

Smallholder farmers' knowledge on management of *Cinchona* in the Democratic Republic of the Congo

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Abstract

Background and aims – *Cinchona* (Rubiaceae) tree bark is the key source of quinine alkaloids used as malaria treatment. *Cinchona* trees were introduced to Democratic Republic of the Congo (DRC) in the early 20th century. Currently, the eastern DRC accounts for an estimated 55% of the global supply of quinine. The aim of this study is to obtain more insights into what context *Cinchona* is cultivated, what the scale of the farming and its management is, and how specific risks are being dealt with.

Material and methods – Data was collected on *Cinchona* tree distribution, socio-economic variables, farm characteristics, and cultivation techniques based on interviews with 185 smallholder farmers in five regions (*groupements*) across the eastern DRC.

Key results – Most *Cinchona* trees are grown at elevations between 1588 and 1627 m a.s.l. and most farmers preferred growing *C. calisaya* in a monoculture cultivation system, with in vivo propagation, and their own seed sources. Cassava was the dominant crop as previous cultivation and as a crop grown together with *Cinchona*. *Eucalyptus* was the dominant tree species grown together with *Cinchona*. Furthermore, most of the farmers apply a 1 × 1 m spacing and most do not use any additional fertilizer input. The most reported plant disease is linear canker.

Conclusion – To sustainably increase the productivity of *Cinchona* in the DRC, smallholder farmers should be given appropriate training to empower them to carry out their own in vitro propagation and apply integrated soil fertility management and integrated pest management. Our results provide information on current cultivation of *Cinchona* in the DRC, which may become more important given the rising resistance of the malaria parasite against other medicines.

Keywords

Cinchona, cultivation techniques, farm characteristics, silviculture, socioeconomics, tropical tree, quinine

INTRODUCTION

Malaria, caused by the parasite *Plasmodium*, remains one of the most prevalent diseases in the world (Sato 2021).

In 2022, an estimated 249 million cases of malaria were registered, of which 94% occurred in the African continent (WHO 2023). Malaria can be treated with medicines inhibiting the growth of parasite and quinine was the first

effective and oldest anti-malarial cure available. Quinine is obtained from the bark of the *Cinchona* L. tree (family Rubiaceae) and it is a natural alkaloid that has been used for centuries as prophylactic measure for treatment of malaria (Achan et al. 2011).

Cinchona calisaya Wedd. is one of the 24 species recognised in the genus *Cinchona* (POWO 2024). It is the species with the highest quinine concentrations identified to date (Maldonado et al. 2017). The four major alkaloids that are produced in *Cinchona* are quinine, quinidine, cinchonine, and cinchonidine (Achan et al. 2011), which are mainly extracted from the bark of the trees. Quinine concentrations in the bark of twigs, trunk, and roots vary significantly, between 1 and 14% (Nair 2010). The use and importance of natural quinine is still significant and even increasing. This is attributed to 1) the increasing resistance of malaria parasite to other antimalarial drugs (e.g. chloroquine), 2) the low price of natural quinine, and 3) the supplementary use of natural quinine against tick-borne diseases in cattle.

Cinchona trees are native to the Andes of South America, roughly from Colombia over Ecuador and Peru to Bolivia, and they occur between 800 and 3000 m a.s.l. (Wasis and Sandra 2020). Conventionally, *Cinchona* trees are mostly vegetatively propagated, coppiced, and the bark is harvested every 6–10 years (Nair 2010). Due to historical exploitation and habitat destruction, several species of *Cinchona* are relatively rare in their native range and even vulnerable to endangered, according to the IUCN Red List (García et al. 2022). Thus, *Cinchona* is of conservation concern in South America.

Europeans learned of the medicinal value of *Cinchona* bark in Ecuador in the 17th century, and quickly exports of *Cinchona* bark from South America to Europe were reaching half a million kilograms of bark per year (Maldonado et al. 2017). As import could not meet the demand, a quest began to establish resources of *Cinchona* by the British, Dutch, and French empires from the 1850s onwards. *Cinchona* was first widely cultivated in Southeast Asia in former British and Dutch colonies particularly in Indonesia, India, and Sri Lanka, where its current production declined due to economic, geopolitical, technical, and phytosanitary reasons. Accordingly, *C. calisaya* and *C. pubescens* Vahl have been cultivated in several countries in South America, Asia, and Africa (De Pessemier 2020). Today, 55% of global quinine production (via Pharmakina SA, www.pharmakina.com) occurs in the Democratic Republic of the Congo (DRC), most likely using seeds obtained from Bolivia (De Pessemier 2020).

However, we lack a good understanding of the local supply chain of *Cinchona* by smallholder farmers. Therefore, the main aim of this study is to obtain more insights into what context (agronomic, socio-economic, and ecological) *Cinchona* is cultivated in the DRC, what the scale of the farming and its management is, and how specific risks are being dealt with.

MATERIAL AND METHODS

Description of the study sites

The study sites were the Baswagha, Kabare, Ngweshe, Ntambuka, and Rubenga *groupements* in the North and South Kivu provinces of the DRC (Fig. 1). “*Groupement*” is an administrative term in the DRC and refers to the grouping of several villages in an administrative unit headed by a local chief. The North Kivu province is located between 0°58'00” and 02°03'00”S latitude and between 27°14'00” and 29°58'00”E longitude, with an elevation range from 1700 to 2000 m a.s.l. The South Kivu province is located between 26°10'30” and 29°14'10”S latitude and between 1°44'13” and 4°51'32”E longitude, with an elevation range from 645 to 2500 m a.s.l. (Bigirinama et al. 2020). The DRC is located near the equator where temperatures range from 23 to 26°C, humidity is high, and rains fall throughout the year averaging between 1,600 and 2,000 mm annually (Dyer et al. 2017). The country's tropical climate is characterized by heavy precipitation and high temperatures and humidity, experiencing more seasonal variability, with distinct dry (April to October) and rainy (November to March) seasons (World Bank Group 2021). The natural vegetation is composed of dense montane forests (dynamic habitats, teeming with plants, mammals, and insects), and grassy savannahs (Bigirinama et al. 2020).

Sampling and data collection

Geographical coordinates of 185 sampling sites (smallholder farms) were obtained in five *groupements* of the North and South Kivu provinces. Similarly, climate data for the period 1981–2010 was extracted using the geographical coordinates from CHELSA (2024) at a resolution of ~1 km. A survey was conducted in 185 households: 125 (Kabare = 4, Ngweshe = 74, Ntambuka = 7 and Rubenga = 40) in South Kivu in 2019 and 60 at Baswagha in North Kivu in 2020. We used a structured questionnaire with open-ended and multiple-choice questions (Supplementary material 1 for the complete survey).

The questionnaire was organized into four themes: ecological variables, socio-economic variables, farm characteristics, and cultivation techniques. The collected data includes: 1) ecological factors such as precipitation, temperature, and elevation; 2) socio-economic factors like gender, marital status, education level, farmer's age (in years), farm's age (in years), total area of *Cinchona* under cultivation (in ha), number of *Cinchona* fields per farm, and dried bark yield (in t ha⁻¹); 3) farm characteristics including the proportion of total area dedicated to *Cinchona* cultivation, cropping system, previous cultivation history, crops associated with *Cinchona*, and trees associated with *Cinchona*; and 4) cultivation techniques such as propagation methods and

seed source, type of fertilizer used, *Cinchona* tree species, assessment of soil fertility, spacing, disease, and insect infestations (Supplementary material 1). Data on the total area of *Cinchona* under cultivation (in ha) and dried bark yield (in t ha⁻¹) were only available for the Baswagha *groupement*.

Data analysis

Descriptive statistics were used to summarize the ecological and economic variables (Supplementary material 2), farm characteristics, and cultivation techniques. All analyses were performed in R v.4.2 (Fox and Weisberg 2019). Nonmetric multidimensional scaling (NMDS) was used to visualize farm characteristics, cultivation techniques, and economic variables (McMurdie and Holmes 2013) analysed using the metaMDS function in the R package vegan v.2.6.4 (Oksanen et al. 2022). NMDS was conducted using the Bray-Curtis dissimilarity matrix and two, three, and four ordination axes were explored and then three ordination axes with similar patterns were generated. Therefore, we standardized our analyses and retained three ordination axes as they appeared to capture a large amount of variation in the data while minimizing NMDS stress. Analysis of similarities (ANOSIM) was conducted (Clarke 1993) for the NMDS dataset using the

R package vegan v.2.6.4 to assess significant differences in farm characteristics, cultivation techniques, and socio-economic variables among *groupements*. The envfit function was then used to overlay environmental vectors onto the ordination plots. Subsequently, the NMDS ordination plot was displayed using variables with high significant p value ($p < 0.05$) as selected by the envfit function (Supplementary material 3).

RESULTS

Environmental factors and distribution of *Cinchona* trees in North and South Kivu

Initially, *Cinchona* was grown in South America and distributed to Asia and Africa. Currently, North and South Kivu province in the eastern DRC are home to the largest *Cinchona* forests in the world (De Pessemier 2020). The climatic characterization of the *Cinchona* farms revealed that average annual precipitation varied between *groupements* ranging from 900 to 3300 mm (Fig. 2A). The average annual temperature ranged from 18 to 21°C across the *groupements* (Fig. 2B). Most of the *Cinchona* trees were found from elevations of 1500 to 1800 m a.s.l., in Kabare, Ngweshe, Ntambuka, and Rubenga. All the

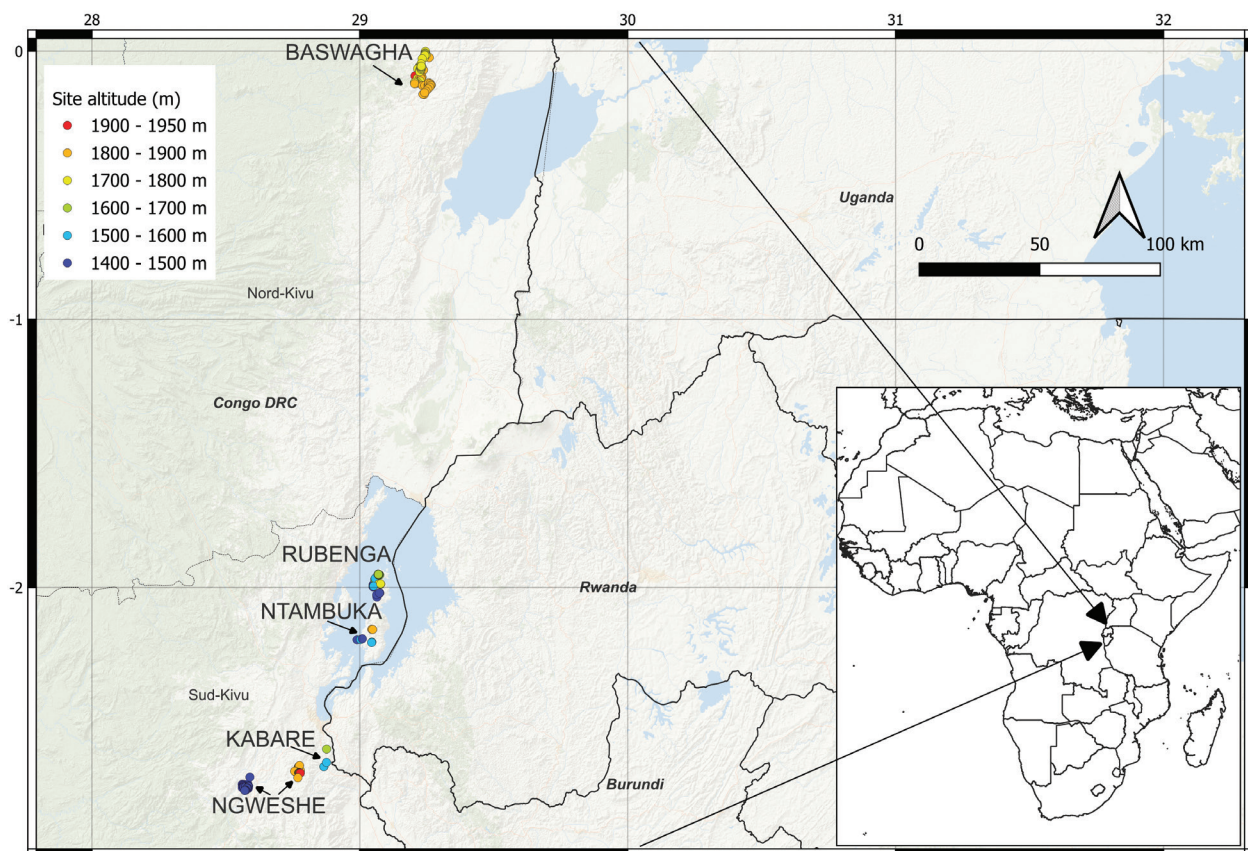


Figure 1. Map of the study areas: Baswagha, Kabare, Ngweshe, Ntambuka, and Rubenga *groupements* in the North and South Kivu provinces of the DRC. The dots represent the *Cinchona* farms.

Cinchona trees at Baswagha were found at high elevations from 1700 to 1855 m a.s.l. The *Cinchona* trees at Ngweshe were found at a wide range of elevation from 1425 to 1858 m a.s.l (Fig. 2C).

Economic variables affecting *Cinchona* production

At Baswagha, the majority (68%) of the smallholder farmers have a maximum land holding of 10 ha, while the remaining 32% have more than 10 ha (Fig. 3A). The average *Cinchona* bark yield at Baswagha was 0.8 ± 0.7 (sd), 2.4 ± 2.4 (sd), and 1.4 ± 1.5 (sd) t ha⁻¹ in 2018, 2019, and 2020, respectively (Fig. 3B). Farm area under *Cinchona* cultivation and mean dried bark yield were not available for the other *groupements*. Concerning number of fields per farm, most of the smallholder farmers (61%), have 2 to 5 plots of *Cinchona* per farm across the *groupements* (Supplementary material 4).

Farm characteristics affecting *Cinchona* production

The proportion of total area occupied by a given crop at the household level indicates the economic importance of that crop. More than half of the land at Baswagha (71%) is used for *Cinchona* production. In Kabare and Ntambuka, 29–33% of the farms had more than three quarters of the total land area reserved for *Cinchona*. In Baswagha, Ngweshe and Rubenga, 12–27% of the farms had 25–50% of the land area reserved for *Cinchona*, while for the remaining *groupements*, the area was mostly less than 25% (Fig. 4A).

Two types of cultivation systems, i.e. mixed (multiple cropping) and monoculture are used in the study areas. The dominant cultivation type for *Cinchona* production at Baswagha, Kabare, and Ngweshe was the monoculture cultivation system that ranges from 67 to 82%, while

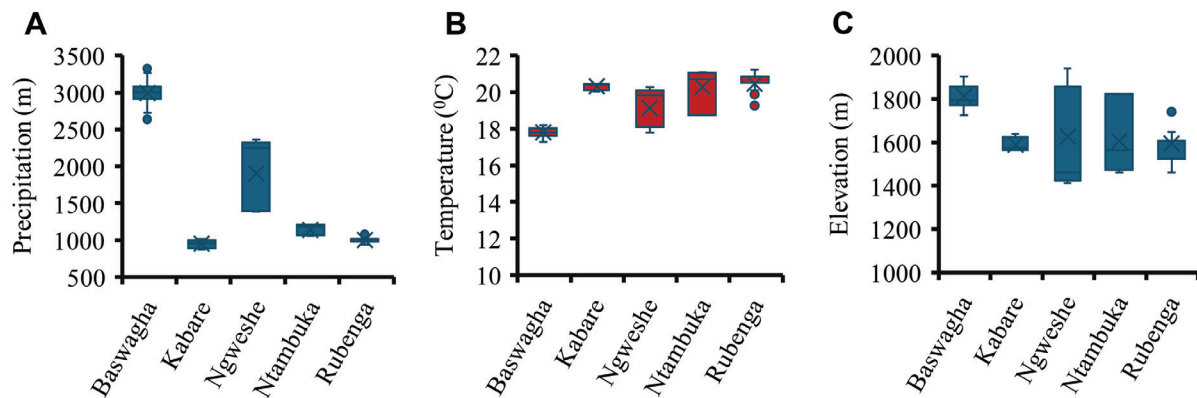


Figure 2. Climate and elevation data for the five *groupements* Baswagha, Kabare, Ngweshe, Ntambuka, and Rubenga in North and South Kivu provinces of the DRC. A. Precipitation. B. Temperature. C. Elevation (n = 185). Bars denote standard errors.

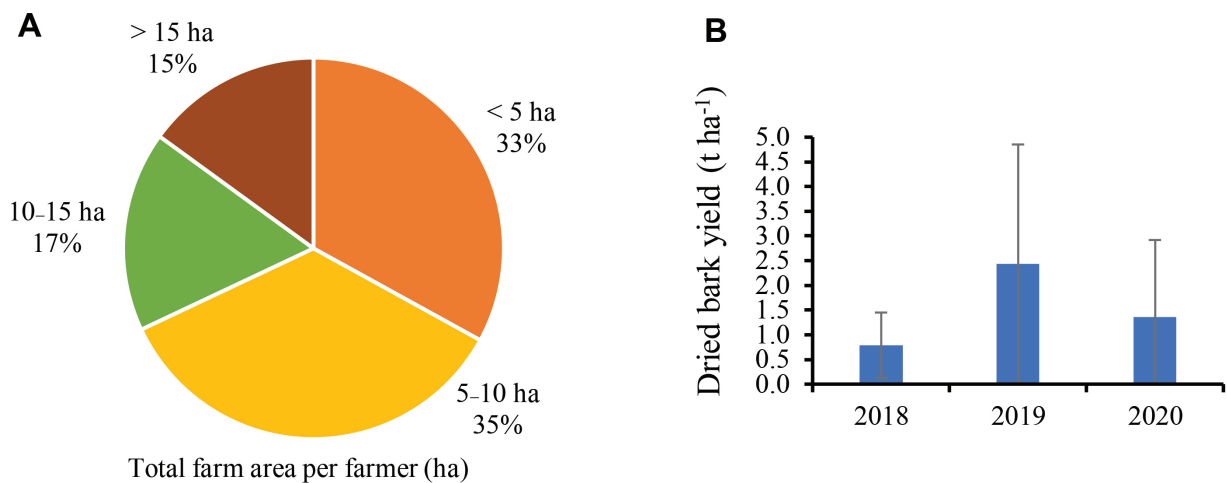


Figure 3. Economic variables in Baswagha in South Kivu province of the DRC. A. Fraction of farms in four categories of total farm area under *Cinchona* cultivation (n = 60). B. Mean dried bark yield of *Cinchona* (t ha⁻¹) (n-2018 = 12, n-2019 = 23, n-2020 = 27). Bars denote standard errors.

mixed cultivation is the dominant system at Ntambuka and Rubenga (70%) (Fig. 4B).

The type of crop in the previous cultivation (PC) commands the economic importance of the crop and the suitability of the land for adoption of the next crop. Among the previously cultivated crops, only cassava (*Manihot esculenta* Crantz) ranges from 65 to 100% at Kabare, Ngweshe, Ntambuka, and Rubenga, indicating the importance of cassava. Only at Baswagha were eight food crops recorded as previous cultivation: corn (*Zea mays* L.), potato (*Solanum tuberosum* L.), apple (*Malus domestica* Borkh.), pineapple (*Ananas comosus* (L.) Merr.), bean (*Phaseolus vulgaris* L.), grape (*Vitis vinifera* L.), peanut (*Arachis hypogaea* L.), and coffee (*Coffea arabica* L.), together accounted for 20% of the previous cultivation. The other 80% at Baswagha included *Eucalyptus* L'Hér., *Acacia mangium* Willd., and *Grevillea* R.Br. ex Knight (Fig. 4C).

In terms of crops grown together with *Cinchona* (CAC), cassava was the dominant crop, accounting for 100% at Kabare, 72% at Ngweshe, and 26% at Rubenga. However, the association of *Cinchona* with other crops such as cape plum (*Cyrtocarpa edulis* (Brandeggee) Standl.), banana (*Musa* L. sp.), corn (*Zea mays*), bean (*Phaseolus vulgaris*), maracuja (*Passiflora edulis* Sims), soya bean (*Glycine max* (L.) Merr.), sweet potato (*Ipomoea batatas* (L.) Lam.), and cabbage (*Brassica oleracea* L.) ranged from 14 to 76% at Baswagha, Ngweshe, Ntambuka, and Rubenga (Fig. 4D). In addition to cassava, pineapple (*Ananas comosus*) was another crop associated with *Cinchona*, ranging from 14 to 50% at Ntambuka and Rubenga.

In terms of trees associated with *Cinchona* (TAC), *Eucalyptus* was the major tree crop associated with *Cinchona*, ranging from 44 to 69% at Baswagha, Ngweshe, and Rubenga. *Grevillea* was the next tree crop associated with *Cinchona*, ranging from 8 to 50%. The association of

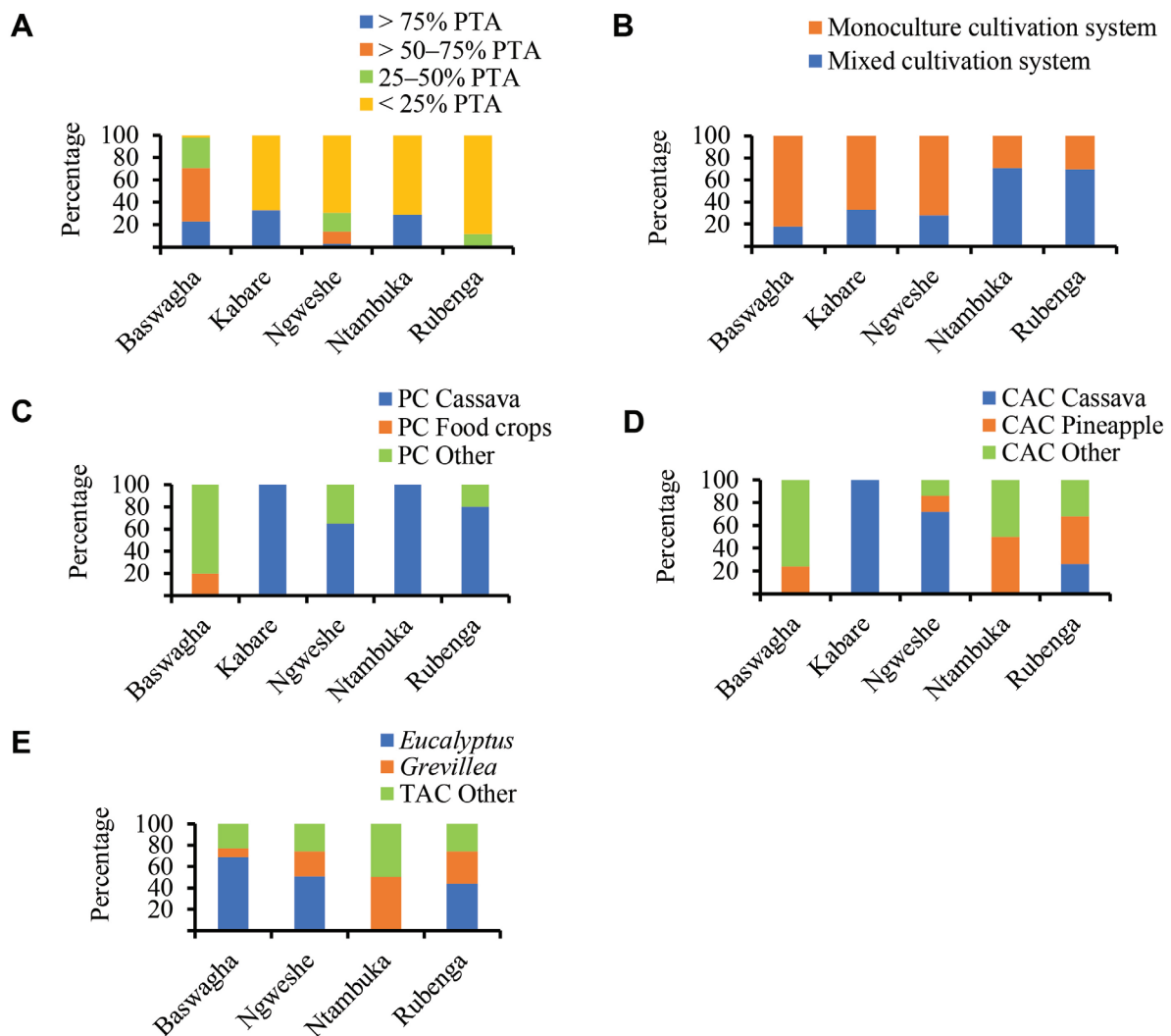


Figure 4. Characteristics of operation in *Cinchona* production in some groupements of North and South Kivu provinces of the DRC. A. Proportion of the total farm area (PTA) used for *Cinchona* cultivation (n = 185). B. Cultivation (cropping) system (n = 184). C. Previous cultivation on *Cinchona* fields (PC) (n = 103). D. Crops associated with *Cinchona* (CAC) (n = 96). E. Trees associated with *Cinchona* (TAC) (n = 112).

the remaining four tree crops, predominantly *Maesopsis eminii* Engl., *Albizia julibrissin* Durazz., *Cupressus sempervirens* L., and *Podocarpus macrophyllus* (Thunb.) Sweet, ranged from 23 to 50% (Fig. 4E).

Cultivation techniques in *Cinchona* production

All of the smallholder farmers used in vivo propagation at Baswagha, Kabare, Ntambuka, and Rubenga. Only 3% of all farmers used in vitro propagation (Fig. 5A). This also only happens at Ngweshe because there, Pharmakina

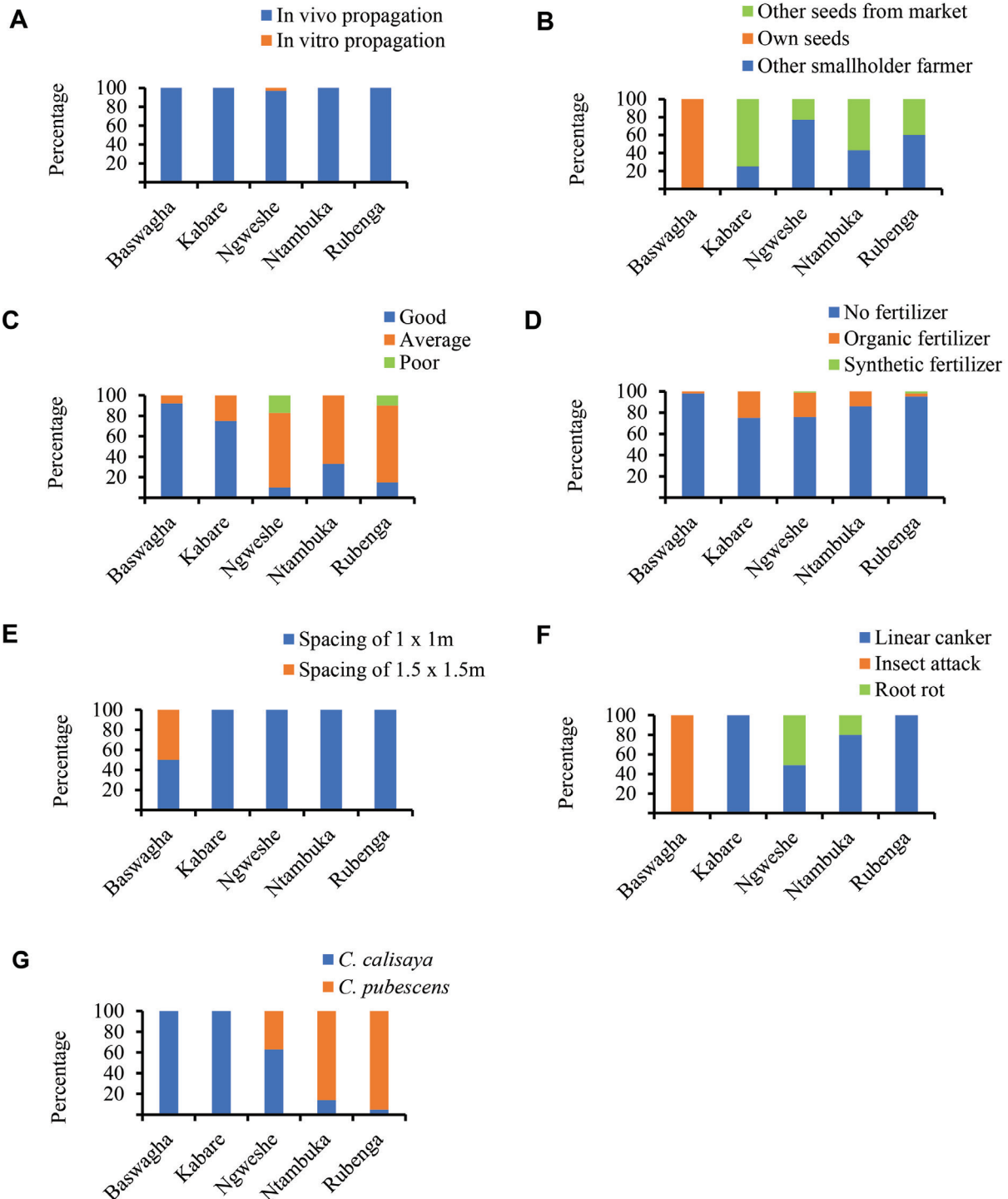


Figure 5. *Cinchona* cultivation techniques in the five groupements: Baswagha, Kabare, Ngweshe, Ntambuka, and Rubenga in North and South Kivu provinces of the DRC. A. Propagation methods (n = 185). B. Seed source (n = 177). C. Soil fertility status (n = 184). D. Fertilizer type (n = 185). E. *Cinchona* tree spacing (n = 178). F. Disease and insect problems (n = 126). G. *Cinchona* tree species (*C. calisaya* (n = 155), *C. pubescens* (n = 30)).

distributes seedlings produced by in vitro propagation to the farmers and collects the bark (via Pharmakina SA, www.pharmakina.com). To regenerate a new plant, different seed sources were used in each *groupement*. Accordingly, the source of seeds for 100% of smallholder farmers at Baswagha is their own seed. However, 25 to 77% of the farmers at Kabare, Ngweshe, Ntambuka, and Rubenga used other smallholder farmers' seeds and 75% of the farmers at Kabare used other seeds bought from the market (Fig. 5B).

Cinchona farmers in each *groupement* also assessed and classified the fertility status of their soils. Most farmers (61%) at Baswagha and Kabare classified the fertility of their soils as good. Similarly, 61% of the farmers at Ngweshe, Ntambuka, and Rubenga, classified the fertility status of their soil as average, whereas 10 to 17% of the farmers at Ngweshe and Rubenga classified the fertility status of their soil as poor (Fig. 5C).

Additionally, farmers were asked about the type of fertilizers used for soil fertility improvement. The majority of the farmers (62%) in the study areas used no fertilizers. However, the remaining *Cinchona* farmers (2–25%) at Baswagha, Rubenga, Ntambuka, Ngweshe, and Kabare used organic fertilizers and only 2% of the farmers at Rubenga and 1% at Ngweshe used synthetic fertilizers (Fig. 5D).

Concerning the spacing of *Cinchona* trees, all the farmers at Kabare, Ngweshe, Ntambuka, Rubenga, and 50% of the farmers at Baswagha used a 1 × 1 m spacing between plants and rows but the remaining 50% of the farmers at Baswagha used 1.5 × 1.5 m (Fig. 5E).

Regarding diseases and insects, the most reported disease was linear canker as reported by 49 to 100% of the farmers at Kabare, Ngweshe, Ntambuka, and Rubenga. Similarly, 20 to 51% of the farmers at Ngweshe reported root rot as the most important disease affecting quantity and quality of *Cinchona* production (Fig. 5F). Insect attacks were reported by all farmers at Baswagha.

Concerning the species, the majority of the farmers (62%) at Baswagha, Kabare, and Ngweshe are growing *C. calisaya*. The remaining farmers at Ntambuka and Rubenga are growing *C. pubescens* (Fig. 5G).

NMDS ordination

The *groupements* of Ngweshe and Rubenga show significant overlap in the NMDS plot (Fig. 6). The arrows indicate the economic variables, farm characteristics, and cultivation technique variables: proportion of total farm area (PTA), cultivation system (CS), previous cultivation (PC), crops associated with *Cinchona* (CAC), trees associated with *Cinchona* (TAC), assessment of soil fertility (ASF), spacing (Sp), diseases and insects (DI), and *Cinchona* tree species (Spe), fitted onto the NMDS ordination plots that were selected as influential variables (p value < 0.05) on *Cinchona* production (Supplementary material 3). Baswagha is associated with a set of variables along the first axis of variation such as proportion of total area (PTA), crops associated with *Cinchona* (CAC), assessment of soil fertility (ASF), previous cultivation (PC), spacing (Sp), and diseases and insects (DI), while Ngweshe and Rubenga are associated with axis 2 such as

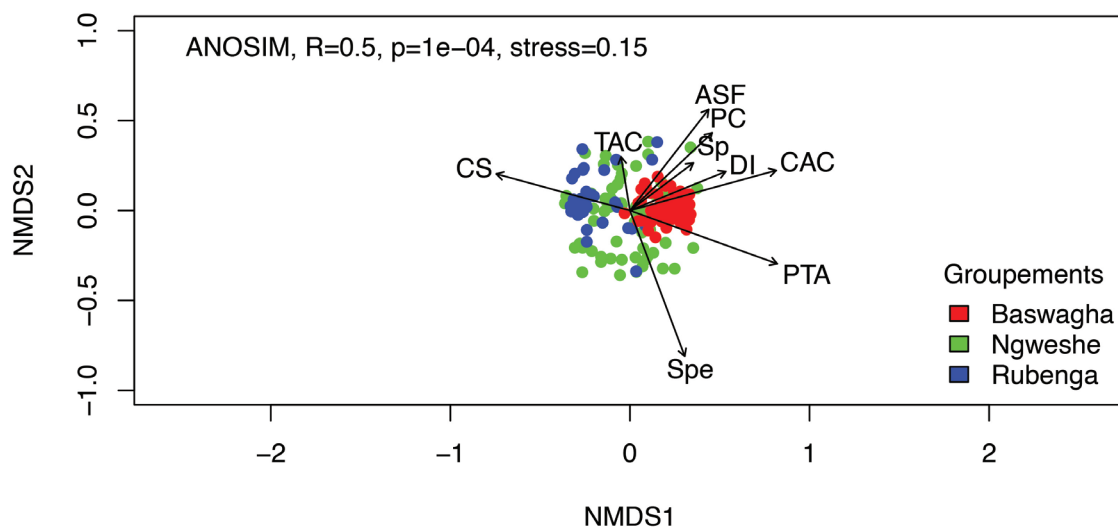


Figure 6. Nonmetric dimensional scaling ordination (NMDS) plot of *Cinchona* survey data from 9 variables in 174 farms. The colour of the points indicates the *groupements* for Baswagha ($n = 60$), green for Ngweshe ($n = 74$), blue for Rubenga ($n = 40$). Kabare ($n = 4$) and Ntambuka ($n = 7$) were excluded due to low sample size. Only significant variables ($p < 0.05$; based on 999 permutations) were visualized. The arrows' length and direction represent the environmental variables' effect on *Cinchona* production across *groupements*. Abbreviations: PTA: proportion of the total farm area used for *Cinchona* cultivation, CS: cultivation (cropping) system, PC: previous cultivation on *Cinchona* fields, CAC: crops associated with *Cinchona*, TAC: trees associated with *Cinchona*, ASF: assessment of soil fertility, TF: type of fertilizer, Sp: *Cinchona* tree spacing, DI: diseases and insects, and Spe: *Cinchona* tree species.

cultivation system (CS), trees associated with *Cinchona* (TAC), and *Cinchona* tree species (Spe). Also, the results of NMDS ordination indicated that farm characteristics and cultivation techniques varied across the *groupements*. The output of ANOSIM, $R = 0.5$, indicates that the variation between *groupements* is relatively much higher ($0.5 < R < 0.75$) (Fig. 6). Baswagha is associated with a set of variables along the first axis of variation, while Ngweshe and Rubenga are associated with axis 2.

DISCUSSION

Cinchona, the source of natural quinine used in the prevention and therapy of malaria, was introduced to tropical Africa in the 1850s and widely grown in plantations. As a consequence, the eastern part of the DRC is a major production centre today. This can be attributed to the favourable climate in the area, which is similar to the native conditions in the Andes with an elevation range of 1,450 to 3,330 m a.s.l. (González-Orozco et al. 2023). Our findings indicate that climate is a key biophysical variable influencing *Cinchona* distribution in the DRC. Orwa et al. (2009) reported that a mean annual temperature of 10–23°C and a mean annual rainfall of 1,020–3,800 mm is ideal for *Cinchona* production. Elevation is indeed a key biophysical variable driving the distribution of *Cinchona* in each *groupements* (Fig. 2C). However, *Cinchona* production is being constrained by the shortage of land and the limited number of fields per farm in the study area. For instance, the majority of *Cinchona* farmers (68%) at Baswagha have a maximum land holding of 10 ha. Also, the smallholder farmers across the five *groupements* typically possess between two and five fields of *Cinchona* per farm, with some having fewer than two fields per farm. Similarly, De Schaepmeester (2021) reported that the *Cinchona* plantations in Africa are currently mainly in the form of smallholder farms of different sizes, but the lack of productive land is their common constraint. *Cinchona* bark yield identified here ranged from 0.8 to 2.4 t ha⁻¹. This is a much lower yield compared to the bark yield in India, which is about of 9,000 to 16,000 t ha⁻¹ (Jäger 2014). The lower yield in the study areas could be attributed to lack of reliable sources of seeds, diseases and insects' attacks, no or low use of fertilizers, and poor and declining soil fertility. The proportion of the total farm area occupied by a given crop at household level may indicate the economic importance of the crop. For instance, 71% of the farming households at Baswagha used more than half of their land for *Cinchona* production, while for 67–88% of the farming households in the remaining four *groupements*, the land occupied by *Cinchona* was less than 25% (Fig. 4A). This indicates that most smallholder farmers at Baswagha used the majority of their available land for *Cinchona* production. Also, *Cinchona* production is mostly concentrated at Baswagha because *Cinchona* producers are looking for disease-free areas to expand their production, and this

is also an area less troubled by conflict. Boa (2015) also reported that the initial *Cinchona* plantations established from the 1930s onward were around Bukavu in South Kivu. These continued to flourish until regional conflict disrupted business in the late 1990s, which worsened after losses due to *Phytophthora* root rot. *Cinchona* is grown in monoculture and mixed (multiple) cropping systems in the study areas. Monoculture is the most common cropping system of *Cinchona* production for the farmers at Baswagha, Kabare, and Ngweshe. However, multiple cropping is the most popular cropping system for the farmers at Ntambuka and Rubenga because these are the regions where *Cinchona* is relatively less important. Munyakazi et al. (2022) reported that multiple cropping is the dominant cultivation system for 92% of the farmers in South Kivu, while the remaining 8% of the farmers practice monoculture.

Cassava is a dominant crop in the previous cultivation and among crops associated with *Cinchona*. Karume et al. (2022) reported that agroecological conditions of areas suitable for cultivating staple crops, mainly cassava, beans, rice, bananas, potatoes, coffee, tea, cocoa, and sugar cane, are also conducive for growing *Cinchona* in the DRC. These results indicate that cassava is highly associated with *Cinchona*, and it is a staple crop grown by the farmers for food security. The main reason that persuades farmers to opt for a mixed cultivation system is the risk reduction in the face of various hazards in the agricultural sector that can also affect their farm income and food security. So, over 15 million tons of cassava are produced yearly and cassava alone accounts for > 70% of all food production in the DRC (Karume et al. 2022). Tabaglio et al. (2023) also reported that cassava is a mainstay crop for food security in the DRC. Similarly, Orwa et al. (2009) reported that *Cinchona* is intercropped with food crops such as beans and other legumes in Central Africa to prevent soil erosion. Concerning trees associated with *Cinchona*, *Eucalyptus*, and *Grevillea*, exotics to the DRC, are the major tree crops associated with *Cinchona* at Baswagha, Ngweshe, Rubenga, and Ntambuka (Fig. 4E).

The *Cinchona* propagation technique did not vary among smallholder farmers in the study areas. Almost all the farmers at Baswagha, Kabare, Ntambuka, and Rubenga used in vivo propagation. They may prefer the in vivo propagation approach because it preserves the beneficial traits of the parent planting materials (Wasis and Sandra 2020), while only 3% of the farmers at Ngweshe hybridize their plants. In addition, all of the farmers at Baswagha used their own seed while farmers in the other four *groupements* used other seeds from market and other smallholder farmers.

The source of seeds for regeneration of new plants used for *Cinchona* production varied among the *groupements* in the study areas. This indicates that there is a lack of improved seeds, reliable source of seeds, and an absence of farmer's cooperatives supplying improved agricultural inputs for sustainable intensification of *Cinchona* production in North and South Kivu. Similarly, most

cropland in Sub-Saharan Africa is characterized by low crop productivity and poor soil health due to long-term nutrient mining and soil carbon decline, which present major constraints for sustainable intensification (Vanlauwe et al. 2014; Mungai et al. 2016).

Several studies have been conducted to assess the local knowledge of farmers on the fertility status of their soils. So far, the research conducted in the study areas mainly focused on documenting how farmers classify the fertility status of their soils (Corbeels et al. 2000). On average, 61% of the farmers at Ngweshe, Ntambuka, and Rubenga classified the fertility of their soils as average, while the farmers at Ngweshe and Rubenga classified the fertility status of their soils as poor. Poor fertility of soils in the study areas could be attributed to no or low use of fertilizers. For instance, 62% of the farmers used no fertilizers across the *groupements*, although fertilizer application is believed to be responsible for at least 50% increase in crop yield in the 20th century (Krasilnikov et al. 2022). For maximum productivity and quality of *Cinchona*, fertile soil with good availability of essential plant nutrients such as nitrogen, phosphorus, and potassium are crucial. Similarly, in Congolese *C. calisaya* samples, an increase in quinidine and cinchonine concentrations was observed for a higher level of plant nutrients (115 kg N, 105 kg P₂O₅, 115 kg K₂O per ha) (De Schaepmeester 2021). Thus, nutrient management is crucial to produce large quantities of bark. The cost of synthetic fertilizer is high in the eastern DRC. Because of this high cost, farmers prefer organic fertilizers (Hameed and Sawicka 2017), moreover since organic fertilizers are part of the traditional ecology knowledge of local farmers across the world, and the global awareness of the negative impacts of synthetic fertilizers. Based on our findings, the majority of the farmers in the study areas classified their soil fertility as good to average and they did therefore not use any synthetic fertilizer. The other reason for the low use of synthetic fertilizers is the lack of knowledge and information by the end users, because the majority of the farmers have received limited agricultural training according to the response of the farmers during the field survey.

Concerning plant spacing, 1 × 1 m is the most commonly used spacing in *Cinchona* production across the *groupements*. Orwa et al. (2009) also reported that for planting of *Cinchona* trees, a spacing of 1 × 1 m is recommended to stop soil erosion at higher altitudes. Disease and insect attacks are also the important problems affecting *Cinchona* production. Linear canker is the most important problem across the study areas, followed by root rot. Insect attacks are the most important problem only at Baswagha. Perennials such as *Cinchona* plants are often more attacked by diseases than the annual plants (De Schaepmeester 2021). Regarding tree species, *C. calisaya* is the most preferred and commonly grown tree species among farmers across the *groupements*, followed by *C. pubescens*, due to its higher quinine content. Pratiwi et al. (2018) also reported that *C. calisaya* is one of the *Cinchona* species that has a high (4–13%) quinine content. However,

a considerable variation in content and composition of alkaloids is found between and within species, and the total content of the four major alkaloids appear to be correlated with phylogeny (Maldonado et al. 2017). The NMDS result also indicates that environmental variables influenced the production of *Cinchona* at Baswagha. This is due to the fact that *Cinchona* producers are looking for disease-free areas to expand their production and because it is also an area less troubled by conflicts (Boa 2015).

CONCLUSIONS

The main contribution of this work is to improve our insights about the local supply chain of *Cinchona*, and specifically how farm organisation relates to the production of *Cinchona*. Our study showed that:

- the majority of the smallholder farmers allocated land for *Cinchona* production, mostly in a monoculture cultivation system, using in vivo propagation, 1 × 1 m spacing, their own seeds and other smallholder farmers' seeds;
- *Cinchona calisaya* is the preferred species by the farmers and is grown alone or in combination with other *Cinchona* species;
- Cassava and *Eucalyptus* are highly associated with *Cinchona* plantations;
- most of the farmers (> 62%) did not use any fertilizer;
- Linear canker and insect attacks are the most reported biotic problems;
- farmers in *Cinchona* growing areas in the eastern DRC have been able to produce *Cinchona* over the years with minimum input and advice from agricultural consultants.

Therefore, for sustainable production of *Cinchona*, attention should be given to facilitating a reliable source of inputs, in general, and improved germplasm and use of integrated soil fertility management practices at Ngweshe and Rubenga. Similarly, integrated pest management practices should be used for controlling disease at Kabare, Ngweshe, Ntambuka, and Rubenga, and insects at Baswagha. Finally, DRC contributes to ca 55% of the global quinine production compared to other *Cinchona*-producing countries, despite a relatively low *Cinchona* productivity.

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SUPPLEMENTARY MATERIALS

Supplementary material 1

Survey for *Cinchona* farmers in North and South Kivu.

<https://doi.org/10.5091/plecevo.125060.suppl1>

Supplementary material 2

Socio-economic variables: (a) gender, (b) marital status, and (c) level of education affecting *Cinchona* production in the North and South Kivu provinces of the DRC.

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Supplementary material 3

Environmental variables selected with envfit.

<https://doi.org/10.5091/plecevo.125060.suppl3>

Supplementary material 4

Socio-economic variables: (a) age of farmers (years), (b) age of the farms (years), and (c) number of *Cinchona* fields per farm in the North and South Kivu provinces of the DRC.

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