particles.

Rainfall data for the survey periods were extracted from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) platform at a spatial resolution of 0.05°. On a monthly scale, CHIRPS data correlate well with precipitation data from weather stations installed in Burundi (Nkunzimana et al., 2019). Temperature data were extracted from the widely used CRU TS (Climatic Research Unit gridded Time Series) climate dataset at a spatial resolution of 0.5° (Ian et al., 2020). Note that the spatial resolution of the CHIRPS (~5 km) and CRU TS (~50 km) data did not allow unique values to be assigned to each plot.

2.3. Rainfall and temperature during the survey periods

Average rainfall varied from 113 mm/month to 157 mm/month over the study area during the 2017–2018 and 2018–2019 seasons (Table 1). Mumirwa recorded significantly more precipitation than the other two agroecological zones while Dry Central Plateau recorded significantly less precipitation. Temperatures varied from 17.7°C to 22.4°C throughout the study area. The Mumirwa and the Dry Central Plateau are significantly warmer than the Humid Central Plateau (Table 1).

2.4. Soil characteristics of surveyed plots

Soils in the surveyed coffee plantations cover a wide range of textures, though clay soils dominate (Fig. S2 in supplementary material). On average, soils in the Humid Central Plateau are significantly more clayey (58 % clay) than in Mumirwa (45 % clay; Table 1). Silt content is generally low in all three zones, averaging 17–18 %.

Mumirwa soils are, on average, the least fertile compared to those of the two central plateaus. They have the lowest average values for pH, organic carbon content, cation exchange capacity, and exchangeable cation content (Table 1). On average, the Dry Central Plateau soils are slightly more fertile than the Humid Central Plateau soils, especially with regard to organic carbon content which is significantly higher in the Dry Central Plateau than in the other two regions. Other parameters such as total nitrogen, available phosphorus, C/N ratio and trace element contents (Mn, Zn, Cu) do not differ significantly between the three zones. However, the Mumirwa region has a significantly higher iron content than the other two regions.

2.5. Statistical analyses

All analyses were performed using R (Smith, 2006). Prior to the analyses, outliers were identified using whisker boxes as those values that surpass 1.5 times the interquartile range, and on the basis of empirical knowledge (Wang et al., 2015). Those outliers were not considered in Boundary line analysis. In addition to descriptive statistical analyses, ANOVAs with mean comparison tests based on LSD (Least Significant Difference) were carried out using the package agricolae in R to compare the three agroecological zones.

Correlation tests (Spearman correlation, Hmisc package in R) and principal component analysis (PCA; FactoMineR package in R) were then carried out to determine the correlations among variables and to provide insights into the relationships between variables, respectively. The dependent variable (yield) was added as an additional quantitative variable and was therefore not part of the PCA. In cases where two variables were significantly correlated, the variable that made the greatest contribution to the construction of the axes was retained. For example, in the case of total nitrogen and organic carbon, it was organic carbon that was retained. Micronutrients were significantly correlated with pH and only pH was considered. Variables were centered and scaled before performing PCA to ensure that all variables have comparable ranges and scales.

Random Forest analysis was performed using the RandomForest package in R to identify the relative importance of different variables in explaining coffee cherry yield. Given this objective, data from all plots were used in the model. The data were centered and scaled prior to building the Random Forest model. We set the number of trees to 1000 based on the error plot which shows how the error rate changes with the number of trees in the forest (Kursa and Rudnicki, 2011). Internal Node Purity (IncNodePurity) was used to assess the relative importance of each variable in contributing to the model's prediction accuracy. IncNodePurity refers to the total decrease in node impurity (measured by the Gini criterion) that occurs when a feature is used in a split within a decision tree. The higher the IncNodePurity value, the more important the variable is to the model's decision-making process (Islam et al., 2023).

The above analyses do not allow identifying the factors that most frequently limit coffee yields in the study area. In order to evaluate the individual contribution of each production factor to yield limitation, we performed boundary line analysis. This approach was developed by Webb (1972) and adapted by other authors to study the factors limiting cassava (Fermont et al., 2009), cereal (Shatar and Mcbratney, 2004), banana (Wairegi et al., 2010; Delstanche, 2011) and coffee yields (Wang et al., 2015).

The boundary points were determined on the basis of scatterplots between yield and each explanatory variable using the algorithm of Schnug et al. (1996). This approach is still the most used because of its simplicity, and is well-suited to limited-size datasets (Miti et al., 2024). Although potentially more robust statistical approaches exist, such as Makowski's quantile regressions or censored bivariate models, their adoption is hindered by various limitations as reviewed by Miti et al. (2024). Furthermore, it has not yet been clearly established whether there are systematic and significant differences in the results depending on whether a statistical or heuristic approach is used (Miti et al., 2024).

In this study, yield per tree was used for boundary line fitting, rather than yield per hectare, as the former showed better correlations with environmental and management factors. Also, agronomic recommendations are traditionally provided on a per-tree basis to farmers, and no significant relationship was found between planting density and yield per tree ($r = 0.11$), which further supports the relevance of using per-tree yield as a metric in this study. Yield per tree was also used by Nibasumba (2013) for coffee and Delstanche (2011) for banana.

Boundary lines were applied to all variables for which a boundary line trend could be visually identified, i.e., for all variables for which a clear upper boundary of the data cloud exists, allowing to draw an upper boundary line which is non-horizontal for at least part of the range of values of the independent variable. Micronutrients such as available Mn, Fe and Cu had no identifiable boundary line trend.

For the boundary lines, a logistic regression equation (Eq. 2) was used for factors showing a logistic relationship and a significant correlation with yield, i.e., nitrogen, organic carbon, available phosphorus, CEC, as well as exchangeable calcium, potassium, and magnesium. For factors with a bell-shaped relationship with yield (i.e., pH-H_2O, C/N, Ca/Mg, Mg/K, (Ca+Mg)/K, elevation, and clay), a second-degree polynomial function was used to generate the boundary line. This function was chosen based on visual observation of the trend displayed by the boundary points. For this study, only these two types of boundary line shapes were observed. The boundary lines were obtained by minimizing the sum of squared deviations between the predicted yield at the boundary line (Yl) and the yield of the boundary points (Yp).

$$Yl = \frac{Ymax}{1 + Kexp(-Rx)} \quad (2)$$

Where Yl is the predicted yield at the boundary line (kg/tree), Ymax is the maximum yield observed in a given agroecological zone (Ymax is specific to each agroecological zone), x is the value of the independent variable, K and R are scaling coefficients.

Determination of the limiting factors was based on the law of the minimum (Liebig's law). For a given plot, the variable leading to the lowest predicted yield (Ymin) based on the boundary line equations was considered to be the most limiting factor (Fermont et al., 2009; Wairegi et al., 2010).

Whenever the lowest predicted yield (i.e., the yield predicted by the most limiting factor) for a given plot i ($Ymin_i$) is higher than the observed yield (Y_i), it is possible to identify the most limiting factor (among those considered in the study). The yield gap for a given plot is then defined as the difference between the maximum observed yield (Ymax) for a given region and the observed plot yield Y_i. Part of this yield gap can be explained. The explained yield gap for each plot is the difference between Ymax of the region and the lowest predicted yield for that plot ($Ymin_i$; see Fig. 7 in results section for an illustration). The unexplained yield gap is the difference between the lowest predicted yield ($Ymin_i$) and the actual observed yield (Y_i).

For each variable whose boundary line matched a logistic function (Eq. 2), a norm was determined. This norm was defined as the value of the variable that allowed achieving 95 % of the region's maximum observed yield. This was done by inversion of Eq. 2. When the boundary line was of the polynomial (bell-shaped) type, the norm corresponded to the range of values of the variable allowing to reach 95 % or more of the predicted maximum yield (the maximum yield is found where $dY/dx = 0$). This tolerance (95 % of the maximum yield) balances biological realism with agronomic feasibility for smallholders. Indeed, by targeting realistic high yields, but not strictly the highest, it avoids advising unattainable optima in resource-limited contexts while minimizing sensitivity to outliers and observational noise near the peak of boundary lines. This analysis was carried out separately for each agroecological zone.

3. Results

3.1. Coffee yields

Coffee yields ranged from 0.2 to 6.5 kg cherries per tree across all surveyed plots (Table 1 and Fig. 1). These yields are the average of two successive years, one of mostly high production (2018) and another of mostly low production (2019) due to the cyclicity of coffee production in Burundi (Fig. 2). However, not all plots had their good production year in 2018, and some plots show low cyclicity (Fig. 2, plots located close to the 1:1 line), hence the need to average yields over two successive years. Besides the cyclicity, it is apparent from Fig. 2 that 2018 is the high production year and 2019 the low production year for a majority of the plots, indicating that most plots are synchronized.

There was a significant difference in average yield per tree between the three agroecological zones (Table 1). The Dry Central Plateau zone had the highest average yield (3.59 kg of cherries per tree), followed by the Humid Central Plateau zone (2.85 kg of cherries per tree) and finally Mumirwa (2.36 kg of cherries per tree). In addition to the significant difference in average yield between regions, there is also considerable between-plot variability within each region (Fig. 1 and Table 1).

Coffee plant densities measured during the diagnostic survey averaged 2365 ± 591 trees per hectare in Mumirwa, 2463 ± 676 trees per hectare for the Humid Central Plateau and 2223 ± 701 trees per hectare for the Dry Central Plateau. Given these plant densities and after converting cherry coffee yield into washed merchant coffee yield, average yields of washed merchant coffee were estimated at 887, 1115 and 1268 kg $ha^{-1}year^{-1}$ for Mumirwa, Humid Central Plateau and Dry Central Plateau, respectively.

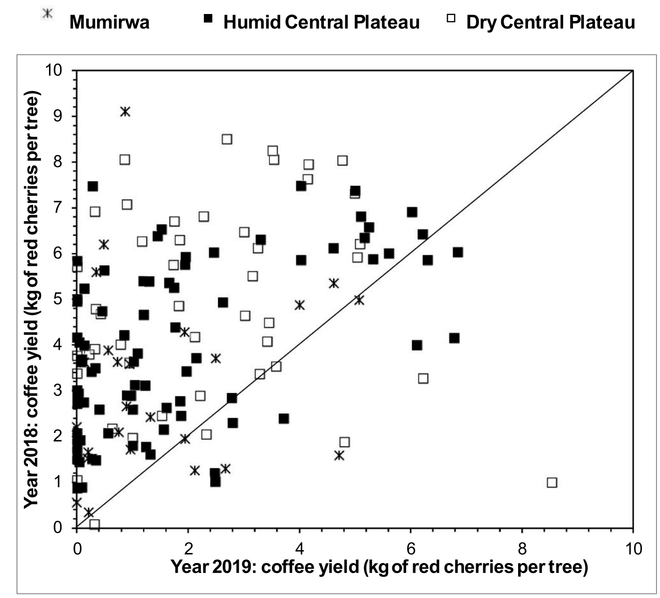

Fig. 2. Comparison of cherry coffee yields (kg per tree) of the surveyed plots in 2018 and 2019. Measurements were performed on the same trees in both years. The diagonal represents the 1:1 line.

3.2. Relationship between yield and production factors

Yield is positively correlated in all three agroecological zones with available phosphorus (correlation coefficient r = 0.35–0.42 depending on the region), organic carbon (r = 0.38–0.56), total nitrogen (r = 0.41–0.55), CEC (r = 0.36–0.55), and mulch thickness (r = 0.35–0.49) (Table S2 to S4 in supplementary material). It is negatively correlated with age of plantation in the Mumirwa (r = -0.43) and in the Humid Central Plateau (r = -0.41), but not in the Dry Central Plateau. In terms of exchangeable cations, yield was positively correlated with Mg (r = 0.45) in the Mumirwa, with Mg (r = 0.43) and Ca (r = 0.44) in the Humid Central Plateau, and with Mg (r = 0.35), Ca (r = 0.34) and K (r = 0.44) in the Dry Central Plateau. Correlations with cation ratios (Ca/Mg, Mg/K, (Ca+Mg)/K) are generally very weak ($r < |0.25|$) except for the (Ca+Mg)/K ratio in the Humid Central Plateau (r = 0.32). Correlations are also very weak with pH ($r < |0.18|$), C/N ratio ($r < |0.15|$), altitude ($r < |0.13|$) or precipitation ($r < |0.09|$).

The principal component analysis (PCA) explains 34 % of the total variance (Fig. 3). Axis 1 explains 21 % of the variance and is strongly determined by exchangeable Ca and Mg content and to a lesser extent by OC content, exch. K content and pH_H_2O. Yield is most correlated to this dimension, albeit not strongly. Axis 2 explains 13 % of the variance and is strongly determined by the (Ca+Mg)/K ratio and to a lesser extent by the Ca/Mg ratio and available P content. Fig. 3 further indicates that, within the space defined by the first two dimensions, coffee yield is most strongly determined by organic carbon and exchangeable Ca content.

The random forest model explained 41 % of the variance in coffee yield (Fig. 4). According to the Increase in Node Purity indicator, organic carbon content was the most important variable for explaining coffee yield, followed by mulch thickness and exchangeable Mg. The remaining variables showed lower importance in the model, indicating they contributed less to explaining coffee yield variation.

3.3. Identification of the most yield-limiting factors

Because of the cyclicity and synchronization of yields in a majority of the plots, restricting the survey to a single year would have strongly

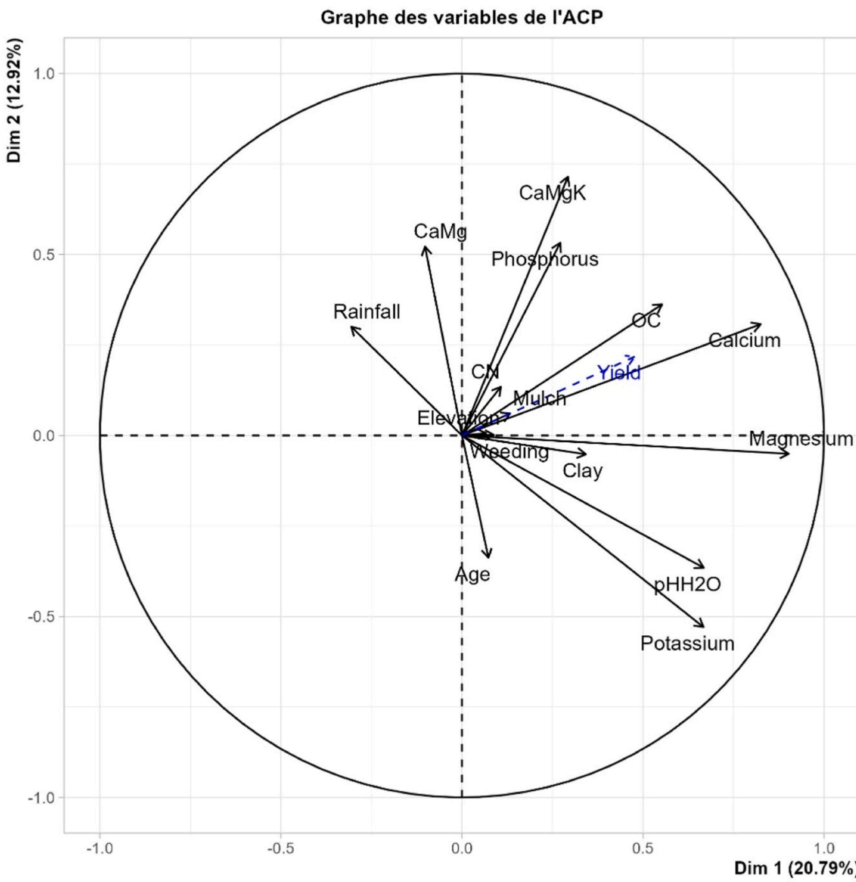

Fig. 3. Projection of soil and coffee plantation characteristics on the first two axes of the principal component analysis. Coffee yield was added as an additional variable, not included in the determination of the principal components. CaMg = Ca/Mg ratio, CaMgK = (Ca+Mg)/K ratio, OC = organic carbon, CN = C/N ratio.

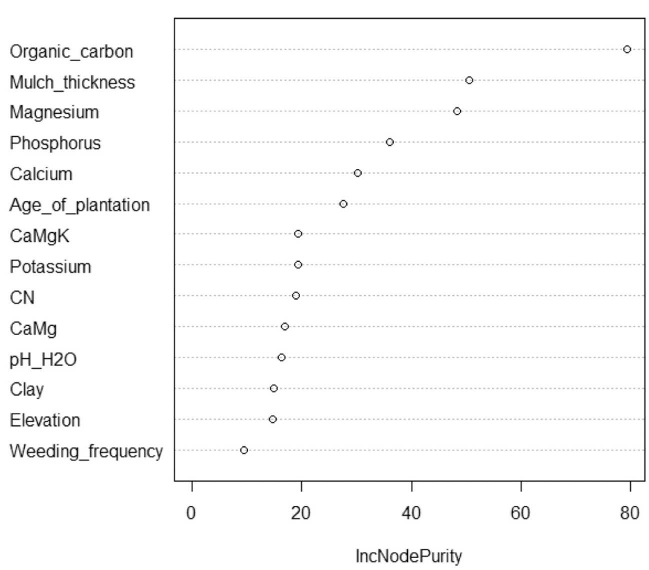

Fig. 4. Importance of environmental and management variables in explaining coffee yield, as measured by the Increase in Node Puriry (IncNodePurity) indicator. Higher values of IncNodePurity indicate greater importance. CaMg = Ca/Mg ratio, CaMgK = (Ca+Mg)/K ratio, CN = C/N ratio.

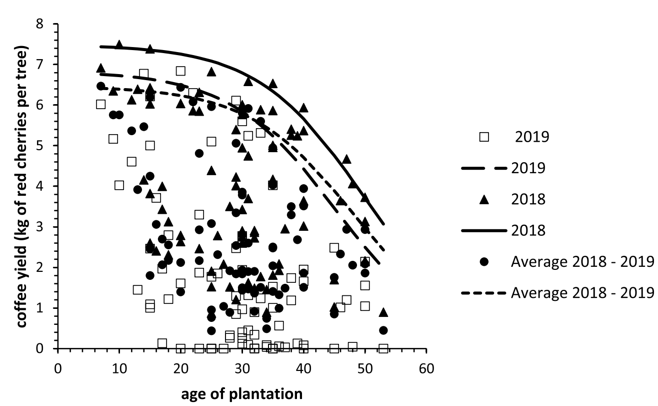

Fig. 5. Impact of the choice of survey year on the shape and position of the boundary lines in the boundary line analysis. This is illustrated here for coffee yield as a function of age of plantation. Each symbol corresponds to a single plot. For each plot, three yield values are depicted: 2018 yield (filled triangles), 2019 yield (open squares) and the average yield of 2018 and 2019 (filled circles). Boundary lines were fitted separately to the boundary points of 2018, 2019 and average of both years.

affected the boundary line analysis, as illustrated in Fig. 5 for a single variable (age of plantation). Indeed, since the boundary line is largely defined by plots which are in a good production year, using a single year of data results in a boundary line positioned higher on the graph in a good production year (2018) than in a bad production year (2019). Besides, using a single year of data also affects the yield gap depending on the strength of the yield cyclicity and synchronicity of each plot relative to the other plots. In the remainder of the analysis, the average yields of 2018 and 2019 were therefore used for each plot.

Boundary lines for the most relevant variables that limit yield are shown in Figs. 6a to 6j. The remaining figures are provided in the

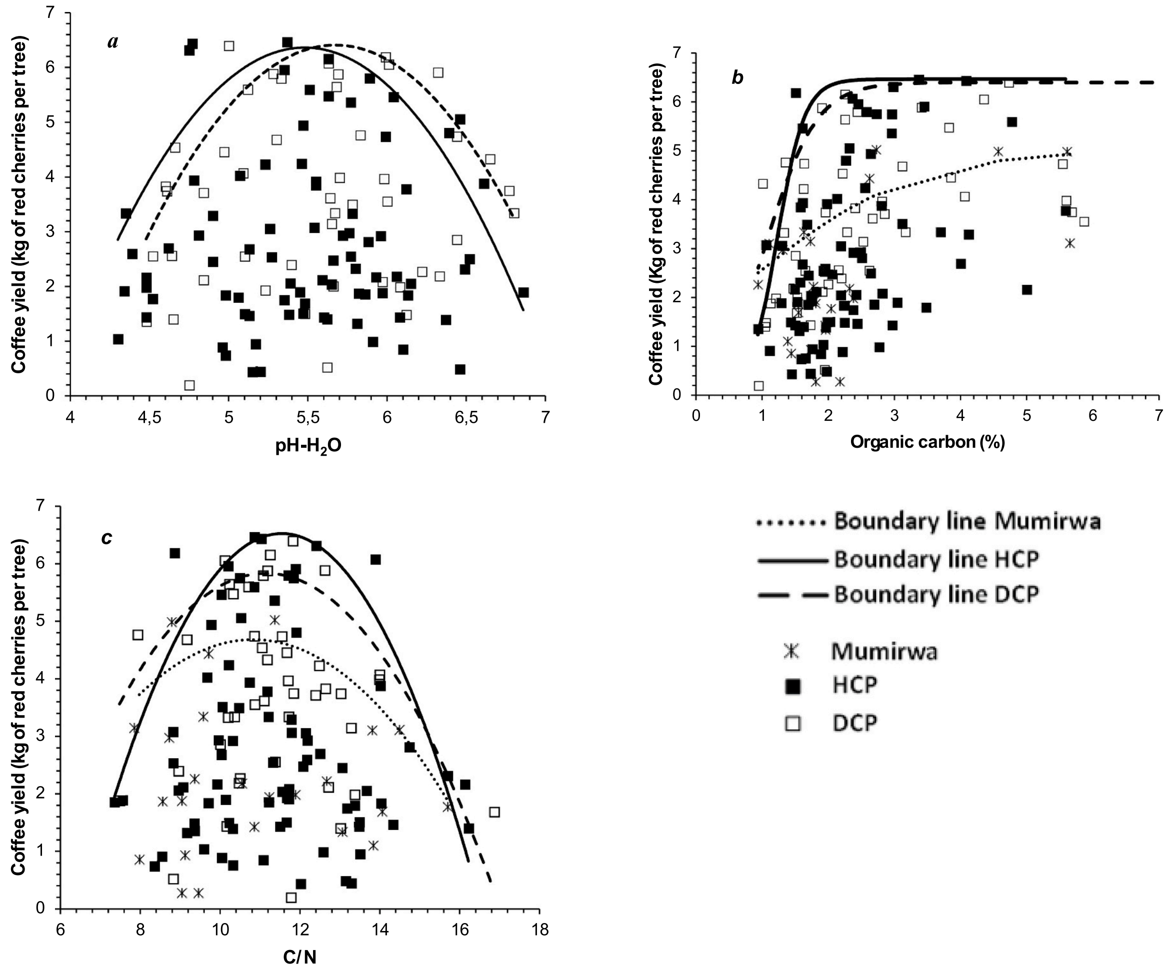

Fig. 6. Boundary lines for the most relevant variables that limit cherry coffee yield. Solid and dashed lines represent boundary lines by region: Mumirwa, Humid Central Plateau (HCP) and the Dry Central Plateau (DCP). Each symbol corresponds to a single plot. The yields are averages over two years (2018 and 2019).

supplementary material (Figure S3a to Figure S3g). For some variables and regions, boundary lines could not be drawn when the boundary points displayed no clear trend. Boundary lines are generally of the logistic type (Eq. 2), except for pH, C/N ratio, exchangeable cation ratios, clay content and altitude, for which polynomial bell-shaped functions seemed more appropriate. The agroecological zones show some similarities in terms of boundary lines, especially in the dry and wet central plateaus, but there are also significant differences, particularly between the two plateau regions and the Mumirwa.

The relationship between observed yields (weight of cherries per tree) and the minimum yields predicted by the boundary lines (Ymin) are shown in Fig. 7. Points on the 1:1 line, or slightly above the 1:1 line, represent plots whose yield is assumed to be limited by the factor that was identified as giving the lowest predicted yield based on the boundary lines. Points clearly above the 1:1 line represent plots for which yield was limited, primarily by the factor identified as most limiting, but also either by one or more other unidentified factors, or by the interaction between several production factors. Points below the 1:1 line correspond to points located above the boundary lines (see e.g. Fig. 6a).

The maximum achievable yield is 6.47 kg cherries/tree in the Humid Central Plateau, 6.40 kg/tree in the Dry Central Plateau and 5.03 kg/tree in Mumirwa (Fig. 7). On average, the yield gap is 2.16 kg cherries/tree in the Humid Central Plateau, 2.52 kg/tree in the Dry Central Plateau and 1.80 kg/tree in Mumirwa. For 75 %, 67 % and 63 % of the plots, yields can be at least partially explained by the boundary lines in Mumirwa, Dry Central Plateau and Humid Central Plateau, respectively. For the remaining 25 %, 33 % and 37 %, the observed yields are higher than those predicted on the basis of the limiting factor analysis. For plots located on or above the 1:1 line in Fig. 7, the average share of yield deficit (ratio of explained yield gap to minimum predicted yield) explained by the most limiting factor is 59 %. The coefficients of determination (R^2) between predicted minimum yields and observed yields were 0.67, 0.48 and 0.41, respectively, for Mumirwa, Humid Central Plateau and Dry Central Plateau for plots on or above the 1:1 line.

The factors that limit yield most in Mumirwa are phosphorus, which affects 34 % of surveyed plots, followed by lack of weeding (30 % of plots; Fig. 8). In the Humid Central Plateau, factors linked to plot management were the most limiting for 55 % of the plots: weeding (28 %), ageing plantations (17 %) and insufficient mulching (10 %). The remaining plots are affected by chemical constraints, mainly pH (12 %), Ca (9 %) and Mg (8 %). In the Dry Central Plateau, the most limiting factors are mainly related to soil fertility rather than plot maintenance. The most common limiting factor is the lack of available phosphorus, which affects 19 % of plots. Exchangeable bases limit yield in 35 % of plots (Ca: 15 %, Mg: 11 % and K: 9 %). The C/N ratio and acid soil pH limit yield in 17 % and 13 % of plots, respectively (Fig. 8). Note that exchangeable cation ratios (Ca/Mg and (Ca+Mg)/K) were significantly correlated with individual exchangeable cation contents (Ca, Mg, K; Table S1), hence only individual cation contents were retained.

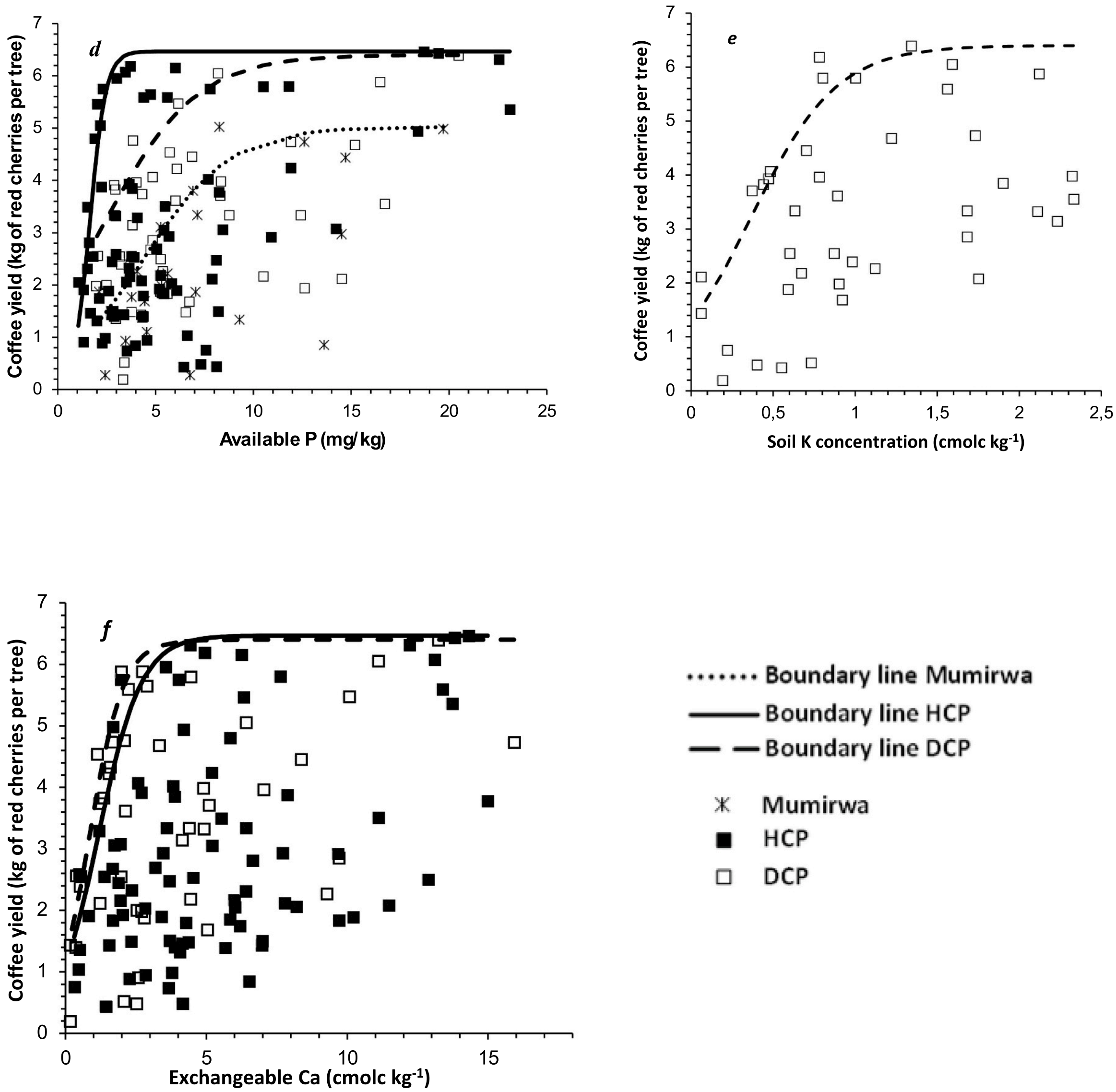

Fig. 6. (*continued*).

3.4. Optimal values of production factors

To achieve a yield corresponding to 95 % of the maximum achievable yield in each agroecological zone, optimum values (also referred to as norms) for soil fertility and coffee management were determined (Table 2). The values proposed for pH-H_2O, total N, and the C/N, Mg/K, Ca/Mg ratios and altitude are consistent with norms already proposed in previous studies. The same is true for organic carbon, except in Mumirwa where the new norm (4.4 %) is much higher than previously proposed. For available phosphorus, the (Ca+Mg)/K ratio and weeding, the results show that there can be optimum production for values below the previously proposed standards. On the other hand, for exchangeable magnesium and potassium, the proposed norms are higher than those previously proposed.

4. Discussion

4.1. Coffee yield

Coffee cherry yield was estimated by considering the average of two successive years. This was done in order to account for the cyclicity in coffee production in Burundi, a widespread feature in perennial crops referred to as alternate bearing (Krasniqi et al., 2017). The biennial bearing of arabica coffee is primarily a physiological mechanism in perennial plants (Monselise and Goldschmidt, 1982), although it may occasionally be exacerbated by depletion of plant-available nutrients (Haberman et al., 2019). Indeed, during a high-yielding season, coffee trees massively mobilize their carbohydrate reserves to support fruit ripening, leading to a temporary depletion of resources (Damatta et al., 2018). This depletion compromises post-harvest flower bud differentiation and vegetative growth, thereby delaying the following production cycle (Adugna and Vos, 2016). In nutrient-poor soils, the restoration of plant carbohydrate reserves takes longer than in fertile soils (Garcia and Orians, 2022). Besides the cyclicity, we also noticed that there was synchronization of most coffee plots, i.e., the majority of plots had a good production during 2018 and a low production during 2019. This is consistent with the coffee export figures for Burundi, which were 42 % higher in 2018 than in 2019 (BRB, 2020). This nationwide synchronization of coffee plantations has been attributed to climate, i.e., a period of drought that affected Burundi in 2002–2003 which caused most plantations not to flower in 2003 (Burundi Coffee Sector Development Office, personal communication). The following year was therefore a year of good production for most of the country and this cycle has been repeating itself ever since on a majority of plots. Such large-scale

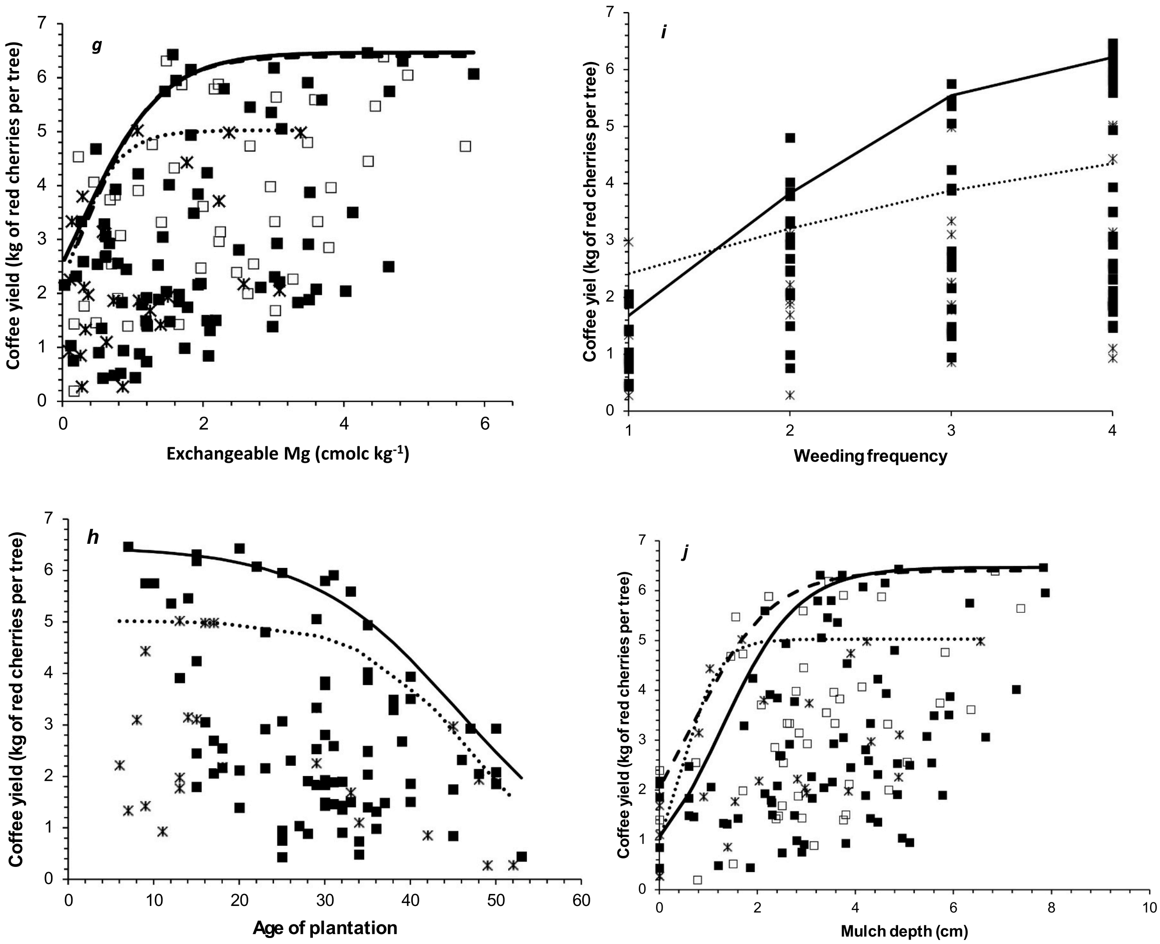

Fig. 6. (*continued*).

synchronization in the cyclicity of coffee production has also been reported in Côte d'Ivoire (Michel, 1989).

Diagnostic surveys are generally carried out for a single cropping cycle for reasons of labour and cost. However, because of the cyclicity of coffee production, performing the survey in a single year would have introduced a strong bias in the results. Indeed, the observed yields would have strongly overestimated (most plots of the 2018 survey) or underestimated (2019 survey) the average yield a smallholder coffee farmer could expect from his plot. The averaging across two successive years also accounts for the fact that not all plots show strong cyclicity (see Fig. 2, points located close to the 1:1 line). In a high production year, plots with low cyclicity will tend to have lower yields than plots with high cyclicity yet, on average over two years, the yields may end up being similar. Under these circumstances, using the average over two years is therefore a more robust estimator of yield than the yield from years of good production. The average yield of two successive years will thus better reflect the inherent fertility of the soils and management practices in the surveyed plots. In systems affected by production cyclicity, it is thus highly recommended to characterize yields over two production cycles for the proper identification of limiting factors and the assessment of their relative importance. Previous studies under similar circumstances did not take this into account (Wang et al., 2015). Although a longer-term assessment over several cycles would provide a more accurate characterization of coffee yields, this would be very difficult to achieve in small-holder farming systems at a reasonable cost. The average yields observed over the two years in the three agroecological zones (Table 1) are higher than the national averages, which were estimated to vary between 0.3 and 1.3 kg of cherries per tree (Nibasumba et al., 2021). Yields per hectare (887–1268 kg ha^{-1} $year^{-1}$ depending on the region) are, however, of the same order of magnitude as those in neighboring countries. For example, yields in Rwanda vary from 800 to 2800 kg ha^{-1} $year^{-1}$ on small farms (Nzeyimana et al., 2013). In Ethiopia, yields can vary from 200 to 2000 kg/ha/year in the coffee plots of smallholder farmers (Kufa et al., 2011) and in Uganda, yields average 750 kg ha^{-1} (Wang et al., 2015). Nevertheless, in major coffee-producing countries such as Brazil, Colombia and Kenya, yields in excess of 5000 kg/ha/year have been obtained in some unshaded coffee blocks with compact-type Arabica cultivars (Van Der Vossen, 2005).

4.2. Physical and chemical characteristics of the soils

The characteristics of soils show that soil pH is generally acidic (Table 2), which is common in soils of the intertropical zone. Slightly acidic soils, ranging from 5 to 6 (Gaie and Flémal, 1988) or from 5.5 to 6.5 (Snoeck and Lambot in Wintgens and Zamarripa, 2008) are favorable for coffee trees (Bitoga et al., 1994). If the pH is too low, the performance of the coffee tree is limited by low levels of exchangeable cations (major nutrients: Ca, Mg, K) P and excess iron, manganese and copper (Landon, 1984). On the other hand, a neutral pH can lead to Mn and Fe deficiencies, often associated with excess Ca (Gaie and Flémal, 1988).

According to previous standards, the optimum soil organic carbon content for coffee in Burundi is between 1 % and 3.5 % (Tessens and Gourdin, 1993). However, according to Snoeck and Lambot (Wintgens and Zamarripa, 2008), it is advisable to grow coffee on soil with an organic carbon content > 3 %. On the basis of this recommendation, soil organic carbon content is too low, on average, in all three zones. Across the three regions, 80 % of plots have an organic carbon content < 3 %.

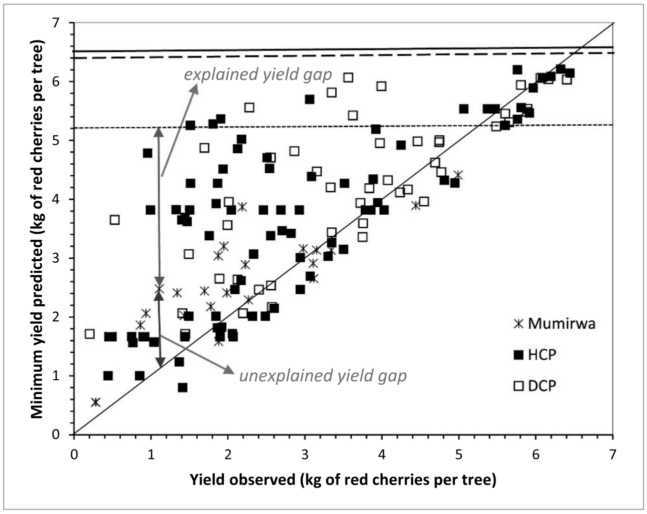

Fig. 7. Observed coffee cherry yield and minimum predicted yield in the three coffee-growing agroecological zones of Burundi. The horizontal lines represent the maximum achievable yield (Ymax) observed in the Humid Central Plateau (HCP) (6.47 kg cherry/tree, solid line), in the Dry Central Plateau (DCP) (6.40 kg/tree, dashed line) and in Mumirwa (5.03 kg/tree; dotted line). The diagonal line represents the relationship y = x (1:1 line). For points above the 1:1 line, the vertical distance between Ymax and a given point represents the yield deficit that can be explained by the most limiting factor. The distance between a given point and the 1:1 line represents the unexplained yield deficit. This is illustrated using vertical arrows in the figure for a plot located in Mumirwa.

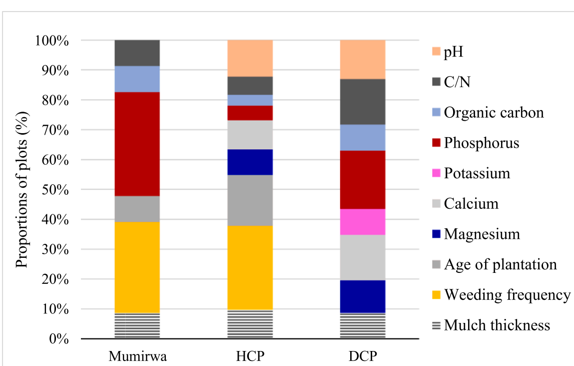

Fig. 8. Most-limiting factors as identified using the boundary line approach and the proportion of plots (in %) affected by these factors in Mumirwa, the Humid Central Plateau (HCP) and the Dry Central Plateau (DCP).

This low level of organic carbon can be explained by the fact that Burundian coffee growers do not apply organic amendments to their plantations except for mulching (source: interview with coffee growers). This is due to competition for organic amendments with other crops and the cost of transport and spreading. Furthermore, a lack of mulching material is observed as a result of the reduction in availability of fallow land (Snoeck et al., 1993). Notwithstanding the sub-optimal content, soil organic matter quality is good on average, with an average C/N ratio of 11–12 in all three regions. However, the C/N ratio can reach 20 in some plots. This is probably related to regular and/or recent mulching of these plots with fresh herbaceous material.

In the surveyed plots, 56 % of plots in the Mumirwa, 51 % in the Humid Central Plateau and 43 % in the Dry Central Plateau had total nitrogen levels below the optimum of 0.2–0.5 % (Tessens and Gourdin, 1993). This is directly related to the low organic carbon content, as carbon and total nitrogen are highly correlated. Similar findings have also been reported previously for coffee plantations in Mumirwa and the Humid Central Plateau (Nibasumba, 2013).

Almost 100 % of the plots in the three zones have P levels that are too low. Indeed, the P-Mehlich content is far below the critical value of 15 mg kg^{-1} (Okalebo et al., 2002). These concur with measurements previously carried out in Burundi in banana plantations (Bizimana, 2018; Rishirumuhirwa, 1997). The P deficiency may be due to several factors, including soil acidity, which enhances P immobilization in variable-charge soils such as ferralsols, which are very common in Burundi, particularly in the central plateaus. Although P-Mehlich is weakly correlated with pH in all three regions (r $\leq$ 0.12), high available phosphorus values are only observed in plots with pH $>$ 5.3 (not shown). The application of sulfates and/or silicates is recommended to limit P fixation and thus improve phosphorus availability, as liming can have negative effects on the structure of variable-charge soils such as ferralsols (Sanchez, 2019).

Exchangeable Ca levels are said to be high when they are $>$ 5 cmol$_c$ kg^{-1} (Smith and Loneragan, 1986) and are classified as good when they are comprised between 3.5 and 5 cmol$_c$ kg^{-1} (Tessens and Gourdin, 1993). According to the latter criterion, 68 % of plots in Mumirwa have low levels of exchangeable Ca, compared with 54 % of plots in the Dry Central Plateau and 32 % of the plots in the Humid Central Plateau. For exchangeable magnesium, values are said to be optimal when they are between 0.2 and 0.5 cmol$_c$ kg^{-1} (Horneck al., 2011). Despite adequate average values, 40 % of plots are below optimum in Mumirwa, compared with 13 % in the Dry Central Plateau and 9 % in the Humid Central Plateau. The low levels of exchangeable Ca and Mg may be due to the acid pH, with exchangeable Ca and Mg levels generally correlating well with pH in the three regions. Exchangeable K content appears to be non-limiting in most surveyed plots (0.2–0.5 cmol$_c$ kg^{-1}) (Tessens and Gourdin, 1993). The satisfactory or even excessive availability of potassium in coffee plantations in Burundi is likely due to the mulching of the coffee trees. Indeed, mulching material is dominated by residues of banana plants and grasses, which are rich in potassium (Pozy and Dehareng (1996), cited by Nibasumba, 2013).

Besides the availability of cations in the soil, a proper balance among cations is very important for adequate plant nutrition. Based on previous standards, imbalances were observed, especially for the (Ca+Mg)/K ratio (optimum between 10 and 20; Tables 1 and 2). This results from a lack of calcium and magnesium and an excess of potassium in almost all zones. These observations corroborate those of Nijimbere et al. (2020). Such imbalances are often found in mulched coffee plantations and most likely result from the type of mulch used as discussed above.

In general, micronutrient deficiencies in soils at pH$<$ 5 are rare except for Zn in tropical coffee plantations (Melke and Ittana, 2014). Heavily weathered soils often show Zn deficiencies (Carneiro et al., 2022; Casagrande et al., 2008). The ranges of optimal contents for coffee are 2–10 mg/kg for Zn, 0.3–10 mg/kg for Cu and $<$ 50 mg/kg for Mn (Melke and Ittana, 2014). On average, soils in the study area are Zn-deficient, especially in the central plateaus, and display excess Mn in all zones. No Cu deficiencies were observed in the surveyed plots. These observations corroborate those of Bitoga et al. (1994) and Nibasumba (2013).

4.3. *The factors that explain coffee yield*

Principal component analysis and the Random Forest model show that the factors that best explain coffee yield are organic carbon content, exchangeable Ca and Mg content, and mulch thickness. Soil organic matter is central to soil health, sustaining soil structure and related functions, playing a key role in nutrient cycling, and supporting biological activity (Gerke, 2022). In particular, it also helps increase the cation exchange capacity of soils dominated by low activity clay (i.e., kaolinite), as is the case in Burundi (Kaboneka, 2015). Calcium and magnesium are crucial macronutrients for coffee, playing key roles in various physiological processes that influence plant growth,

Table 2
Optimum levels (norms) of production factors calculated by means of the boundary line approach for each agroecological zone, as compared to standards derived from various previous studies. The proposed norms allow to achieve 95 % of the maximum observed yield in each region: Mumirwa, Humid Central Plateau and the Dry Central Plateau (DCP).

	Mumirwa	Humid Central Plateau	Dry Central Plateau	Published standards	Authors*
pH-HO_2	n.d.	5,2–5,7	5,4–6,0	5,5–6,5	1
Total N (%)	$\geq$ 0,21	$\geq$ 0,21	$\geq$ 0,21	0,2–0,5	2
Corg (%)	$\geq$ 4,4	$\geq$ 1,8	$\geq$ 2,2	1,16–3,48	2
C/N (-)	10–11,1	10,9–12,1	10,5–11,7	9–12	2
P-Mehlich3 (mg kg^{-1})	$\geq$ 10,9	n.d.	$\geq$ 9,4	> 15	3
Exch. K ($cmol_c$ kg^{-1})	n.d.	n.d.	$\geq$ 1,1	0,2–0,5	1
Exch. Ca ($cmol_c$ kg^{-1})	n.d.	$\geq$ 3,4	$\geq$ 2,4	> 3,5	2
Exch. Mg ($cmol_c$ kg^{-1})	$\geq$ 1,1	$\geq$ 1,5	$\geq$ 1,8	0,2–0,5	2
Mg/K (-)	n.d.	3,6–4	2,1–2,3	2–5	2
Ca/Mg (-)	n.d.	2,9–3,2	1,8–2	2–5	2
(Ca+Mg)/K (-)	n.d.	12,4–13,7	8,3–9,1	10–20	1
Altitude (m)	n.d.	1670–1846	1586–1753	-	-
Weeding frequency	> 4 times	> 4 times	n.d.	-	-

n.d.: could not be determined
* 1 = Wintgens and Zamarripa, (2008); 2 = Tessens and Gourdin, (1993); 3 = Okalebo et al. (2002)

development, productivity, and its response to stress (Meireles da Silva et al., 2014 ; Ramírez-Builes et al., 2020). Well-managed coffee plantations that applied mulch demonstrated higher productivity compared to those without mulch. Besides its contribution to the replenishment of soil organic matter, mulch helps conserve water by limiting evaporation and protects the soil against runoff and erosion (Nzeyimana et al., 2013).

4.4. Yield-limiting factors

Boundary line analysis allowed identifying the most limiting management and soil fertility-related factors per agroecological zone. In terms of management, insufficient weeding, ageing plantations and lack of mulch stand out. In terms of fertility, acid pH, P deficiency, soil organic matter and exchangeable bases contents, especially calcium and magnesium, are the most common limiting factors. These soil yield-limiting factors are related to the nature of the soils in the study area - which are typically highly weathered and therefore nutrient-poor - and to the fact that nutrients exported in the cherries at harvest are insufficiently compensated for by nutrient applications. These same limiting factors have been identified in other countries in the sub-region with similar coffee production systems as Burundi. In Rwanda, for instance, acid pH, low OM content, N, P, Ca and Mg deficiencies were identified among the factors limiting coffee productivity (Nzeyimana et al., 2013).

In the surveyed plots, mulch thickness averaged 3 cm in the three agroecological zones, whereas 10 cm of mulch thickness is recommended at the time of mulching in Burundi and Rwanda (Gaie and Flémal, 1988; Nzeyimana et al., 2013). Most farmers are aware of the advantage of mulching, and this activity is carried out in almost all coffee plantations, but with a quantity of mulch that is often insufficient due to the availability of straw and cost of labor. This mulching problem has long been reported in Burundi (Cochet and Ndarishikanye, 2000), where access to mulch is a widespread issue. Nevertheless, the reliability of mulch thickness assessment can be questioned since it depends on the date of the visit relative to the date of application. Indeed, coffee growers do not necessarily apply mulch at the same time, even though mulch application at the start of the dry season (June) is recommended. As the surveys took place in April, at the end of the rainy season, the recorded mulch thicknesses are probably underestimated compared to the thicknesses right after application (Kufa et al., 2011).

Weeding is also an activity that limits coffee yield if not performed often enough to limit competition for water and nutrients (UCDA, 2019). In Brazil, good yields require weeding every 45 days, i.e. 6–8 times a year (De Toledo et al., 1996). In Burundi, coffee growers from the three surveyed areas stated during the surveys that this activity is carried out one to four times a year, with weeds pulled out by hand. This low frequency of weeding in Burundi can be attributed in part to the cost of labour. In addition, farmers often give lower priority to coffee than to other more remunerative or self-consumption crops. Similarly, the average age of coffee plantations is problematic, as few farmers renew their plantations given the cost of this operation and the low income generated by coffee compared with other crops (Ntimpirangeza, 2019).

Rainfall and temperature did not emerge as a yield-limiting factor in this study. Moreover, yield and rainfall were only weakly correlated ($r < |0.09|$). This lack of climatic influence is likely due to the fact that our study was carried out during two years of near optimal climatic conditions. In fact, the optimal annual rainfall and temperature (150 mm of rain per month, a short dry season and temperatures between 18°C to 22°C; Gaie and Flémal, 1988) were reached in both years of observation (Figure S1 in supplementary material and Table 1). This allowed to better identify yield-determining variables that can be managed by farmers (as opposed to climatic variables which are not under the control of the farmers).

Micronutrients such as manganese, iron, and copper were not retained for the boundary line analysis due to the lack of clear trend in the upper limits in the scatter plots. Hence, they do not appear as yield-limiting factors. However, we recognize that deficiencies in these micronutrients could impact yield through interactions with other factors, such as soil pH. Unfortunately, one of the limitations of the boundary lines analysis approach is that it does not consider these interactions when fitting the boundary lines. Future studies could further explore such complex interactions, which are often pH dependent.

The limiting factors discussed above were identified after averaging yields over two successive production years to take account of the cyclicity in coffee cherry production. Using a single year of data affects the position and shape of the boundary lines (Fig. 5). Perhaps more importantly, it leads to a larger unexplained yield gap for all plots that are in their low production year and, in case the survey is carried out in a good production year, for the plots that do not show strong cyclicity. Indeed, low observed yields would in those cases result either from the 'resting period' of the coffee trees (and not from a specific environmental or management constraint) or from the fact that some plots are subject to low interannual variability and therefore yield less (in good years) than plots with strong cyclicity but similar average yield. It is therefore essential that similar analyses on coffee yield (and more generally on perennial crops) across the world be carried out over a period of minimum two years lest the boundary line analyses be biased and the yield-limiting factors be badly identified. Even longer yield time series would further allow to better capture climatic constraints which would, for instance, be valuable to assess the sensitivity of coffee production to future climatic conditions.

4.5. Yield gaps

The yield deficit reaches 59 % on average compared with the maximum yield observed in each zone. These yield gaps show the potential of coffee plantations to improve yield. The yield gaps can be reduced or closed by correcting for all the factors limiting yield in each agroecological zone (Wairegi et al., 2010). According to Ntwari et al. (2017), average yields can reach 5.5 kg of cherries per tree when all good practices are applied, while plots with poorer maintenance yield an average 1.6 kg of cherries per tree. This illustrates the magnitude of the rise in productivity that can be expected in case of proper management. Yield deficits averaging around 50 % were also observed in coffee plantations in Uganda by Wang et al. (2015) using the same boundary line analysis approach. The unexplained yield gaps (Fig. 7) are caused either by yield-limiting factors not considered in this study, such as shading (which was not quantified), diseases and pests, or by interactions between factors.

The widespread involvement of smallholder coffee producers represents an opportunity for the development of Burundi as well as neighboring countries in the east-African highlands. However, it is also a weakness in the sense that it implies a wide variability in yields across farms as a result of high variability in environmental conditions (soil types, altitude, …) as well as in management practices. To close the yield gaps, besides improved management of plantations (e.g., renewal of old coffee trees, regular pruning, proper weed and pest control), the application of good practices for integrated soil fertility management is the way forward. The new standards proposed for achieving optimum coffee production provide an up-to-date reference to this end (Table 2). The applicability of these standards likely extends to similar soils and production systems (small-holder farms) in the east-African highlands, well beyond the boundaries of the coffee-producing areas of Burundi. To improve soil fertility, practices relying on locally available resources should be prioritized such as integrating agroforestry trees and legumes into coffee plantations, reinforcing biomass production for mulching, or recycling coffee residues such as pulp through composting.

5. Conclusions

Coffee plays an essential role in the economy of Burundi, but yields are, on average, well below the potential yields. Based on a large number of surveyed plots (155 coffee farms), this study provides an update of the factors driving cherry coffee production in the three agroecological zones suitable for coffee growing in Burundi. The study took into consideration the biennial cyclicity of coffee yield, which is important to account for in the case of perennial crops, especially in smallholder coffee production systems.

We found that yield-limiting factors vary from one agroecological zone to another but are mainly linked to soil fertility and poor plantation management. In Mumirwa, phosphorus deficiency and poor weeding were key constraints. In the Humid Central Plateau, inadequate weeding, ageing plantations and low mulching dominated, with additional effects from low pH and calcium and magnesium deficiencies. In the Dry Central Plateau, soil fertility issues, especially phosphorus deficiency, base cation imbalances, low pH, and C/N ratio were most limiting. These results highlight the importance of zone-specific management interventions.

An average yield deficit of 59 % in coffee cherry yield was observed. It appears that if suitable management techniques were to be implemented, Burundi's coffee farms could increase yield significantly. This would require not only the renewal of ageing plantations and better plantation maintenance practices but also soil fertility improvement.

Even though this study focused on yield-limiting factors in Burundi, the findings have wider implications, in particular for other Arabica coffee producing areas in the East African highlands. Indeed, the factors limiting coffee production in Burundi, as well as the norms provided, could contribute to the preservation and improvement of plantation management in order to ensure long-term coffee production in the east African highlands.

CRediT authorship contribution statement

Charles L. Bielders: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Alain Kagisye:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Gilbert Nduwayo:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Anaclet Nibasumba:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127788.

Data availability

Data will be made available on request.

References

Adugna, B.D., Vos, J., 2016. Branch growth dynamics, photosynthesis, yield and bean size distribution in response to fruit load manipulation in coffee trees. Trees Struct. Funct. 30 (4), 1275–1285. https://doi.org/10.1007/s00468-016-1365-x.

Bernardes, T., Moreira, M.A., Adami, M., Giarolla, A., Rudorff, B.F.T., 2012. Monitoring biennial bearing effect on coffee yield using MODIS remote sensing imagery. Remote Sens. 4 (9), 2492–2509. https://doi.org/10.3390/rs4092492.

Bitoga, J.P., Flémal, J., Lambot, C., Snoeck, D., 1994. La recherche sur caféier arabica au Burundi. Tropicultura 12 (3), 109–113. ⟨http://www.tropicultura.org/text/v12n3/109.pdf⟩.

Bizimana, S., 2018. L'agriculture de conservation peut-elle améliorer la fertilité des sols et la productivité des systèmes bananiers en Région des Grands Lacs ? [PhD dissertation]. Université catholique de Louvain, p. 349.

BRB. (2020). Rapport annuel de la Banque de la république du Burundi. Retrieved from https://www.brb.bi/sites/default/files/RA 2020.pdf.

Carneiro, J.S., da, S., Leite, D.A., da, C., Gustavo, M., de, C., Franca, J.R., Botelho, L., Soares, J.R., Melo, L.C., 2022. Biochar-graphene oxide composite is efficient to adsorb and deliver copper and zinc in tropical soil. J. Clean. Prod. 360, 132170. https://doi.org/10.1016/j.jclepro.2022.132170.

Casagrande, J.C., Soares, M.R., Mouta, E.R., 2008. Zinc adsorption in highly weathered soils. Pesqui. Agropecu. Bras. 43 (1), 131–139. https://doi.org/10.1590/S0100-204X2008000100017.

Cilas, C. (1993). Methods of yield forecasts in coffee. Mission Report in Burundi. Retrieved from ⟨https://agritrop.cirad.fr/323133/⟩.

Cochet, H., Ndarishikanye, B., 2000. La production caféiere au Burundi: agronomie, vulgarisation et rapports sociaux. Can. J. Afr. Stud. Rev. Can. Des. Études Afr. 34 (2), 218–248. https://doi.org/10.1080/00083968.2000.10751193.

Damatta, F.M., Avila, R.T., Cardoso, A.A., Martins, S.C.V., Ramalho, J.C., 2018. Physiological and agronomic performance of the coffee crop in the context of climate change and global warming: a review. J. Agric. Food Chem. 66, 5264–5274. https://doi.org/10.1021/acs.jafc.7b04537.

De Toledo, S.V., De Moraes, M.V., De Barros, I., 1996. Effects of weeding frequency on coffee yield. Bragantia 55 (2), 317–324. https://doi.org/10.1590/s0006-87051996000200017.
Delstanche, S., 2011. Drivers of soil fertility in smallholder banana systems in the African Great Lakes Region. [PhD dissertation]. Université Catholique de Louvain. ⟨http://hdl.handle.net/2078.1/105014⟩.
Espe, M.B., Cassman, K.G., Yang, H., Guilpart, N., Grassini, P., Wart, J., Van, Linquist, B. A., 2016. Yield gap analysis of US rice production systems shows opportunities for improvement. Field Crops Res. https://doi.org/10.1016/j.fcr.2016.07.011.
Everaerts, E., 1947. Monographie agricole du Ruanda-Urundi, second ed. Ministère des colonies ⟨https://books.google.bi/books/about/Monographie_agricole_du_Ruanda_Urundi.html?id=vJZ-ibhMibEC&redir_esc=y⟩.
Fermont, A.M., van Asten, P.J.A., Tittonell, P., van Wijk, M.T., Giller, K.E., 2009. Closing the cassava yield gap: An analysis from smallholder farms in East Africa. Field Crops Res. 112 (1), 24–36. https://doi.org/10.1016/j.fcr.2009.01.009.
Gaie, W., Flémal, J., 1988. La culture du caféier d'Arabie au Burundi. AGCD. Publication du service agricole N° 4. 196p.
Garcia, G.M., Orians, C.M., 2022. Reproductive tradeoffs in a perennial crop: Exploring the mechanisms of coffee alternate bearing in relation to farm management. Agric. Ecosyst. Environ. 340, 108151. https://doi.org/10.1016/j.agee.2022.108151.
GCP, 2016. Introducing national coffee: addressing national investment agendas on a continental scale. Burundi case study. ⟨https://agri-logic.nl/wp-content/uploads/2019/11/African-Coffee-Investment-Agendas_Burundi_Full_Report.pdf⟩.
Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, In.A. (Ed.), Methods of soil analysis: Part 1 Physical and mineralogical methods, 5, pp. 383–411. https://doi.org/10.2136/sssabookser5.1.2ed.c15.
Gerke, J., 2022. The Central role of soil organic matter in soil fertility and carbon storage. Soil Syst. 6 (2). https://doi.org/10.3390/soilsystems6020033.
Haberman, A., Dag, A., Shtern, N., Zipori, I., Erel, R., Ben-Gal, A., Yermiyahu, U., 2019. Significance of proper nitrogen fertilization for olive productivity in intensive cultivation. Sci. Hortic. 246, 710–717. https://doi.org/10.1016/j.scienta.2018.11.055.
Hatungimana, A., 2008. Le café et les pouvoirs au Burundi. Cah. D. 'OutreMer. 61 (243). https://doi.org/10.4000/com.5298.
Horneck, D.A., Sullivan, D.M., Owen, J.S., Hart, J.M., 2011. Soil Test. Interpret. Guide. ⟨https://www.researchgate.net/publication/265097991_Soil_Test_Interpretation_Guide⟩.
Ian, H., Osborn, T.J., Phil, J., Lis, D., 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci. Data 1–18. https://doi.org/10.1038/s41597-020-0453-3.
ICO, 2021. A Flagship Report of the International Coffee Organization, pp. 1–94. ⟨https://www.internationalcoffeecouncil.com/_files/ugd/0dd08e_deb0d827997f42f28029bf2952b561ec.pdf⟩.
Islam, K.I., Elias, E., Carroll, K.C., Brown, C., 2023. Exploring random forest machine learning and remote sensing data for streamflow prediction: an alternative approach to a process-based hydrologic modeling in a snowmelt-driven watershed. Remote Sens. 15 (16). https://doi.org/10.3390/rs15163999.
ISTEEBU, 2010. Annu. Des. Stat. Agric. Ann. ée 2009. ⟨https://bi.chm-cbd.net/fr/implementation/rapports-nationaux/ann-stat-agri-2009-bi⟩.
ISTEEBU. (2019). Troisième recensement des caféiers et Caféiculteurs au Burundi de 2019. Bujumbura. 96p.
Kaboneka, S., 2015. Soil fertility status and challenges in Burundi: an overview. EGU Gen. Assem. Conf. Abstr. 1134. ⟨https://ui.adsabs.harvard.edu/abs/2015EGUGA.17.1134K/abstract⟩.
Keringingo, T., Kayakayacı, Z., 2023. Agricultural land access and use in Burundi. East Afr. Sch. J. Agric. Life Sci. 6 (02), 42–53. https://doi.org/10.36349/easjals.2023.v06i02.002.
Kimonyo, J.P., Ntiranyibagira, D., 2007. Réformes de la Filière Café au Burundi: Perspectives d'Avenir. pour la Participation. la Prosperite et la Paix. ⟨https://www.international-alert.org/app/uploads/2021/10/Reformes_cafe_Burundi.pdf⟩.
Krasniqi, A.L., Blanke, M.M., Kunz, A., Damerow, L., Lakso, A.N., Meland, M., 2017. Alternate bearing in fruit tree crops: past, present and future. Acta Hortic. (1177), 241–248. https://doi.org/10.17660/ActaHortic.2017.1177.35.
Kufa, T., Ayano, A., Yilma, A., Kumela, T., Tefera, W., 2011. The contribution of coffee research for coffee seed development in Ethiopia. J. Agric. Res. Dev. 1 (1), 9–16.
Kursa, M.B., Rudnicki, W.R., 2011. The All Relevant Feature Selection using Random Forest. ⟨http://arxiv.org/abs/1106.5112⟩.
Landon, J.R., 1984. Booker tropical soil manual: a handbook for soil survey in the tropics and subtropics. Longman Sci. Tech. Group. ⟨https://api.pageplace.de/preview/DT0400.9781317902096_A23916227/preview-9781317902096_A23916227.pdf⟩.
Lenaghan, T., Clay, D., Kamwenubusa, E., 2018. Burundi Coffee Sector: Diagnostic Study. ⟨https://www.researchgate.net/publication/329130289_Burundi_Coffee_Sector_Diagnostic_Study⟩.
Mehlich, A., 1984. Communications in soil science and plant analysis mehlich 3 soil test extractant: a modification of mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15 (12), 1409–1416. https://doi.org/10.1080/00103628409367568.
Meireles da Silva, D., Brandão, I.R., Alves, J.D., de Santos, M.O., de Souza, K.R.D., de Silveira, H.R.O., 2014. Physiological and biochemical impacts of magnesium-deficiency in two cultivars of coffee. Plant Soil 382 (1–2), 133–150. https://doi.org/10.1007/s11104-014-2150-5.
Melke, A., Ittana, F., 2014. Nutritional requirement and management of arabica coffee (Coffea arabica L.) in Ethiopia: national and global perspectives. Am. J. Exp. Agric. 5 (5), 400–418. https://doi.org/10.9734/ajea/2015/12510.
Michel, R., 1989. In: Michel, E.M. (Ed.), Le risque en agriculture. Orstrom. Retrieved from. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers07/27222.pdf.
Miti, C., Milne, A.E., Giller, K.E., Sadras, V.O., Lark, R.M., 2024. Exploration of data for analysis using boundary line methodology. Comput. Electron. Agric. 219. https://doi.org/10.1016/j.compag.2024.108794.
Monselise, S., Goldschmidt, E., 1982. Alternate bearing in fruit trees. Hortic. Rev. 128–173. https://doi.org/10.1002/9781118060773.ch5.
Nehbandani, A., Soltani, A., Hajjarpoor, A., Dadrasi, A., Nourbakhsh, F., 2021. Comprehensive yield gap analysis and optimizing agronomy practices of soybean in Iran. J. Agric. Sci. https://doi.org/10.1017/S0021859621000241.
Nibasumba, A., 2013. Evaluation agronomique de l'association bananiers-caféiers: application au Burundi (PhD dissertation). Université Catholique de Louvain.
Nibasumba, A., Jassogne, L., Nduwayo, G., Ngayempore, E., Simbashizubwoba, C., Van Asten, P., Bielders, C., 2021. Status and management of coffee plantations in Burundi: reasons to worry. Afr. J. Agric. Res. 17 (9), 1180–1191. https://doi.org/10.5897/ajar2021.15494.
Nijimbere, S., Kaboneka, S., Ndihokubwayo, S., Irakoze, W., Ndikumana, J., 2020. Caractérisation physico-chimique des sols d'une exploitation agricole du Mumirwa en commune Rumonge, 29. Revue de l'Université Du Burundi, Burundi, pp. 34–44, 1.
Nkunzimana, A., Bi, S., Jiang, T., Wu, W., Abro, M.I., 2019. Spatiotemporal variation of rainfall and occurrence of extreme events over Burundi during 1960 to 2010. Arab. J. Geosci. 12 (5). https://doi.org/10.1007/s12517-019-4335-y.
Ntimpirangeza, R., 2019. Effect of Participation in Cooperatives on Profit Efficiency of Coffee Farmers in Kirimiro Region. Makerere University, Burundi, p. 87. ⟨http://hdl.handle.net/10570/7546⟩.
Ntwari, B.O., Emile, K., Gilbert, N., Didier, S., Gilbert, N.E.N., Joselyne, N., Niyungeko, T., 2017. Guide sur la gestion durable d'une exploitation caféicole au Burundi. Outil De. Form. Des. caféiculteurs 101. ⟨https://agritrop.cirad.fr/588339/⟩.
Nzeyimana, I., Hartemink, A.E., de Graaff, J., 2013. Coffee farming and soil management in Rwanda. Outlook Agric. 42 (1), 47–52. https://doi.org/10.5367/oa.2013.0118.
Nzigidahera, B. (2012). Description du Burundi: Aspects physiques. Bujumbura. 10p.
Okalebo, J.R., Gathua, K.W., & Paul, L.W. (2002). Laboratory Methods of Soil and Plant Analysis: A Working Manual (Second edi). Nairobi, 127p.: TSBF-CIAT and SACRED Africa.
Page, A. (1982). Methods of soil analysis:Part 2 chemical and microbiological properties. In Methods of Soil Analysis (Second). https://doi.org/https://doi.org/10.2134/agronmonogr9.2.2ed.frontmatter.
Pham, Y., Reardon-smith, K., Mushtaq, S., Cockfield, G., 2019. The Impact of Climate Change and Variability on Coffee Production: A Systematic Review Content Courtesy of Springer Nature, Terms of Use Apply. Springer Nature, pp. 609–630.
Pozy, P. Dehareng, D. 1996. Composition et valeur nutritive des aliments pour animaux au Burundi. AGCD-ISABU, Publication agricole n° 37. 59p.
Ramírez-Builes, V.H., Küsters, J., de Souza, T.R., Simmes, C., 2020. Calcium Nutrition in Coffee and Its Influence on Growth, Stress Tolerance, Cations Uptake, and Productivity. Front. Agron. 2 (December). https://doi.org/10.3389/fagro.2020.590892.
Rishirumuhirwa, T., 1997. Rôle du bananier dans le fonctionnement des exploitations agricoles sur les hauts plateaux de l'Afrique orientale (application au cas de la région du Kirimiro). EPFL, Burundi. https://doi.org/10.5075/epfl-thesis-1636.
Sanchez, P.A., 2019. Properties and management of soils in the tropics. In: Pedro, A. Sanchez (Ed.), Properties and Management of Soils in the Tropics, second ed. https://doi.org/10.1017/9781316809785.002
Schnug, E., Heym, J., Achwan, F., 1996. Establishing critical values for soil and plant analysis by means of the boundary line development system (BOLIDES). Commun. Soil Sci. Plant Anal. 27 (13–14), 2739–2748. https://doi.org/10.1080/00103629609369736.
Shatar, T.M., Mcbratney, A.B., 2004. Boundary-line analysis of field-scale yield response to soil properties. J. Agric. Sci. 142 (5), 553–560. https://doi.org/10.1017/S0021859604004642.
Smith, E.P., 2006. Using R for introductory statistics. Technometrics 48 (2), 307–308. https://doi.org/10.1198/tech.2006.s387.
Smith, F.W., Loneragan, J.F., 1986. Plant analysis: an interpretation manual. In: Reuter, D.J., Robinson, J.B. (Eds.), Plant analysis: An interpretation manual, Second ed. CSIRO Publishing, Melbourne, pp. 1–12.
Snoeck, D., Bitoga, jean, P., Barantwaririje, C., 1993. Avantages et inconvénients de l'utilisation des divers modes de couverture dans les caféières au Burundi. Quinzième Colloq. Sci. Int. Sur Le. Café 793–795. ⟨https://agritrop.cirad.fr/466926/⟩.
Sualeh, A., Dawid, J., 2014. Relationship of fruit and bean sizes and processing methods on the conversion ratios of arabica coffee (Coffea arabica) Cultivars. Time J. Agric. Vet. Sci. 2 (2), 70–74. ⟨www.timejournals.org/tjavs⟩.
Tessens, E., Gourdin, J., 1993. Critères d'interprétation des analyses pédologiques, programme pédologique de laboratoire de chimie agricole. In: Fiche Labo n, 19. ISABU, Bujumbura, p. 27.
UCDA, 2019. Arabica Coffee Handbook: A Sustainable Coffee Industry with High Stakeholder Value for Social Economic Transformation. ⟨https://bukomansimbi.go.ug/sites/files/Arabic⟩. Coffee Handbook-web2.pdf.
Van Der Vossen, H.A.M., 2005. A critical analysis of the agronomic and economic sustainability of organic coffee production. Exp. Agric. 41 (4), 449–473. https://doi.org/10.1017/S0014479705002863.
Wairegi, L.W.I., Asten, P.J.A.Van, Tenywa, M.M., Bekunda, M.A., 2010. Field Crops Research Abiotic constraints override biotic constraints in East African highland banana systems. Field Crops Res. 117 (1), 146–153. https://doi.org/10.1016/j.fcr.2010.02.010.

Walkley, A., Black, I.A., 1934. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38. https://doi.org/10.1097/00010694-193401000-00003.

Wang, N., Jassogne, L., van Asten, P.J.A., Mukasa, D., Wanyama, I., Kagezi, G., Giller, K. E., 2015. Evaluating coffee yield gaps and important biotic, abiotic, and management factors limiting coffee production in Uganda. Eur. J. Agron. 63, 1–11. https://doi.org/10.1016/j.eja.2014.11.003.

Webb, R.A., 1972. Use of the Boundary Line in the analysis of biological data. J. Hortic. Sci. 47 (3), 309–319. https://doi.org/10.1080/00221589.1972.11514472.

Wintgens, J.N., Zamarripa, C.A., 2008. Coffee Propagation. Coffee: Growing, Processing, Sustainable Production: A Guidebook for Growers, Processors, Traders, and Researchers. https://doi.org/10.1002/9783527619627.ch4.

Wolde, Z., 2018. A review on coffee farming, production potential and constraints in gedeo a review on coffee farming, production potential and constraints in Gedeo Zone, Southern Ethiopia. J. Nat. Sci. Res. 7 (2), 5. ⟨https://www.researchgate.net/publication/323278573%0AA⟩.

WRB, 2015. World Reference Base for Soil Resources 2014 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. ⟨https://openknowledge.fao.org/server/api/core/bitstreams/bcdecec7-f45f-4dc5-beb1-97022d29fab4/content⟩.