Monitoring Wild Coffee Using Ground Survey and Satellite Observation in Community-Managed Forest in Sheko, South-West Ethiopia

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Abstract: Preserving wild coffee in the natural forest, especially in southwest Ethiopia, is important for maintaining the genetic diversity of Arabica coffee and sustaining coffee production. To monitor the changes in wild coffee in the natural forest, we conducted an in situ baseline survey in 2015, and 30 of those survey sites were re-visited in 2019. Those surveys involved counting the number of mature mother trees, saplings and seedlings, as well as recording details of the sites, including disturbance, accessibility and forest conditions. Satellite imagery was combined with the site-specific in situ survey data to provide evidence of the forest condition around the study sites and therefore help more fully explore the causes for the changes in the wild coffee stock. The results show that, overall, the population of mother coffee trees was maintained during the 4-year period, and a slight increase in saplings occurred. Closer examination reveals considerable variations between sites, with some equally accessible sites showing a sharp decline in the number of mother trees while others show consistent increases. This study demonstrates the importance of systematic surveys, especially for the areas where forest cover and wild coffee plants are highly variable, and this may help explore community-specific approaches in managing wild coffee in the forest.

Keywords: wild coffee; Ethiopia; GIS; remote sensing; community forest management

1. Introduction

The natural high forest cover in Ethiopia has been declining rapidly for many decades, with only 4% of the country’s forested area remaining at the end of the twentieth century [1,2]. Even this remaining natural forest is suffering from various forms of degradation which alter its composition and threaten its survival [3,4]. The two major remaining blocks of Afromontane forest, in the south-west and south-east highlands, both contain stands of wild Arabica coffee [4,5]. These are unevenly distributed, requiring specific shade conditions and temperatures found between 900 and 1800 m amsl [4,6]. The patchy stands of wild coffee are globally important as Ethiopia is the only area in the world where Arabica coffee grows wild. Hence, Ethiopia is the genetic hearth of this type of coffee, and it is from these wild plants that Arabica coffee has been domesticated and disseminated around the world [7].

The wild coffee in the natural forest is valuable for the forest fringe communities, as the cherries from these bushes are harvested for domestic use or sale, although such use varies depending on
accessibility into the forest. The seedlings in these wild coffee stands are also transplanted by the local communities to more accessible areas where the forest canopy is thinned and the understory plants replaced by the coffee seedlings [4,8]. Such areas are known as “coffee forest”. They are individually controlled and have a high density of coffee bushes, unlike the natural forest with its very much lower density of coffee bushes [9]. The production and trade in coffee has generated important revenue not just for those who have the rights to use the coffee bushes but also for the local government through taxation and for people involved in picking the coffee. Other sources of income in these forests include non-timber forest products, such as wild honey and spices, as well as various wood products [10].

Maintaining the natural forest has been a major challenge over the last 50 years with population growth and economic development. The state, which took the forests from the local communities in the 1880s, has never had the resources to manage them effectively and in most cases they have been “open access” areas, subject to deforestation for cultivation and degradation through small-scale wood harvesting [3,4]. To address this challenge, Ethiopia has been introducing Community Forest Management (CFM) since the mid-1990s with communities agreeing to protect, enhance and manage their forests in return for rights over these forests, including limited sustainable harvesting of forest product, including wild coffee [11,12]. Maintaining the stands of wild coffee, as well as the forest, are one part of the CFM agreements that the participating communities sign with the local government [11]. If the community fails to achieve this, the government can take back the forest and the rights to forest use. The wild coffee has traditionally been collected for domestic use, but with greater market interest in this coffee, the collection of wild coffee has increased for sale to the local coops who have links to international markets. Hence, there are economic pressures on these stands of wild coffee within the natural forest and the Forest Management Groups (FMGs) in each community have to ensure that they are maintained, if the communities are to retain their rights to use the forest. This maintenance of the wild coffee in situ is also of global importance for future research to identify specific characteristics and for breeding to address possible challenges to the monoculture of Arabica coffee on estates around the world should there be major disease or pestilence outbreaks [13].

The CFM approach is one way which is being explored to maintain the wild coffee. Another is the use of biosphere reserves with local legislation supported by UNESCO recognition, the aim being to exclude communities from major areas of forest [10], especially those with wild coffee, and therefore protect the forest and the wild coffee. This contrasts with the CFM approach with its focus on community engagement in the management and sustainable use of the forest, including wild coffee [11]. The relative effectiveness of these two different approaches will only be seen over the coming decades, and although comparative studies will be needed, they are not the focus of this paper. In this study, a first attempt is made to explore the effectiveness of the CFM approach and identify lessons for better monitoring of the wild coffee stands and the processes which affect their survival.

The work reported in this research has been conducted by the University of Huddersfield since 2010 in partnership with the local government and an Ethiopian NGO, Ethio-Wetlands and Natural Resources Association. An initial five-year CFM project (2010–2015), funded by the EU, was designed to preserve the natural forest and the wild coffee stock within it in Sheko District in south-west Ethiopia. This area was chosen as it is where a study for the earlier EU-funded Coffee Improvement Project IV had identified major stands of wild coffee [5], while other studies had pointed to important genetic diversity amongst the wild coffee in these forests [14,15]. Support to the CFM has continued to 2021 to build stronger institutions and establish routines which will maintain the forest and the wild coffee.

Results from the five-year project have shown that CFM can help to almost halt loss of the natural forest, maintain biodiversity and increase carbon storage [11]. That research, however, did not address the effect of CFM on the wild coffee in the natural forest as the CFM arrangement arrangements were only in place towards the end of the project period. Hence, in this study, four years after that project ended, we focus on an assessment of how well wild coffee bushes have been maintained in the natural forest since CFM was established.
2. Materials and Methods

2.1. Description of the Study Area

Study area is located within Sheko District (blue rectangle in Figure 1a) in Bench Sheko Zone of Southern Nations, Nationalities and Peoples Regional State in south-west Ethiopia. The elevation of the area ranges between 1000 and 2000 m (Figure 1b). More than 70% of the district is forested, and the annual rainfall is over 2000 mm [16]. There is a wide range of ethnic groups including ones from around Ethiopia that have settled in this district. The indigenous people are the Sheko, who are traditionally hand hoe cultivators, and the Mejengir who are hunter-gatherers known for their collection of honey from the natural forest. Communications to this part of Ethiopia have improved considerably in the last decade with a tarmac road linking the zonal capital, Mizan Teferi to Addis Ababa and an improved gravel road from Mizan Teferi to Sheko town and seasonal roads to many settlements in that district. This improved access has increased human threats to the forest.

Figure 1. (a) Map of Ethiopia, (b) study area digital elevation map (DEM) and (c) administrative division map. In (b), the thin black polygon is the boundary of Sheko District, and red dots are the survey sites shown in three areas displayed on DEM (range from 1000 m to 2000 m). In (c), the survey sites are shown on map of local authority level. There are five “kebeles” (mid-level local authorities): Shimi, Gizmeret, Bonki, Bardika and Jenjeka. Each kebele consisted of two to four “gots” (lowest local authorities), e.g., Shimi kebele has Usika, Mehalshimi, and Shekomender gots.
The study focuses on three areas in the district: Areas A, B and C. Area A consists of part of Amora Gedel, a high steep mountain (>2000 m), where most of the wild coffee stands studied are distributed on the mid slopes of the mountain (Figure 1b). The survey sites in Area A were taken at the eastern and western edges of the mountain. At the eastern edge, the survey sites (1–5) are distributed within Jenjeka and Bardika kebeles (Figure 1c), and some close to local settlement in the south (Figure 2). At the western edge, the survey sites are in Bonki kebele, with local settlement to the south-west (Figure 2).

Figure 2. Survey sites are shown in got-level demarcation maps for three types of land use: natural forest—green, coffee forest—light blue, and agricultural and settlement—pink.

The survey sites in Area B stretch from south to north across Kontir Berhan, a mountain rising to ~1800 m (Figure 1b). The survey sites (12–17) in the south are within Mehalshimi got of Shimi kebele (Figure 1c), with local settlement to the east (Figure 2). The survey sites (18–28) in the north are distributed in Birhander and Mesgidzuriya gots of Gizmeret kebele (Figure 1c), and these sites are further away from the settlement in the east (Figure 2). Survey sites (29-30) in Area C are all located in Usika got of Shimi kebele (Figure 1c), deep into the natural forest on Kontir Berhan, away from the settlement (Figure 2).

2.2. CFM Approach to Wild Coffee Conservation

CFM is an approach which involves empowering the communities to manage the forests near to them and which they traditionally use or had used in the past. It usually involves returning such use or usufruct rights to communities who lost them to the state at times in the past. In this case, that alienation of the forest occurred during the development of the south-western boundaries of Ethiopia in the 1880s. As part of the CFM approach, agreements are developed between communities and the local government. These CFM agreements are focused on communities developing their own FMGs...
to protect, rehabilitate and use the forest with a management plan agreed with the local government and monitored regularly. Amongst the key activities by the FMGs are regular patrolling to prevent incursions into the forest, and the control of activities which involve the use of forest products allowed in the management plan and legislation to ensure sustainable use. In this area, given the economic and genetic value of the wild coffee, central aspects of all management plans are the protection of the stands of wild coffee, control of the removal of seedlings, the careful management of harvesting coffee berries to avoid damage to these bushes or trees, and the development of international markets via which to sell the wild coffee. For the communities to maintain their newly recovered rights to the forest, they need to be able to prove that they are fulfilling the management plans and protecting the wild coffee stands. This study is a first attempt to show to what extent this is being achieved.

2.3. Wild Coffee Surveys

Two wild coffee surveys were conducted during the dry season in 2015 and 2019 (Table 1). In 2015, the wild coffee survey was conducted in March, toward the end of the five-year project. For the survey, a group of 3–4 people, comprising project staff and FMG members, with wild coffee pickers acting as local guides, visited sites where wild coffee was known to exist in the natural forest (Figure 3). At each site, they counted the number of coffee bushes which occur in stands or groups in the natural forest and recorded the plants according to their growth stages: seedling, sapling and mother tree (Figure 4). Any coffee plants smaller than 50 cm in height were defined as “seedlings”, the ones between 50 cm and 1 m as “saplings”, and the ones taller than 1 m as “mother trees” (see Table 1). At each survey site, the details recorded were the GPS coordinates, community (got) and government administrative area (kebele) names, surveyor name, general description of the site (indication of disturbance), as well as the number of seedlings, saplings and mother trees.

Table 1. Wild coffee survey conducted in 2015 and 2019.

| Year | Month  | Data Collected                                                                 |
|------|--------|-------------------------------------------------------------------------------|
| 2015 | March  | Number of seedlings (<0.5 m), sapling (0.5–1 m) and mother trees (>1 m); GPS location; community and government administrative names; description of topography |
| 2019 | December | Number of seedlings (<0.5 m), sapling (0.5–1 m) and mother trees (>1 m); GPS location; community and government administrative names; description of topography, disturbance |

Figure 3. Photos of (a) FMG members during the 2019 survey and (b) a FMG leader with wild coffee plants.
Within an area, the 2019 survey was conducted at a point only due to limited resources and time. The difference in GPS locations between 2015 and 2019 surveys are below 8 m for the sites shown. In (b), one site is shown where the survey was conducted in an area (see the light grey polygon bounded by blue dots) in 2015 while the same area was surveyed in multiple points (yellow triangles) in 2019. The images shown in (a,b) are the red-green-blue (RGB) band composite of Pleiades-1B imagery acquired on 29th January 2015 and Worldview-3 imagery acquired on 3rd March 2015, respectively.

During the 2015 survey, the number of wild coffee plants were counted at a point or within a wider area. At the point survey sites, a mother tree was selected as the reference point, and the location was recorded with a hand-held GPS (Garmin GPS 72H, Garmin GPSMAP 62 and 64s). After that the surveyors searched for other mother trees nearby until no more were found. While the search radius varied site by site, depending on how far the group of mother trees stretched, a typical radius was 5 m, and rarely stretched more than 15 m. If another group of mother tree was found more than 15 m from the reference mother tree, the new group was considered as a separate point survey site. Where point counts were not used, the total number of wild coffee plants were counted within the area rather than counting at each group of mother trees, in order to get overall estimate of wild coffee density of the area. The size of the area varies 34 m$^2$ to 8800 m$^2$ (see an example for site 26 in Figure 4b).

In 2019, a selection of sites from the 2015 survey was revisited. A set of criteria were used to select sites, namely accessibility, numbers of wild coffee plants found in 2015 and resource availability in 2019. To find the same location surveyed in 2015, the surveyors first used a hand-held GPS to navigate to the site, and when they were near the site, local guides (wild coffee pickers) lead the way to identify the same group of mother trees surveyed in 2015. Note that the GPS location accuracy from a hand-held GPS is typically 5 to 10 m, but the location accuracy can be significantly degraded [17]. Therefore, working with local guides and handheld GPS units together, the 2019 survey was able to identify 2015 sites within 2–20 m of accuracy (Table A1). While the 2015 survey was conducted either at a point or within an area, the 2019 survey was conducted at a point only due to limited resources and time.

The comparison was relatively straightforward where both 2015 and 2019 surveys were done at points (i.e., point-to-point matching case in Figure 4a). This point-to-point matching can provide a direct comparison of changes in wild coffee plants. In contrast, where the 2015 survey was conducted using an area, the 2019 survey selected a number of specific points within or near that area (see area-to-point matching case in Figure 4b). To reconcile the difference, the density of wild coffee plants was estimated for 25 m$^2$ for both 2015 and 2019. From the 2015 area survey sites, the density was estimated by dividing the total number counts by the total area and multiplying the unit density by 25 m$^2$. From the 2019 survey sites, we made an average of the number counts from all the sites within and near the area (see Figure 4b). We selected 25 m$^2$ as the typical search radius was 5 m. Therefore, the area-to-point matching sites cannot provide a direct comparison, but an estimation of the changes in number of wild coffee plants was obtained. Note that the comparison would be most accurate where the wild coffee plants found in 2015 and resource availability in 2019.

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plants are homogenously distributed across the area, while the comparison would be less accurate if the distribution of wild coffee significantly varies in the area. This is discussed further in Section 4.

2.4. Satellite Data

Wild coffee requires a degree of shade in order to grow. Forest removal will cause its disappearance over time. Changes in forest conditions usually reflect human activities and increased human presence in the forest can lead to damage to wild coffee stands and the removal of seedlings. In order to help contextualize the sample sites and help contribute to an initial explanation of the changes, a set of high- and medium-resolution satellite imagery was acquired for the study area. For the medium-resolution (30 m) satellite imagery, Landsat-8 Level 2 surface reflectance products (LaSRC product for Landsat-8 OLI) were acquired from Earth Explorer at the U.S. Geological Survey (Table 2). For the high-resolution satellite images, we acquired two Pleiades-1B images for Area A, and one Worldview-3 image and one TripleSat-3 image for Areas B/C (Table 2). The resolution of Pleiades-1B and Worldview-3 multispectral images (top-of-atmosphere reflectance) are higher than 2 m, yet the resolution of TripleSat-3 is slightly coarse at 4 m (Table 2). From Landsat-8 surface reflectance data, we calculate the normalized difference vegetation index (NDVI) [18] and the normalized burned ratio (NBR) [19,20] to evaluate changes in forest cover.

### Table 2. Satellite imagery data used in this study.

| Region | Satellite/Sensor | Year/Date               | Resolution          |
|--------|------------------|-------------------------|---------------------|
| A-C    | Landsat-8/OLI    | 2015/8 March 2015       | Medium (30 m)       |
|        |                  | 2016/10 March 2016      |                     |
|        |                  | 2018/12 February 2018   |                     |
|        |                  | 2019/3 March 2019       |                     |
| A      | Pleiades-1B      | 2015/29 January 2015    | High (2 m multispectral) |
|        |                  | 2019/26 December 2019   |                     |
| B/C    | Worldview-3      | 2015/3 March 2015       | High (1.2 m multispectral) |
|        | TripleSat-3      | 2019/18 March 2019      | High (4 m multispectral) |

2.5. Community Engagement

During the 2019 wild coffee survey, we conducted a small number of Focus Group Discussions. These discussions explored at a general community level how communities had engaged in forest and wild coffee management before and after the achievement of their CFM agreements. They also explored the types of damage which may occur to both the forest and the wild coffee, as well as the arrangements for monitoring and the way rules developed by the community are enforced.

3. Results

3.1. In Situ Survey Data: Overall Changes in Wild Coffee Stands

Changes in the number of wild coffee plants from the 2015 to the 2019 survey are summarized in Table 3. Overall, the number of mother trees (>1 m in height) has shown a slight decline in 2019 (Table 3). In Area A and C, the number of mother trees were reduced by 5.8 and 13.7 plants in the four years to 2019 on average, while the numbers of mother trees in Area B increased by 1.8 plants in 2019 (Table 3). However, these changes are not statistically significant at a significance level of 0.1, indicating no significant changes in the number of mother trees between 2015 and 2019. For changes in the number of saplings, the survey data show an overall increase by 6.2 plants in 2019 on average (Table 3). Except for Area A, the number of saplings had increased in both Areas B and C. In particular, the increase of saplings (by 9.4 plants) in Area B is statistically significant within 90% confidence level. It is worth noting that Area B shows an increase in the number of both mother trees and saplings, while Area A is where both mother trees and saplings show a decrease (Table 3).
Table 3. Mean and standard deviation (in parenthesis) of the number of mother trees and saplings. Bold $p$-values indicate that the mean difference is statistically significant within 90% confidence level.

| Area Type | 2015 Mean Difference | p-Value Number of Sites |
|-----------|----------------------|-------------------------|
| All Mother Sapling | 22.6 (30.9) | 9.3 (11.4) | 20.6 (17.1) | 15.5 (22.1) | -2.0 | 6.2 | 0.75 | 0.18 | 30 |
| A Mother Sapling | 25.9 (41.1) | 15.3 (13.9) | 20.1 (18.2) | 12.8 (18.1) | -5.8 | -2.5 | 0.67 | 0.73 | 11 |
| B Mother Sapling | 18.1 (23.5) | 19.9 (14.5) | 14.7 (20.9) | 9.4 | 1.8 | 9.4 | 0.80 | 0.09 | 17 |
| C Mother Sapling | 43.0 | 29.3 | -13.7 | -26.6 | * | * | 2 |

3.2. In Situ Survey Data: Changes in Wild Coffee Stands at Individual Sites

Examining the individual sites, 17 sites showed an increase in the number of mother trees, while 13 sites showed a decline in the number of mother trees in 2019 compared to 2015 (Figure 5a,b). The declining cases are dominated by sites 4, 5, 27 and 30 which are found in all three areas, while sites 12–17, all in Area B, showed a consistent increase in the number of mother trees (Figure 5b). For saplings, 17 sites showed an increase, and 13 sites showed a decline (Figure 5c,d). The significant increase occurred at sites 12, 18, 19 and 29 (Figure 5d). These changes in saplings, however, do not exactly match with the changes in mother trees, e.g., both sites 4 and 5 recorded significant declines in mother trees, but the number of saplings increased at site 5 (Figure 5b,d).

Figure 5. The number of mother coffee trees and saplings counted at the matching survey sites. (a) The number of mother trees at individual sites is shown in blue (2015 survey) and red (2019 survey). (b) The difference in the number of mother trees between 2019 and 2015. The negative numbers indicate a decline of coffee stands in 2019 relative to the corresponding numbers in 2015. The numbers 4, 5, 27, 30 in (b) mark the sites showing significant declines in the number of mother trees in 2019, while the numbers 12 to 17 are the sites showing consistent increase in the number of mother trees in 2019. (c,d) are the same but for saplings.
3.2.1. Cases Showing Significant Decline in Mother Trees in 2019

We examine the four cases showing considerable decline in mother trees. Sites 4 and 5 recorded 78 and 131 mother trees during the 2015 survey but declined by 52 and 66 in number in 2019, respectively (Figure 5, Table A1). These two sites are situated in the natural forest at the border between Jenjeka and Wezeka gots (Figure 2). At site 4, six saplings were also lost by 2019 from the 21 saplings found in 2015, despite the fact that 54 seedlings were found in 2015. On the other hand, at site 5, 20 saplings were added by 2019 from the 45 saplings found in 2015 where almost 180 seedlings were found in 2015 (Figure 5). During the 2019 survey, it was recorded that these sites are wild coffee harvesting areas with thinned canopy cover, regularly visited by wild coffee pickers and with easy accessibility for communities (Table A1).

The other two sites showing significant declines are sites 27 and 30. In 2015, the number of mother trees at site 27 were 100, but only 2 mother trees were recorded in 2019 (Figure 5; Table A1). At the same site, a decline was recorded of 14 saplings in 2019. This site is located in the natural forest in Mesgidzuriya got (Figure 2) and is characterized by aged mother trees with climbers and a gentle slope with spices found nearby (Table A1). Site 30 recorded a decline of 60 mother trees and 22 saplings between 2015 and 2019 (Figure 4; Table A1). This site is located deep into the natural forest in Usika got (Figure 2). During the 2019 survey, it was reported that illegal clearing and conversion to coffee forest had occurred recently during a period of political instability (Table A1).

3.2.2. Cases Showing Significant Increase in Mother Trees in 2019

We now examine the cases showing considerable increase in mother trees. Sites 12–17 show consistent increases in mother trees (Figure 5b). These sites are close to the settlement and some are in natural forest and others at the border between natural and coffee forests in Mehalshimi got (Figure 2). At these sites, the increase in saplings was not as evident as that shown in mother trees, in fact some sites only showed a slight increase or even a decline (Figure 5d). Common reporting from these sites recorded in 2019 was that the wild coffee stands are “owned” by farmers paying tax for them and are cared for, not least because they are close to the coffee forest area managed by other farmers (Table A1).

Site 29 in natural forest in Usika got is another site showing significant increase in mother trees (Figure 2). At this site, both mother trees and saplings increased in number by 33 and 50, respectively, between 2015 and 2019 (Figure 5; Table A1). This site was recorded as being dense forest with no disturbance, but it was noticed that illegal clearing and conversion to managed coffee forest had occurred in nearby areas. In fact, site 30 is only 150 m away from this site, and that site shows a significant decline in mother trees and saplings and had reports of illegal clearing and land use change.

3.3. Satellite Imagery

3.3.1. Overall Changes in Forest Cover at Survey Sites

To help understand the forest changes at the in situ survey sites, we derived NDVI and NBR indices at the survey sites. NDVI is commonly associated with leaf area index, canopy structure and photosynthesis [21], and is used to detect seasonal phenological changes [22,23]. NBR has been used to detect various types of disturbance from severe disturbance such as the conversion of forest to agriculture fields to moderate disturbance such as selective cutting, drought and diseases and even slight changes in forest stand structure [19]. In this study we examine these two indices to evaluate changes in forest conditions during the 4-year period.

Figure 6 summarizes the temporal changes in NDVI and NBR for the four-year study period. On average, NDVI and NBR values of all survey sites show a slight increase between 2015 and 2019 (think black line in Figure 6), but with large standard deviations. The NDVI and NBR values for Area A (green lines) follow closely to the mean values for all three sites (thick black lines) (Figure 6). NDVI and NBR values for Area B follow closely to the overall mean of three areas in 2015 but are increased in 2019 above the overall means (Figure 6). For Area C, the mean NDVI and NBR values
(red lines) remained below the overall means in 2015 and 2016, and then increased to close to the overall means in 2018. Both NDVI and NBR values show a similar trend. In Area A, there are large standard deviations around the means, indicating heterogeneous forest cover from degraded forest to dense canopy cover at those survey sites. On the other hand, the standard deviations in Area B are much smaller, indicating more homogenous forest cover at those survey sites.

Figure 6. Temporal changes in (upper) NDVI and (lower) NBR values derived at the survey sites. In the graphs, thin grey lines are NDVI and NBR values at individual sites; the thick black lines are mean NDVI and NBR values for all three areas with one standard deviation in error bar. The mean NDVI and NBR values for Area A, B and C are shown in green, blue and red lines, respectively. NDVI is calculated as $\text{NDVI} = (R_{\text{nir}} - R_{\text{red}})/(R_{\text{nir}} + R_{\text{red}})$, and NBR as $\text{NBR} = (R_{\text{nir}} - R_{\text{swir}})/(R_{\text{nir}} + R_{\text{swir}})$, where $R_{\text{nir}}$, $R_{\text{red}}$ and $R_{\text{swir}}$ are surface reflectance in near-infrared (Landsat-8 band 5), red (Landsat-8 band 4) and shortwave-infrared (Landsat-8 band 7).
3.3.2. Changes in Forest Cover at the Specific Sites

We now examine the changes in NDVI values at the sites showing considerable increase or decline of the mother trees (see Section 3.2.2). Sites 4 and 5 in Area A have shown a quite significant decline in the number of mother trees by 52 and 66 plants, respectively (Figure 3b). At these sites, the NDVI values are higher (~0.8) than the overall means and show only a slight increase between 2015 and 2019 (Figure 7). This indicates that the canopy cover at those sites is relatively dense with no significant alteration during the study period. In fact, these NDVI values from these two sites are higher than the means for Area A (Figure 5), indicating a denser canopy cover at these sites, which can be seen in NDVI map shown in Figure 8. Site 4 is close to degraded forest (yellow), yet the canopy cover at the site or surrounding area is not severely degraded (see close-up high-resolution satellite imagery in Figure 8). This indicates that the decline of mother trees at this site does not relate to land use change or alteration of forest, but rather potentially community management practice of wild coffee or other factors.

![Figure 7](image7.png)

**Figure 7.** Temporal changes in NDVI values at the sites showing significant changes in the number of mother trees from in situ survey data. NDVI is calculated as $\text{NDVI} = \frac{(R_{\text{nir}} - R_{\text{red}})}{(R_{\text{nir}} + R_{\text{red}})}$, and NBR as $\text{NBR} = \frac{(R_{\text{nir}} - R_{\text{swir}})}{(R_{\text{nir}} + R_{\text{swir}})}$, where $R_{\text{nir}}$, $R_{\text{red}}$ and $R_{\text{swir}}$ are surface reflectance in near-infrared (Landsat-8 band 5), red (Landsat-8 band 4) and shortwave-infrared (Landsat-8 band 7).

![Figure 8](image8.png)

**Figure 8.** Cont.
Figure 8. Close-up high-resolution satellite imagery and Landsat-8 derived NDVI maps at the sites showing significant loss of mother trees in 2019. The high-resolution satellite images on the left panel are shown in red-green-blue (RGB) band composite of Pleiades-1B and Worldview-3 acquired in 2015. The legend of the NDVI maps on the right panel is the colour bar of the NDVI values. The yellow dots with the numbers are the wild coffee survey site.

Site 27 was another case that showed the loss of mother trees by 98 in 2019 from 100 stands in 2015 (Figure 5b). At this site, the NDVI values closely follow the overall means with a slight increase between 2015 and 2019 (Figure 7). It is also noteworthy that these values are slightly lower compared to the NDVI means for Area B (Figure 6), indicating slightly thinner canopy cover at this site. The NDVI map shows a large area of low NDVI leading to the site from the settlement (Figure 8), indicating degraded forest cover or coffee forest (Figure 2). In fact, this site, among other sites ranging from 24–28, is located at the edge of coffee forest in Mesgidzuriya got (Figure 2). At those sites, the number of mother trees had either slightly increased (sites 22, 25-26) or somewhat declined (sites 23–24, 28) (Figure 5b), but none showed a sharp decline as found at site 27. At the same time, the NDVI value at site 27 shows no obvious changes, except a slight increase (Figure 7), so such a sharp decline in mother trees at the site is not related to any alteration of forest cover, but rather is likely to be due to other factors.

Site 30 was another site showing a significant loss of mother trees and saplings in 2019 (Figure 5b). Contrary to this considerable loss in wild coffee plants, site 29, which is only 150 m away from site 30, recorded a gain in both mother trees and saplings (Figure 5b). The NDVI values between these two sites also show a contrast. The NDVI values at site 30 are much lower (0.7) than the overall means, and increased to 0.75 in 2019, while the NDVI values at site 29 are consistently higher or at the overall means (Figure 7). During the 2019 survey, it was observed that there had been illegal clearing at
site 30, but no disturbance at site 29. The NDVI map shows that these sites are far away from the settlement, yet the close-up high-resolution satellite image (Worldview-3) taken in 2015 shows an area of disturbance to the west of the sites (Figure 8). This indicates that human encroachment occurred in that area at least from 2015, which may affect the conservation of wild coffee stands in that area, as noted during the 2019 survey.

Sites 12–17 were the cases showing a consistent increase in mother trees and saplings in 2019 (Figure 4). At these sites, the NDVI values are much lower (0.65–0.7) than the overall means (Figure 7). The NDVI map shows that these sites are very close to settlement and within degraded forest (Figure 9) or at the edge of managed coffee forest areas (Figure 2). The close-up high-resolution satellite imagery (Worldview-3) taken in 2015 shows that canopy cover at these sites was significantly reduced (Figure 9). This suggests that the canopy cover had been thinned at these sites at least from 2015 with no significant regeneration by 2019. During the 2019 survey, it was recorded that wild coffee stands were occupied by farmers, indicating the increase of mother trees may be the result of planting of saplings by farmers at the sites, rather than from growth of saplings under natural conditions.

![Worldview-3 (2015.03.03) and NDVI – Landsat-8/OLI (2019.03.03)](image)

**Figure 9.** Close-up high-resolution satellite imagery and Landsat-8 derived NDVI maps at the sites showing significant gain of mother trees in 2019.

4. Discussion

4.1. Overall and Sub-District Changes in Wild Coffee

The results from the survey data show a slight decline in the number of mother trees but a slight increase in the number of saplings between 2015 and 2019, yet both cases are without statistical significance at the 90% level of confidence (Table 3). Part of the reason for this is that in this pilot study, the number of matching data sets were rather small, so it is difficult to draw a more robust conclusion. This suggests that more matching data sets would be required in a future study. Despite this, the findings from this study suggest that overall, the wild coffee stands have remained intact and at least without a major overall decline during the first four years of applying CFM, between 2015 and 2019.

However, there is some variability in the experience which is seen when comparing the three study areas. Wild coffee stands in Area A within Jenjeka and Bonki kebeles have shown a decline but with a large variance (Table 3). The largest decline occurred in Area C, but only two sites were recorded in this area (Table 3). Area B shows an increase in both mother trees and saplings at all sites, with the increase in saplings being statistically significant at the 90% confidence level (Table 3).
4.2. Sites Showing Significant Decline in 2019

Investigation into individual cases showing major decline or increase indicates that the changes in wild coffee plants observed from the surveys cannot be fully matched with changes in forest cover, except in one case (site 30). Hence, the causes of the changes must be sought in other factors, including local management practice or sampling issues. Satellite imagery was used to detect land use change or disturbance in the forest, which allows us to evaluate whether loss or gain of wild coffee plants is related to a large-scale forest alteration or disturbance or local management practice by local community. For example, large-scale land use change can be seen from the low NDVI at site 30 (Figure 7), and the loss of both mother trees and saplings at this site could be related to a large-scale land use change such as illegal clearing and conversion to coffee forest happening in the area. Another factor to consider for site 30 is the difference in survey methods between 2015 and 2019. This site is an area-to-point matching case (Table A1). In 2015, the total number of wild coffee plants was counted for an area of 1376 m², while in 2019 the number of wild coffee plants was counted at three survey points near the area. There is a possibility that wild coffee is distributed across a large area with high spatial variability while the 2019 survey points were collected in places with low wild coffee bushes. In that case, changes may reflect the mismatch in survey methods and sites.

Around site 30, high-resolution satellite imagery also shows the forest canopy density varies greatly within the area (Figure 10). As wild coffee requires a moderate level of canopy shade, this indicates the likely high spatial variability of wild coffee in the area. So, improper selection of the 2019 survey points may cause a mismatch in estimating the changes. Another point to note is that satellite imagery also indicates that the disturbance nearby the site was already evident in 2015 (Figure 8; Figure 10), so such encroachment happened before the start of the CFM period. This suggests that more survey data, both from imagery and focus groups discussions, are needed to understand the severity and extension of such illegal land use change affecting wild coffee in the area and then develop a CFM strategy to reverse this situation in this area.

![Figure 10. Map of (a) site 30 and (b) site 27 shown with high-resolution satellite imagery acquired in 2015.](image)

A decline in mother trees at sites 4 and 5 in Area A (Jenjeka and Bardika kebele) is not associated with either illegal encroachment or changes in forest cover based on satellite imagery analysis. These two sites are at the border between two kebeles, and high-resolution imagery shows that these sites are regularly accessed by farmers from Wozeka Got (see the path leading to the sites from degraded coffee forest areas in Figure 8). It should be noted that these two sites are point-to-point matching cases, meaning there is a direct comparison within 2–5 m difference in GPS location (Figure 4a; Table A1). So unlike site 30 described above, the observed changes are accurate. From the field notes during the
2019 survey, it was suggested by project staff that the sharp decline in mother trees at the sites may be a side effect of the local management practice of transplanting wild coffee stands from natural forest into their managed coffee forest farm nearby, especially as noted in Section 3.3.2, these two sites are regularly visited by the farmers through the path leading to the site. Another consideration is that some communities take the stems of the coffee bush for local house construction or sometimes remove weak coffee plants to encourage strong branched mother trees to grow. In order to verify this fully, it would require further field inquiries on management practice with the communities nearby.

The loss of mother trees at site 27 also shows no clear association with changes in forest cover. This site is located at the edge of degraded coffee forest, but far away from settlement in Gizmeret Kebele (Figure 2). Within a 300 m radius from this site, six other sites were surveyed, and some of those sites show a slight gain, while others show some loss of the mother trees (Figure 5b). However, none of those sites has recorded as sharp a decline as seen at site 27, although a loss of 26 mother trees at site 23 was reported (Figure 5b). Averaging the gain and loss of mother trees at the sites, excluding site 27, shows a slight loss by three mother trees in area B. Site 27 is an area-to-point matching case. In 2015, the total number of wild coffee plants was counted within an area of 34 m² (Figure 10). The sharp decline in mother trees at this site may be related to a mismatch of survey methods between 2015 and 2019.

4.3. Sites Showing Significant Increase in 2019

Consistent gain of mother trees and saplings at sites 12–17 is intriguing and no obvious changes in forest cover were recorded at the sites. These sites are characterized by low canopy cover (NDVI values ~0.65) with managed coffee forest farm nearby (Figure 9). These sites belong to Mehalshimi got, Shimi Kebele (Figure 1), and all the sites were recorded as “wild coffee stands occupied by farmers” (Table A1). This community is known to have experience in developing their own coffee seedlings and does not transplant wild coffee from natural forest.

They manage their coffee in stands which are both wild coffee and managed/planted coffee. From the demarcation created in 2015, many sites are within coffee forest, while some fall into natural forest (Figure 2), so it is questionable whether wild coffee plants at these sites can be all considered as wild coffee in natural forest. If the management practice for wild coffee by people in Shimi has a positive impact on conserving wild coffee stands, then would the same management practice benefit the conservation of wild coffee deeper in the natural forest in Mehalshimi got? Another question relates to the sharp decline in wild coffee at sites 29 and 30 in Usika got (Figure 2). Can this difference be attributed to different communities with different management practices, experience and attitudes toward wild coffee?

4.4. Need for Focus Group Discussions and Policy Implications

The focus group discussions along with the records of the survey team members have helped in several cases to explain some of the factors affecting the observed changes in the numbers of mother trees and coffee saplings. It is clear that different ethnic communities have had different levels of success in maintaining the wild coffee and that skills in forest management vary between communities and this affects the sites they manage. However, many questions remain to be answered. Above all, this survey has helped illuminate the need for future studies to allocate more time and resources to understand and compare community attitudes and management practices, as well as to gather historical knowledge.

Future research could usefully consider the relative value of wild coffee to the communities involved in its protection and seek to identify the key factors that motivate communities to participate in conservation of the wild coffee stands. For instance, in economic terms, is protection of the wild coffee stands linked primarily to the revenue that can be generated through direct sale of the wild coffee? Is it also linked to its value as a “free” source of seedlings that can be transplanted to the more intensively managed forest coffee farms? From a farming perspective, is it linked to its relative
value in terms of yield, longevity, resistance to wild animals and/or to diseases as compared to similar relative value assigned to commercial coffee varieties that are sold to coffee farmers in Ethiopia? Is its protection linked to an awareness of its genetic (and by extension economic) value, both now and in the future? Alternatively, is there a perceived and real contractual element to its conservation? For instance, is its protection understood in terms of the CFM agreements and community rights to the other forest resources including dead wood, spices and honey? Or is any conditionality viewed more broadly, for instance being linked to a sense of freedom of movement within the forests, for social, cultural or economic reasons other than the harvesting of forest products?

While the specific experiences by site do need further investigation, there are policy lessons already appearing from this study. These show that CFM should be considered for further use in in situ conservation of wild coffee in this part of Ethiopia, and more widely for other specific forest species which are threatened. While biosphere reserves are often seen to be the gold standard in biodiversity protection, there can be challenges with the resources they need for long-term sustainability. CFM may offer an alternative and more sustainable approach with lower costs through community engagement in the management of all the forest, including the wild coffee stands.

5. Conclusions

In conclusion, this study has shown that despite the difficult conditions for surveying in the natural forest, it is possible to monitor changes in the wild coffee population in that forest through repeated ground surveys which map the number of wild coffee plants (i.e., saplings and mother trees), at selected sites. Changes in the number of those plants can be related to alterations in the forest canopy using high-resolution satellite images, and this can sometimes help to explain the changes in the coffee plant populations when major land use changes have occurred. However, the use of ground surveys and remote sensing alone is not able to fully explain the reasons for the changes observed. Field discussions have helped identify some of the other influences on the changing number and distribution of wild coffee trees which have been identified, but over all this predominantly mapping study has raised many questions for which more in-depth discussions with the Forest Management Groups and communities using these areas are needed.

Despite these limitations, this mapping study has shown that, overall, there has been no statistically significant change in the population of wild coffee mother trees across the three study areas combined between 2015 and 2019, while a small but statistically significant increase has been seen in the population of wild coffee saplings. A finer-grain analysis shows many different patterns of increase or loss of coffee plants of different age across the three areas which need further investigation with the local communities and users of these forests as there could be many factors affecting these patterns. Such a combination of mapping and intensive social survey approaches is needed to monitor the wild coffee population and assess the impact of the CFM approach in conserving this resource of national and global significance. Our findings from this study suggest that different policy and management approaches are being applied by the different ethnic communities, rather than a uniform approach across the communities.

To the best of the authors’ knowledge, this is the first attempt to measure wild coffee plants in Bench Sheko Zone and as such makes an important contribution to understanding of this significant genetic resource and the attempts to support its long-term survival and evolution. Future work can build on the clue provided by this study that the experience and management practices of the communities and their attitudes toward the value of wild coffee and the forest may make a significant contribution to the in situ conservation of wild coffee and the success of the CFM arrangements for protecting wild coffee.

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A.W., M.S., D.F., E.B., B.M.; visualization, B.H., A.W.; supervision, B.H., A.W., M.S.; project administration, B.H., A.W., M.S.; funding acquisition, B.H., A.W., M.S. All authors have read and agreed to the published version of the manuscript.

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**Appendix A**

More details of the matching data set are described in Table A1. This includes study area, kebele and got of the sites, changes in mother trees and saplings, the description of the site and information on how the site was matched between 2015 and 2019.

**Table A1.** Summary of survey data from 2015 and 2019. In “difference in coffee plants between 2019 and 2015”, a positive number indicates an increase in number of plants and the numbers in parentheses are the number of plants found in 2015. Site description contains description from the 2019 survey on disturbance, forest condition, accessibility and signs of age or disease of wild coffee plants, as well as the number of seedlings observed during the 2015 survey. Site matching contains information on how the specific site matched between 2015 and 2019, i.e., point-to-point means the site was surveyed at a point both in 2015 and 2019 and the number in parentheses is the difference of reference points in distance between 2015 and 2019; area-to-point means the survey was conducted in an area in 2015 but at a point in 2019 (see text for the details).

| Site | Area | Kebele/Got | Difference in Coffee Plants between 2019 and 2015 (Number in 2015) | Site Description from 2019 Survey | Site Matching between 2015 and 2019 |
|------|------|------------|---------------------------------------------------------------|-----------------------------------|-----------------------------------|
| 1    |      |            | mother trees: +12 (4) saplings: −3 (8)                        | Small number of seedlings; steep slope with many seedlings, no record on seedlings in 2015 | Point-to-point (8 m)               |
| 2    |      | Jenjeka/Jenjeka | mother trees: +9 (5) saplings: −3 (15) | Good proportion of seedling, sapling and mother trees; no record on seedlings in 2015 | Point-to-point (8 m)               |
| 3    |      |            | mother trees: −1 (6) saplings: +3 (4)                        | Less coffee stands, 58 seedlings found in 2015 | Point-to-point (6 m)               |
| 4    |      | Bardiks/Wezeka | mother trees: −52 (78) saplings: −6 (21) | Easier accessibility but no apparent encroachment; dispersed and small number of shade trees; 54 seedlings found in 2015 | Point-to-point (2 m)               |
| 5    | A    |            | mother trees: −66 (131) saplings: +20 (45) | Coffee harvesting area; no apparent encroachment; 180 seedlings found in 2015 | Point-to-point (5 m)               |
| 6    |      |            | mother trees: −4 (8) saplings: 0 (1)                        | Dense canopy cover; some coffee trees died due to age; no seedlings found in 2015 | Area-to-point                     |
| 7    |      | Bonki/Mehal bonki | mother trees: −13 (17) saplings: −27 (33) | Dominated by mother trees; only 4 seedlings observed in 2015; 4 seedlings found in 2015 | Area-to-point                     |
| 8    |      |            | mother trees: 10 (0) saplings: −10 (10)                      | Steep slope; dominated by old mother trees; 2 seedlings found in 2015 | Point-to-point (12 m)             |
| 9    |      |            | mother trees: −8 (21) saplings: +2 (8)                      | Steep slope; some dead coffee trees observed; 8 seedlings found in 2015 | Area-to-point                     |
Table A1. Cont.

| Site | Area | Kebele/Got | Difference in Coffee Plants between 2019 and 2015 (Number in 2015) | Site Description from 2019 Survey | Site Matching between 2015 and 2019 |
|------|------|------------|---------------------------------------------------------------|----------------------------------|-----------------------------------|
| 10   |      | Bonki/Bench| mother trees: +16 (13) saplings: −18 (23)                    | Adjacent to farmer coffee; valuable to encroacher; illegal encroacher regularly monitored by forest management group; dense forest with climber; a few seedlings found in 2015 | Area-to-point                     |
| 11   |      |            | mother trees: +33 (3) saplings: +15 (1)                     | Adjacent to farmer coffee; likely managed coffee area; illegal encroacher regularly monitored by forest management group; closed undergrowth but with open canopy | Area-to-point                     |
| 12   |      |            | mother trees: +32 (3) saplings: +32 (3)                     | Half of coffee stands occupied by farmer; medium slope; some aged coffee trees; 4 seedlings found in 2015 | Point-to-point (9 m)               |
| 13   |      |            | mother trees: +20 (3) saplings: +13 (3)                     | Coffee stands occupied by farmer; medium slope; 1 seedling found in 2015 | Point-to-point (5 m)               |
| 14   |      | Shimi/Mehal Shimi | mother trees: +25 (8) saplings: +2 (2) | Coffee stands occupied by farmer; medium slope with open canopy cover; high deforestation and clearance of natural forest by farmer occurred for a long time for coffee plantation; 4 seedlings found in 2015 | Area-to-point                     |
| 15   |      |            | mother trees: +11 (26) saplings: −4 (8)                    | Coffee trees occupied by farmer; gentle slope; 10 seedlings found in 2015 | Both points (2 m)                  |
| 16   | B    |            | mother trees: +41 (10) saplings: +7 (8)                    | Coffee trees occupied by farmer; high disturbance; 12 seedlings found in 2015 | Point-to-point (2 m)               |
| 17   |      |            | mother trees: +17 (14) saplings: +6 (4)                    | Coffee trees occupied by farmer; gentle slope with open canopy cover; aged coffee trees; 10 seedlings found in 2015 | Point-to-point (5 m)               |
| 18   |      |            | mother trees: +17 (4) saplings: +33 (0)                    | Dense forest; wild coffee harvest area; danger from illegal collector encroachment; a few seedlings found in 2015 | Area-to-point                     |
| 19   |      | Gizemret/Brihanber | mother trees: +2 (30) saplings: +86 (0) | Wild coffee harvest area; danger to illegal collector and encroachment; large number of seedlings; a few seedlings found in 2015 | Area-to-point                     |
| 20   |      |            | mother trees: −14 (15) saplings: +3 (0)                    | Small number of mother trees; no record on seedlings in 2015 | Point-to-point (25 m)              |
| 21   |      |            | mother trees: −1 (4) saplings: 0 (0)                      | Dense forest; steep slope; dispersed coffee stands; no record on seedlings in 2015 | Point-to-point (27 m)              |
| 22   |      |            | mother trees: +2 (6) saplings: +4 (0)                     | Steep slope; dispersed coffee stands; no sign of coffee disease; no record on seedlings in 2015 | Point-to-point (7 m)               |
Table A1. Cont.

| Site | Area | Kebele/Got | Difference in Coffee Plants between 2019 and 2015 (Number in 2015) | Site Description from 2019 Survey | Site Matching between 2015 and 2019 |
|------|------|------------|-------------------------------------------------|---------------------------------|-----------------------------------|
| 23   |     |            | mother trees: −26 (38)  saplings: −19 (25)    | Undisturbed forest; far from farmer coffee; gentle slope with less undergrowth; a few seedlings found in 2015 | Area-to-point                      |
| 24   |     | Gizmeret/ Meskidzuria | mother trees: 0 (10)  saplings: +6 (1)           | Dense forest with good canopy cover; gentle slope; undisturbed dense forest; far from farmer coffee; a few seedlings found in 2015 | Area-to-point                      |
| 25   |     |            | mother trees: +3 (15)  saplings: −11 (15)      | Open canopy; gentle slope; a few seedlings found in 2015 | Area-to-point                      |
| 26   |     |            | mother trees: +8 (3)  saplings: +2 (2)          | Dense forest; well conserved forest; dispersed wild coffee stands; far from farmer coffee; a few seedlings found in 2015 | Area-to-point                      |
| 27   |     |            | mother trees: −98 (100)  saplings: −14 (20)     | Aged mother trees with climbers; gentle slope with spices nearby; a few seedlings found in 2015 | Area-to-point                      |
| 28   |     |            | Mother trees: −5 (20) Increase of +14 (0)      | Open canopy cover; gentle slope; a few seedlings found in 2015 | Area-to-point                      |
| 29   | C   | Shimi/Usika, Mehal Shimi | mother trees: +33 (25)  saplings: +50 (25)    | Dense forest; gentle slope; far from community; no disturbance recorded but illegal conversion to managed coffee forest observed nearby areas; 50 seedlings found in 2015 | Point-to-point (12 m)             |
| 30   |     |            | mother trees: −60 (61)  saplings: −22 (22)     | Illegal clearing during political instability; easy accessibility with gentle slope; near private coffee; wild coffee harvesting area; 30 seedlings found in 2015 | Area-to-point                      |

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