Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-021-17605-0

RESEARCH ARTICLE

Characterization and mapping of enset-based home-garden agroforestry for sustainable landscape management of the Gurage socioecological landscape in Ethiopia

Mesfin Sahle[1,2] · **Osamu Saito**[3] · **Sebsebe Demissew**[4]

Received: 8 April 2021 / Accepted: 14 November 2021

Abstract

Developing strategies that counter the ongoing homogenization trends of home-garden agroforestry systems is required to maintain diversity and sustainability. This study aimed to map and characterize traditional enset-based home-garden agroforestry for managing sustainability in the Gurage socioecological landscape in Ethiopia. We generated plots and land use land cover (LULC) spatial data from orthophotomosaic and collected household survey data of the field. Five home-garden types were identified explicitly through integrating the home-garden composition, functional structure, and agroecological zones. Most home-garden types had similar horizontal functional structures in which perennial crops were planted close to homesteads, annual crops grew in outer fields, and woodlots were located at the end of the parcel. Diverse woody species, crop varieties, and plot sizes were identified in individual household parcels, and these varied across the home-garden types. Enset-based home-garden agroforestry production has been declining in the Ethiopian landscape because of socioeconomic changes and a lack of technological inputs. These challenges may compromise the community's food security with loss of the product diversity provided by the home-garden system. Thus, technological adoptions and scaling up of agroforestry practices according to the home-garden types are necessary for the continue provision of multiple contributions. This study demonstrated site-specific spatial characterization of the agroforestry systems by considering a holistic approach to reduce the local challenges and support the development of sustainable landscape management in an altering socioecological landscape.

Keywords Home-garden structure · Spatial explicit · Enset plant · Agrobiodiversity · Home-garden types · Scaling up

Introduction

Home-garden agroforestry is a recognized land use system that supports human well-being on small plots of land while enabling an ecologically sustainable landscape worldwide (Abbas et al. 2017; Shin et al. 2020; van Noordwijk et al. 2020). The composition, structure, and functions of home-garden agroforestry are diverse (Gbedomon et al. 2017). They vary according to their design, objectives, selected species, cultural practices, and ecological regions (Muschler 2016). The most common home garden includes annual and perennial crops under a shade cover along with multistrata systems such as successional agroforests, silvopasture, live fences, and windbreaks (Feliciano et al. 2018). The survival of the home-garden agroforestry system depends on the economic, social, and political conditions of the countries where the home garden is located (Galhena et al. 2013).

Agroforestry has the transformative potential to reduce rural poverty, regenerate food systems, restore degraded

Responsible Editor: Philippe Garrigues

✉ Mesfin Sahle
achemo@unu.edu

Osamu Saito
o-saito@iges.or.jp

Sebsebe Demissew
sebseb.demissew@gmail.com

1 United Nations University Institute for the Advanced Study of Sustainability, Tokyo, Japan

2 Department of Natural Resources Management, Wolkite University, Wolkite, Ethiopia

3 Institute for Global Environmental Strategies, Kanagawa, Japan

4 Department of Plant Biology & Biodiversity Management, College of Natural Sciences, Addis Ababa University, Addis Ababa, Ethiopia

Published online: 26 November 2021

lands, overcome water scarcity, foster climate change mitigation and adaptation, and contribute to biodiversity conservation (IPES-Food 2016; Borelli et al. 2017; Minang et al. 2018; IPBES 2019). Despite these advantages, recent trends indicate that the agroforestry systems are disappearing (Rolo et al. 2020). Large traditional, diverse, and ecologically sustainable home gardens are gradually changing into monospecific agricultural systems with uncertain levels of sustainability (Guillerme et al. 2020). The maintenance of species-rich, multistrata agroforests is important because of their material, nonmaterial, and regulating contributions to biodiversity and sustainability (Rendón-Sandoval et al. 2020). To sustain the positive contributions of traditional home gardens, it is necessary to develop strategies that address the ongoing homogenization trend (Plieninger et al. 2020).

Landscape characterization approaches can generate distinct features and values in the current environment (Warnock and Griffiths 2020). Information on the setting and characteristics of landscapes is critical for understanding and seeking solutions for landscape sustainability. These methods of landscape characterization will inevitably aid in a unified communication between management and research (Simensen et al. 2018). Integrating agroforestry as a central role in landscape characterization can help overcome the lack of adoption and maintenance that plagues many agroforestry practices and systems (Buck et al. 2020). This approach would help in comparing the economic, ecological, and sociocultural significance of home-garden agroforestry and drive local landscape-level solutions for its sustainability (Mohri et al. 2013; Plieninger et al. 2020; Shin et al. 2020).

To better understand the home-garden systems as an alternative development path in changing land usage, it is necessary to study the characteristics and trends of home gardens in detail (Galhena et al. 2013; Plieninger et al. 2020). Because of the worldwide diversity of traditional home gardens, it is important to properly understand the different home garden systems. Many studies outline the basic characteristics of home-garden agroforestry in terms of species diversity, size, structure, and socioeconomic factors using cluster analysis (Abebe et al. 2006; Gbedomon et al. 2015). However, the spatial characteristics together with the composition, agrobiodiversity, and management of the home-garden system are not explored well (Shin et al. 2020). Nevertheless, our proposed approach offers a good opportunity for obtaining a systematic insight into different types of home gardens for sustainable landscape management.

Traditionally, the home-garden system in Ethiopia is known as the enset-coffee home-garden system, characterized by the combination of two perennial crops: enset and coffee (Abebe et al. 2013). Enset, also known as "false banana," is an herbaceous perennial crop and a staple/co-staple food for a population of 20 million (Borrell et al. 2019). In many parts of Ethiopia, there is a remarkable experience of traditional agroforestry practices mainly with parkland agroforestry practice on cultivated land, for example, in Minjar Shenkora districts. Despite being grouped together under the umbrella term "home gardens," the home-garden system is characterized by a huge diversity of farms and farming systems. Within the southern regions, two types of home-garden structures can be observed. For example, in the Gedeo agroforestry system, perennial crops are combined with woody trees and cereal crops in a vertical structure design (Negash et al. 2012), whereas, in south–central Ethiopia, perennial crops such as enset are grown in the home garden while annual food crops are grown in outer fields (Mellisse et al. 2018). Recognizing this variability within and among the farming systems and localities is the first step in designing new technologies to improve agricultural production (Descheemaeker et al. 2016).

Farm trajectories revealed a shift from the food-oriented enset-based and enset–livestock systems to cash–crop-oriented khat-based systems as well as a combined food and cash–crop-oriented enset–cereal–vegetable systems (Mellisse et al. 2018). The Gurage socioecological production landscape in Ethiopia is characterized by a mosaic of different land cover types such as forests, home-garden agroforests, cereal crops, grasslands, woodlots, wetlands, surface water, roads, and human settlements (Sahle and Saito 2021a). The Gurage communities live in elongated village settlements with their own parcel of land. The landscape is one of the regions where the enset-based home-garden agroforestry system has been established extensively. However, detailed studies are unavailable to formulate sustainable landscape management strategies according to the home-garden type. To understand and identify the constraints and seek sustainable landscape development options for the improvement of the home-garden agroforestry systems, detailed information on the spatial structure, composition, agrobiodiversity, and trends is required. Therefore, this study aimed to characterize the home-garden agroforestry system comprehensively for sustainable landscape management in the Gurage socioecological landscape in Ethiopia. This study demonstrated the diversity of home gardens in a spatially explicit manner by integrating the functional structure of the home gardens, agroecological zones (AEZs), and land use land cover (LULC) information for sustainable management of an important ecosystem. Limited attention has been paid to the spatial differences within specific locations in home-garden agroforestry studies. Our study will contribute to this regard and support the development of specific strategies for each garden type.

Materials and methods

Study area

The Gurage people inhabit a mountainous landscape in south–central Ethiopia, 155 km from Addis Ababa (the capital) (Fig. 1). The Gurage socioecological production area is bordered by the Awash River Basin toward the north, the Gibe River (a tributary of the Omo River) Basin toward the southwest, the Rift Valley Basin toward the east, and the Bilate River catchment toward the south (Sahle et al. 2019). The topography of the region is separated into three categories. The mountainous highland is represented by the Gurage Mountain chains that divide the landscape from east to west, with highest peak at 3605 m above sea level (a.s.l). Much of the central region is formed by plateau flatlands, with elevations ranging from 1500 to 3000 m a.s.l. The lowest area, the western fringes of the Wabe–Gibe valley, has an elevation from 968 to 1500 m a.s.l. The elevation differences cause diverse climatic conditions with warm, humid, and cold conditions in different parts of the landscape. The agroecological pattern follows the rainfall distribution, which ranges from 700 to 1600 mm annually.

The Gurage zone covers 5932 km^2 with 13 woredas (districts) (Fig. 1). Based on the 2007 census conducted by the Central Statistical Agency (CSA) of Ethiopia, the Gurage zone had a total population of 1,279,646 (51.4% women) (CSA 2009). An overwhelming majority of the population, 92.4%, lived in rural areas and led a subsistence-based life. In long Jefoure roads, they are wide grass-covered streets run through the middle of Gurage villages (Sahle and Saito 2021b). Houses and trees flank these roads on both sides. In the backyards, often enset crop is grown with other perennial and annual crops. Enset is a keystone species in the landscape, giving rise to the label "enset-based home garden agroforestry." The landscape communities adopted an enset-based home-garden agroforestry production system, similar to other regions in south and southwestern Ethiopia. They produce abundant enset, making it an indigenous staple/costaple crop. Enset-based home-garden agroforestry exists on both sides of the Gurage Mountain chains. This study focuses on the western Gurage, where enset is grown in the home garden and annual food crops are grown in the outer fields.

Methods

To characterize the enset-based home-garden agroforestry system, we classified the LULC of the landscape using orthophotomosaic and conducted household surveys and

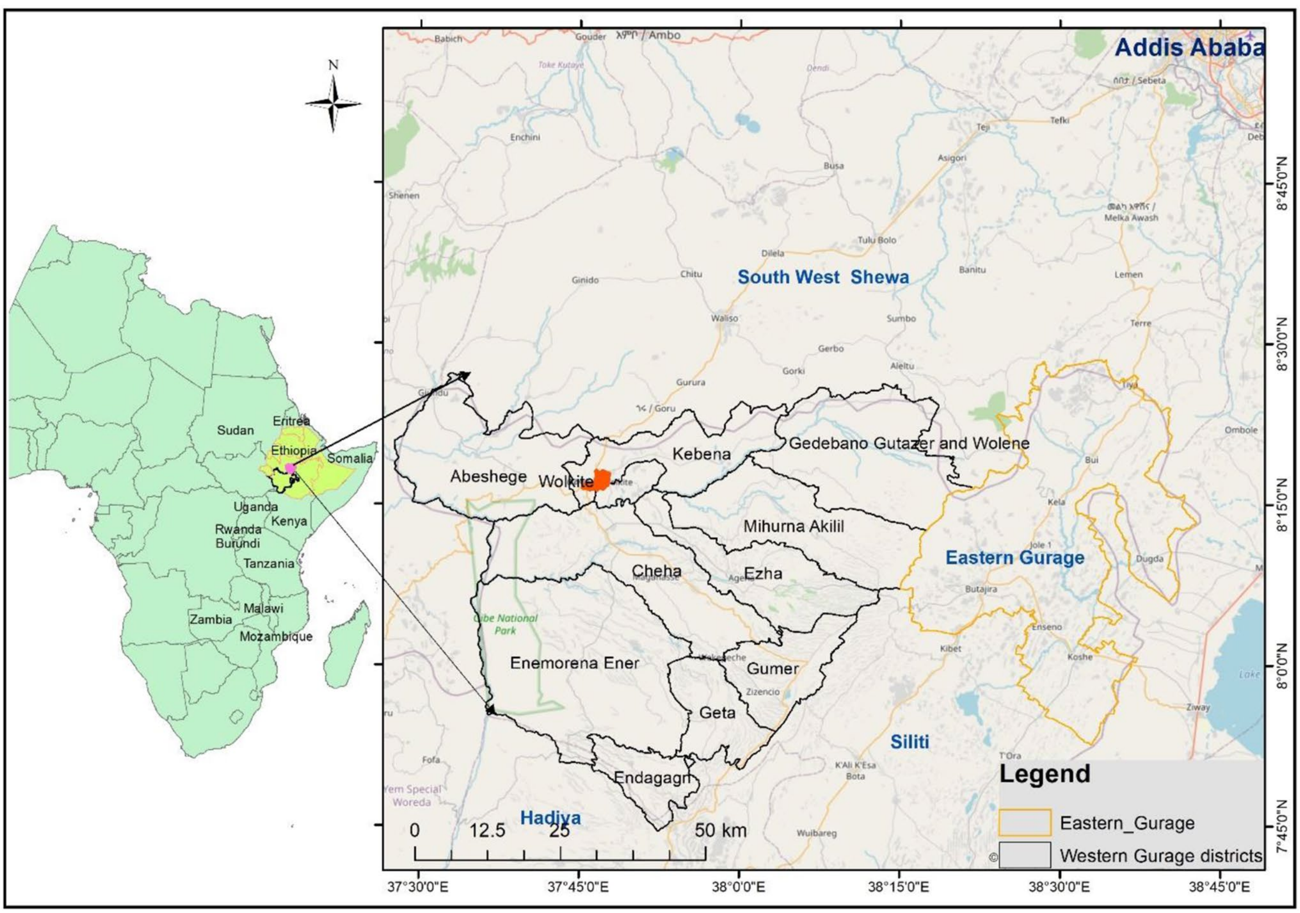

Fig. 1 Map of Ethiopia's western Gurage socioecological production landscape

focus group discussions (FGDs). The following subsections outline how the data was collected and analyzed to achieve each specific objective.

LULC assessment in the Gurage socioecological landscape

In this study, we used orthophotomosaic, which had a 0.15-m spatial resolution with a natural color combination, obtained from the Ministry of Agriculture and Natural Resources Management, Ethiopia. The orthophotos were captured and orthorectified for land administration and certification purposes in 2017 (EMA 2017). Geometric and radiometric corrections were made to the orthophotos before we received them, and no further preprocessing was required. However, the orthophotos contained many scenes, and mosaicking was conducted according to our requirements. The orthophotos had a high spatial resolution, and it was challenging to process them using the available computers. To make this easier, we aggregated the spatial resolution to 1 m using the export tool in ArcGIS 10.7 (ESRI, Redlands, CA), which did not affect our results.

We first considered a mixed image classification approach to identify the LULC in the Gurage socioecological landscape. We tested various feature extraction techniques such as supervised, unsupervised, and object-oriented classification, including machine learning in pilot sites, using ArcGIS 10.7. However, we could not generate reliable data in any of the approaches. The supervised classification in ERDAS Imagine 2014 software (Hexagon AB) generated an accurate output. However, some spatial features were confusing, such as the enset-based agroforestry with eucalyptus plantations, pasture with cereal crops, and degraded lands with built-up lands and lakes. To reduce these effects, we extracted the proximate coverage area of all enset-based home-garden agroforestry through visual interpretation using ArcGIS, with the aid of field observations and a prior understanding of the landscape. The digitized polygons helped us to distinguish enset home gardens from eucalyptus plantations and other vegetation covers via supervised classification. Similarly, other land uses (such as wrongly classified cereal crops, lakes, degraded lands, and built-up lands, which were only found in specific locations) were extracted through manual digitization. The study area was divided into five regions to process the orthophotomosaic efficiently using the available computers. This landscape division allowed us to reduce the spectral value similarity between different land uses because of AEZs.

After several trials, orthophotomosaic were classified using several spectral signature values for each class using the maximum likelihood method. The final raster data obtained from supervised classifications were converted into vector polygons for further analysis using ArcGIS. The polygon features extracted through visual interpretations of the orthophotomosaic helped us to mask the wrongly classified LULC. After reclassifying the masked shapefiles to the correct LULC, they were merged with the master classified land uses. The ten LULC identified in this study were degraded land, grazing land/pasture, cereal crops, forest, woodland, built-up land, eucalyptus plantations, lakes, afroalpine vegetation, and enset-based home-garden agroforestry (Supplemental Material 1). We attempted to separate the enset crop from other home-garden crops, but collecting reliable spatially explicit data from the spectral values of orthophotomosaic was challenging. Therefore, we combined all the perennial crops associated with enset in this study as enset-based agroforestry.

An accuracy assessment was performed to check the validity of the classified orthophotomosaic. The corresponding reference class for each LULC type was collected using global positioning system (GPS) during field visits and visual interpretation of the raw orthophotomosaic with prior knowledge of the study area. In total, 440 reference points were used for the assessment, which were proportional to the areal size of each LULC. The overall accuracy of the classification was 90.9%.

Characteristics of enset-based home-garden agroforestry We characterized the enset-based home-garden agroforestry system by analyzing the composition, structure, agrobiodiversity, and type of home garden. Primary data were gathered from household surveys, FGDs, and geospatial data analysis. We conducted 130 household surveys during February and March 2020. Stratified and systematic sampling methods were used to identify and interview households in the landscape. First, based on prior knowledge and consultation with the zonal offices of the Ministry of Agriculture and Tourism and Culture, we stratified the landscape based on AEZs, districts, settlement histories, home-garden types, and accessibility. Thirteen sites/villages were selected to represent the various configurations of home-garden agroforestry in the Gurage landscape (Fig. 2 and Supplementary Material 2).

In each village, 10 households were systematically identified. Two surveyors started the interviews at the beginning of the Jefoure road in each village. The first surveyor randomly selected one household among the nearest homesteads. The second surveyor began interviewing in the 11th homesteads on the opposite side of the road. The interviews were conducted face-to-face based on a structured questionnaire. After finishing the first interview, they moved 20 households down on each side of the Jefoure road to conduct the second interview.

The household surveys were conducted in a group manner to avoid bias in interview selection. One author supervised the surveys and provided training about their administration at the beginning of the interview process. The surveyors had

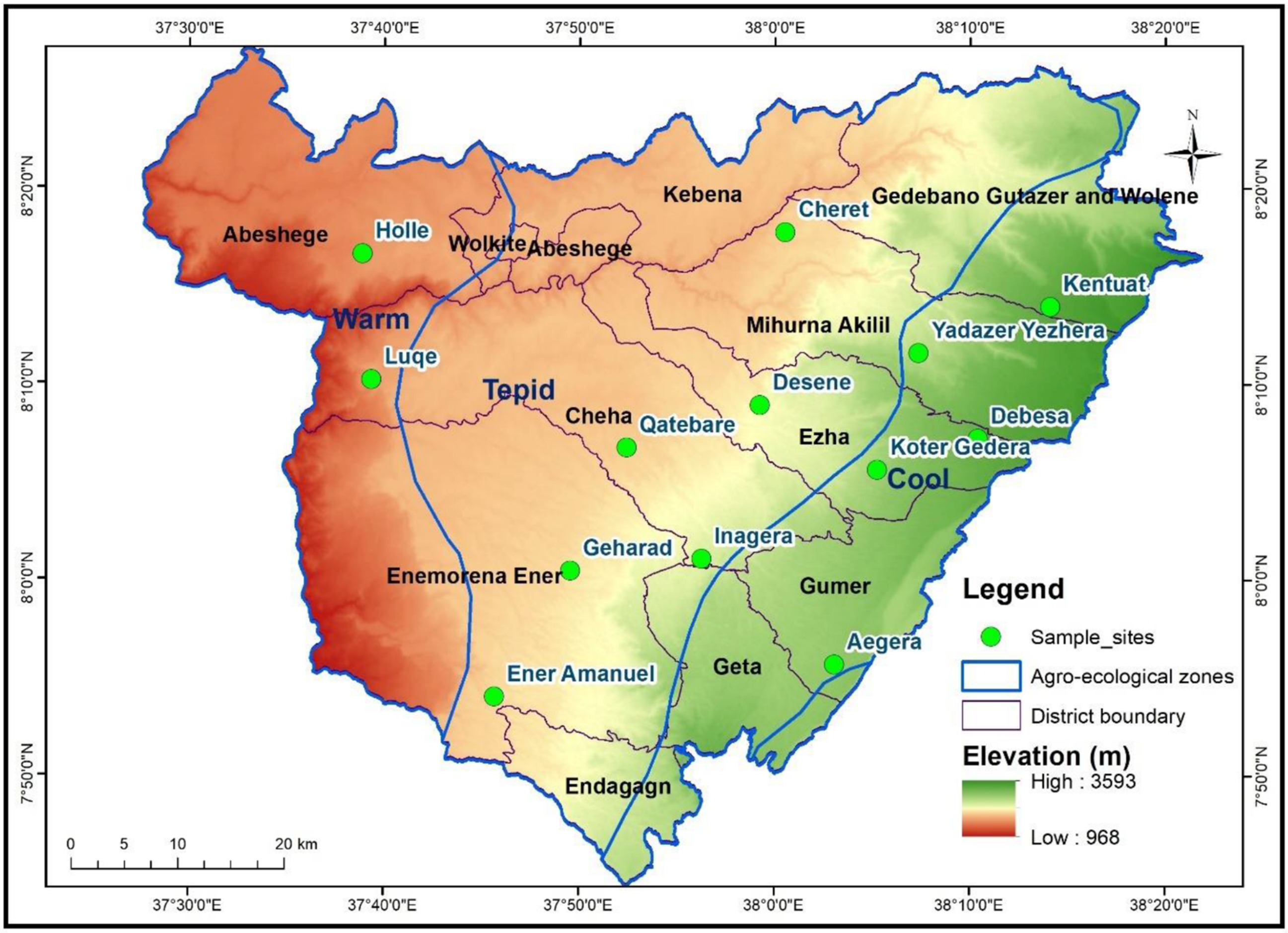

Fig. 2 Sample villages used for the collection of survey data

prior experience in working with households and spoke the local languages. In this manner, five household interviews on each side of the road in a village were conducted. After finishing the first site, they moved to the next village.

A large number of questions were included in the questionnaire to explore the overall characteristics of the homegarden agroforestry system in the landscape. The questionnaire began with general information on the household profile and then on land acquisition and village history (Table 1). The main questions began with the availability of gardens in each plot belonging to the household. The questionnaire included the information on the fencing system, compound size, number and type of housing, enset crop size, vegetable availability, khat coverage, coffee and fruit availability, grazing plot size, cereal crop type, livestock number and type, and woodlot size and species composition according to AEZs. Each of the interviewed households was asked questions regarding the location, type/variety, size, production, use, consumption, selling, challenges, and future solutions. The surveyors prompted the householders to answer each question according to their understanding level and noted down their answers on the hard copy of the questionnaire; interviews were recorded as well.

We conducted 13 FGDs, one in each village with five to nine participants, for a total of 98 participants. The heterogeneity of individuals was considered during the participant

Table 1 Sample household characteristics in the study landscape ($N=130$)

Household attributes	Value
Interview gender (male, %)	58
Average household age (years)	48
Education (Illiterate, %)	47
Household occupation (farming, %)	100
Mean household size (number)	5.5
Religion of respondent (Christian/Muslim, %)	60/40
Land source (acquired through inheritance, %)	80
Mean landholding size (ha)	1.1
Village establishment (after 1960s, %)	31
Landholding size (decrease after land reform in the 1970s, %)	24

selection for FGDs. The FGD participants were selected based on age, gender, life experiences, knowledge, and community role (see Supplementary Material 3). The FGDs were conducted to get an overview of the land use system, examine the differences in home gardens, identify perceived changes and challenges, and discuss possible solutions for the home-garden system's sustainability.

The location of each surveyed household was recorded using a handheld Garmin GPS on the field. In each household land parcel, the typical plots, such as those for growing enset, khat, coffee, fruit, cabbages, potatoes, and cereal crops as well as woodlots and grazing land, were extracted from the orthophotomosaic with reference to the interview records. These recorded locations and SRTM DEM were overlaid on the orthophotomosaic to generate additional spatial information about the household. Although various garden area estimation questions were included in the interviews, the estimation was not expected to be accurate. Therefore, we substituted the rough estimate of garden area by the household with the accurate geospatial quantification. In addition, spatial data showing each household parcel of land were obtained from the woredas land administration offices. The boundary data were overlaid on the orthophotomosaic to ensure accurate extraction of spatial features from the sampled household plots of land.

The type and spatial composition of the landscape home-garden system were obtained from the household survey and the spatial features-extracted orthophotomosaic. From the data, descriptive analysis was performed using SPSS 20 software. These data helped us to determine the average area composition of each plot, the number of sample households involved in growing various crops, and the proportional use of each household's land parcel. We described the home-garden structure qualitatively and quantitatively, starting from the front fence to the far end of a given parcel of land.

The home-garden agroforestry systems include diverse plant species and a variety of crops. Based on the household survey data, we identified several species/varieties of plants/crops, such as enset, fruit, vegetables, woodlots, spices, medicinal plants, cereal crops, and livestock. The agrobiodiversity of the home garden in the landscape was described qualitatively through narratives and quantitatively using descriptive statistics.

Enset-based home-garden agroforestry in the Gurage socioecological landscape is not the same in every household's parcel of land. To identify different home-garden types, first, we considered the household crop composition. We listed all the home-garden crops, and based on specific codes for the collected household data, we assigned a value of one for their presence and zero for their absence. Hierarchical cluster analysis in SPSS 20 was used for grouping the home-gardens. The top five clusters/groups created with clear boundaries were considered as the potential number of classes for home garden types. Then, we regrouped the sample household's data according to their clusters.

The data regarding perennial crops such as enset, khat, coffee, and fruit and annual crops including cereals and vegetables were gathered from the household surveys. The plot size was estimated from the extracted spatial features. The most frequently obtained crops were used to name the home-garden type. The landscape LULC, home-garden composition, agrobiodiversity, and plot sizes were reclassified as per the home-garden types.

The spatial zoning of home-garden types was conducted by integrating the sampled household home-garden composition, the landscape AEZ spatial data, and the substantial crops visually interpreted from the orthophotomosaic. Using these aids, we created home-garden type zones and used them as proximate explicit spatial data.

Results

State of LULC in the Gurage socioecological landscape

The Gurage socioecological landscape reflects a mixed farming system. As a result, the LULC of the landscape includes forests, woodlands, eucalyptus plantations, afroalpine vegetation, home-garden agroforestry, cereal cropping, and open-grazing lands (Fig. 3). In 2017, the built-up environment covered ~ 0.4% of the landscape, and the remaining landscape was either covered with vegetation or used for various land use practices. The natural forest, which included riverine environments and dry Afromontane Forest, covered 32,152 ha (7.4%). The dry Afromontane forests were found in conservation areas, scattered patches remaining in communal land, and sacred forests, including the traditional beliefs and the Ethiopian Orthodox Tewahedo Church forests. The LULC analysis showed that only 0.7% of the landscape was covered with afroalpine vegetation, which remained in the mountain areas that were too high for agricultural expansion. Eucalyptus plantations existed as woodlots in household plots and covered 39,294 ha (9.1%). The woodland area, which was primarily found in the lower elevations of the landscape, covered 20,906 ha (4.8%). The woodland areas were mainly found in the Gibe Sheleko National Park.

Enset-based agroforestry covered ~ 10.2% of the landscape. The home gardens in the Gurage socioecological landscape had a horizontal structure. Enset is a dominant crop either as the only perennial plant or integrated with other crops, such as khat, coffee, fruit, cabbages, potatoes, and cereal crops, according to the growing potential of the AEZ. Large portions of the landscape (64.1%) are utilized for cereal crop cultivation and livestock grazing. As these

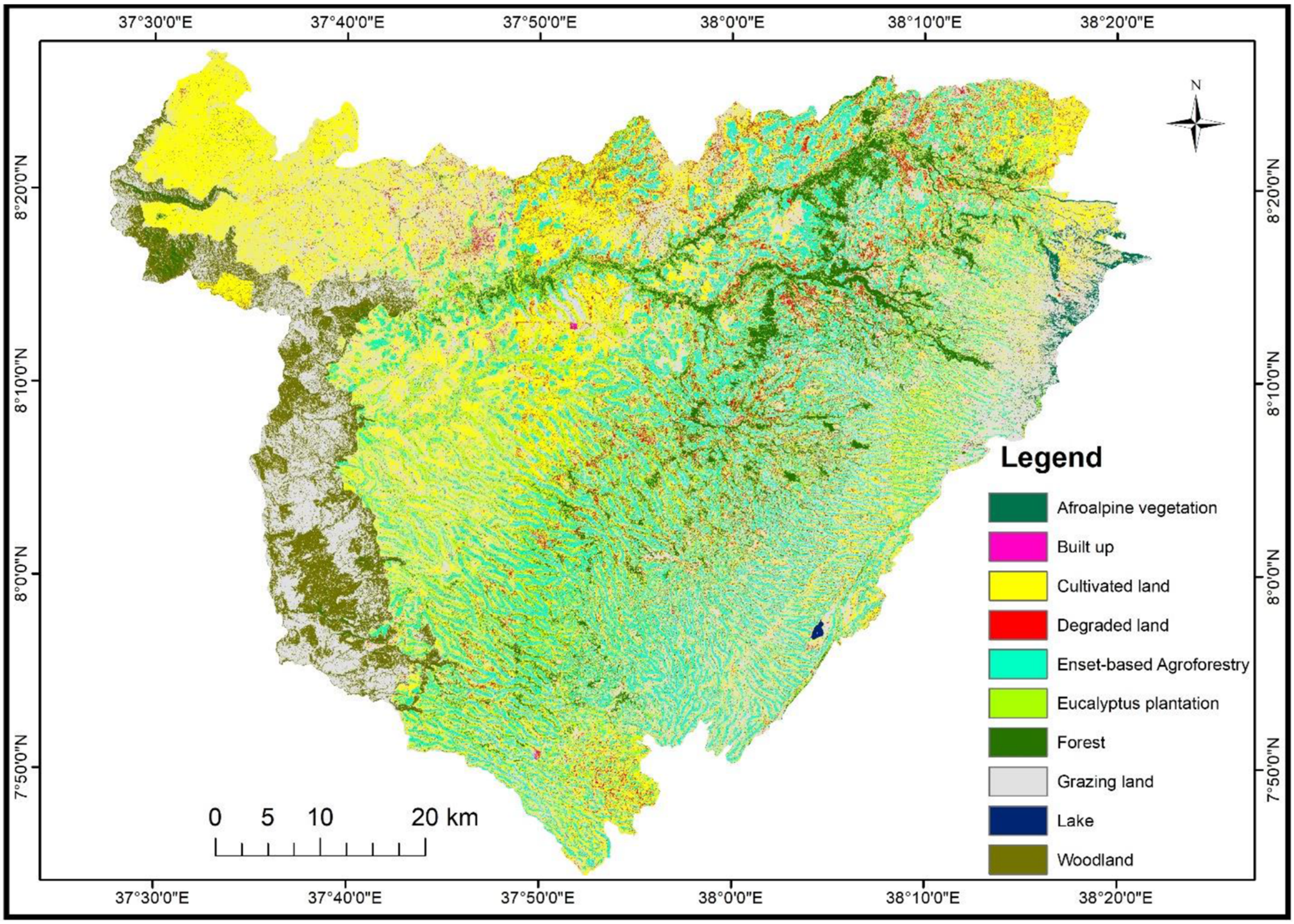

Fig. 3 LULC map of the Gurage socioecological landscape

two land uses are interchanged at least every 2 years, except in communal lands, it is difficult to determine the exact proportions between them. During the dry season (January–May), the reflectance value from cereal crops is similar to pasture plots in a majority of the landscape owing to crop residue. In 2017, cultivated land covered ~ 32.3% of the total landscape. The degraded lands, which were found in the center of the landscape, covered ~ 13,073 ha (3% of the total landscape). Degradation occurred primarily because of soil erosion. Many rivers and streams emerged from high the mountain parts of the landscape. However, except for a few perennial rivers and lakes, the surface water availability during the dry season is minimal. The four small lakes found in the upper catchment area covered only 0.1% of the landscape.

Composition and structure of enset-based home-garden agroforestry

Home gardens in the Gurage socioecological landscape varied in composition, shape, and size. The typical configuration of home gardens included growing enset, khat, coffee, fruit, greens and root vegetables, cereal crops, medicinal plants, and spices as well as their use as woodlots and grazing land. Enset was the dominant home-garden crop and planted in 92% of the surveyed households. Khat and coffee, which are stimulant perennial crops, were grown in 43.4% and 38.2% of the surveyed households, respectively. Fruit such as avocados and mangoes were grown in the central humid region of the landscape and were identified in 39.5% of households. Vegetables such as cabbages and potatoes were grown in 26.3% and 63.2% of households, respectively. Woodlots, which are the source of fuelwood and various other materials, were available in almost all surveyed households ranging from the lower elevations to high mountains. Although their production was small and mainly for household consumption, medicinal plants and spices were grown in 47.4% and 28.9% of the surveyed households. Livestock were kept by almost all the sampled households, and occasionally, beehives were available in home gardens (11.8%).

Enset-based home-garden agroforestry in the landscape had a horizontal structure (Fig. 4). Home gardens were secured with live fences in front of the homestead. Traditional fencing in the landscape included soil bunds, timber fences, shrubs, and woody trees. Additionally, there was a mixed fencing type that included live trees such as eucalyptus, Mexican cypress (*Cupressus lusitanica*), and fruit. Vegetation along the fences was identified in 80% of the surveyed households, of which 40% were eucalyptus species. Among the surveyed households, only 5% did not have any fencing system. Live tree fencing, which was considered as a separation between adjacent parcels of land, was identified in 25% of households.

Inside the fences of each household land parcel, there was one or more vernacular homesteads and grass cover ranging from an area of 84 to 2178 m^2. Approximately 70% of the surveyed households had two or more vernacular huts or modern types of houses (Fig. 4). The average area of land occupied by the homesteads was 200 ± 50 m^2. The large open spaces between the homesteads allowed some households to plant fruit, such as avocados and mangoes, and other shade trees. Most homesteads were separated from the backyard by a wood fence or live shrubs. The surveyed data indicated that ~ 16% of households had live fences as a separation.

The main home-garden crops were grown in the backyard immediately beside the homesteads (Fig. 4). Enset was planted around the houses with a proximate radius between 5 and 30 m. Although the production capacity was low, farmers planted crops such as fruit, cabbages, medicinal plants, and spices between their homesteads and the enset crop garden. The enset crop was grown over large parts of the landscape except in the high mountains above 3300 m and lowlands below 1700 m a.s.l. According to the households, they planted enset nearest to the homesteads because the crop favors smoke from the homesteads. This meant that the crop grew well in the presence of warm air and residues generated from nearby homesteads. A clear difference in size and the period of maturity was observed in the crops nearest to the homesteads compared with those further away.

There was little incorporation of other crops within the enset fields. Most enset gardens are open and cleared to

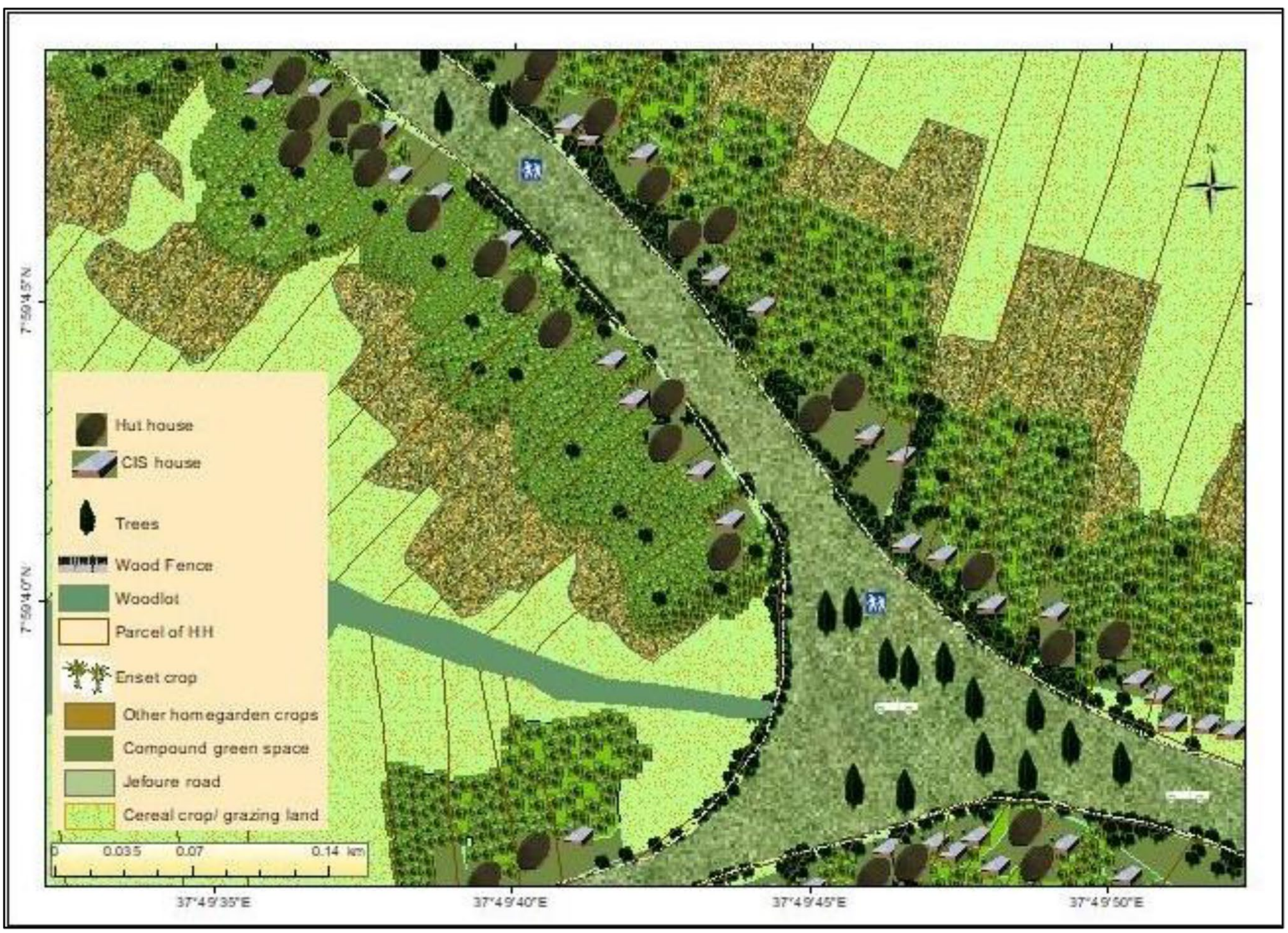

Fig. 4 Illustration of enset-based home-garden agroforestry in the Gurage socioecological landscape (sketched from orthophotomosaic in the Gahirad locality, Enemoherena Ener district)

grow and harvest seasonal herbs for livestock feed. From the surveys, 85% of the households harvested herbs and feed for their livestock during the wet season between June and September. Almost half of the coffee growers planted coffee under the shade of the enset crop, although the production was minimal. Among the surveyed household, 43% grew fruit, and 20% of fruit was planted in the enset garden. The survey data indicated that households rarely grew root vegetables such as potatoes, medicinal plants, and spices within the enset garden.

The garden type next to enset depended on the AEZ. In the upper catchment of the landscape, vegetables such as cabbages and potatoes were the most frequent crops, while in the lower catchment, khat and fruit were common garden plants. Grass, which could be harvested for livestock, was grown between the gardens. Large parts of each land parcel were used to cultivate cereal crops, alternated with livestock pasture to enhance soil fertility. These land uses were found between the enset gardens and the woodlots at the end of the garden.

In the center of the household parcel, woodlots, either natural or plantation trees, frequently existed for fuelwood and other material uses. From the survey, 66% of households had trees in a line or scattered around the edges of plots. The natural forest was leftover from clearing the land for farming. Most wood plots were located at the end of the parcel of land, furthest from the house (Fig. 4).

Agrobiodiversity in enset-based home-garden agroforestry

In total, the households identified ~ 27 woody species within their parcel of land. Eucalyptus is dominant throughout the landscape and very important for use in fuelwood and other materials. Recently, the area of plantations has increased owing to the demand for timber in the country and households use timber as a source of income. The other most common wood species were *Juniperus procera* (Tid), *Afrocarpus falcatus* (Zigba), *Cuppressess lutistinica* (Yeferenji-Tid), and *Cordia africana* (Wanza). On average, the household identified 2.6 woody species with a minimum of two and a maximum of eight tree species. *Acacia abyssinica* (Girar), which is a legume plant and important for soil fertility, was grown by only 8% of the surveyed households. *Hagenia abyssinica* (Kosso) is an endangered species that survived in household plots and is rarely found in the upper catchment.

There are several varieties/farmers' landraces of enset, and households identified 3–33 varieties in their home garden. They cultivated a variety of landraces because of the difference in their quantity, quality, and adaptation to climatic conditions. The households listed several suitable enset varieties depending on their AEZs and districts. The most frequently listed landraces were *Agade*, *Ferezeye*, *Yeshira Qenqe*, *Ameratye*, and *Zober*. Approximately 42.3% of the household listed at least one landrace that had medicinal values, such as *Astara*, *Guarye*, or *Qebenar*. None of the farmers in the study cultivated improved varieties developed and released from the research institutes.

The type of cereal crop depended on the AEZ of the landscape. In the highland areas, cereal crops such as barley, peas, and beans were the most frequently identified crops. Wheat, barley, and pea crops were cultivated in the central catchment of the landscape. In the lower catchment, cereal crops such as teff (*Eragrostis tef*), maize (*Zea mays*), sorghum (*Sorghum bicolor*), Niger seed (*Guizotia abyssinica)*, chickpeas, red kidney beans, lentils, and pepper were grown.

Although the production was low in this region, fruit such as avocados, mangoes, bananas, papayas, oranges, white sapote (*Casimiroa edulis*), lemons, and apples were grown. Except for some farmers who grew avocados and mangoes, improved varieties of fruit were not used. Approximately 70% of the surveyed households grew root vegetables such as potatoes, carrots, garlic, and onions. Potatoes were cultivated by 56% of the surveyed households, who listed ~ 13 varieties of potatoes grown in their home garden. Three varieties of cabbage were grown in household gardens.

Diverse medicinal plants used for the treatment of people and livestock were available in home gardens. The surveyed households listed ~ 18 species of medicinal plants in different AEZ of the landscape. On average, on a given parcel of land, 3.4 ± 1.2 species of medicinal plants were identified by farmers with a maximum of 13 species. *Ruta chalepens* (Tena-Adam) and *Ocimum lamiifolium* (Damakese) were the most frequently grown species. Although 40% of the surveyed households grew spices on their land parcels, they listed only three species, including rosemary.

Livestock were commonly kept by farmers in the landscape. The households reared cows, oxen, chickens, sheep, goats, horses, donkeys, and mules for dairy, meat, manure, and transportation. On average, 5.4 head of livestock were reared by each household, without considering chickens. Cattle were the most frequently kept livestock (95% of households).

Spatial characteristics of home gardens in the landscape

The type and spatial composition of home gardens were diverse in the Gurage socioecological landscape. The proportions of different land use varied within the home garden of the households (Table 2). The parcel size ranged from 0.7 to 4.5 ha, with an average of 1.1 ± 0.7 ha. On average, within the household parcel area, 0.17 ± 0.08 ha (13.2%) was covered by an enset crop. Farmers left large areas of land for grazing, estimated to be ~ 31% of their parcel. Although cereal crops were not grown throughout the landscape area, on average, they covered 0.24 ± 0.1 ha of land. Woodlots were found along the fences, in the center of parcels, and at the end of the gardens, often grown in rows. On average, trees covered ~ 15.9% of the household parcel. Vegetation, including shrubs and large trees, covered ~ 0.2 ± 0.05 ha of the household parcel. Khat, which is a stimulant, was grown in the humid AEZs, and on average, it covered 8.5% of a household parcel. The remaining land was used for housing, compounds, and growing fruit or vegetables (Table 2). All types of land uses were identified in 10% of the surveyed households and the remaining household parcels lacked one or more land uses.

Five home-garden types were identified on the basis of dominant cropping systems, which were mainly governed by the AEZs in which they occurred (Fig. 5). These types included vegetables–barley cropping, enset–vegetables–barley cropping, enset–khat–fruit–coffee–mixed–cereal cropping, enset–khat–fruit–coffee–teff cropping, and mixed–cereal cropping. The difference in the type of home garden meant that the areal extent of the general LULC of the landscape was diverse. The survey data indicated that land use in household parcels depended on the types of the home garden.

On average, the household parcel of land in the vegetables–barley cropping home-garden type was 1.6 ± 0.5 ha (Table 3). In this home-garden type, large parts of the landscape were covered by cultivated and grazing lands (76.3%). Farmers interchanged the two land uses with grazing occurring during the fallow crop period. Green vegetables such as cabbages and root vegetables (potatoes) covered 6.8% and 14.7% of land, respectively. Afroalpine vegetation was a dominant vegetation type in the landscape with a coverage of 17.3%. Eucalyptus trees as woodlots covered a small area (2.3%) as compared with other home-garden types. On average, eight types of mixed livestock, such as dairy cows, oxen, horses, donkeys, and sheep, were kept.

Table 2 Average proportion of land uses on a given parcel of land

Land uses	Average area (ha)	% of land use
Compound	0.04 ± 0.01	3.0
Houses	0.02 ± 0.01	1.4
Enset	0.17 ± 0.08	13.2
Fruit	0.03 ± 0.01	2.3
Cabbage	0.04 ± 0.01	2.7
Khat	0.11 ± 0.05	8.5
Potato	0.05 ± 0.01	4.1
Grazing	0.41 ± 2	30.9
Cereal crop	0.24 ± 0.1	17.9
Woodlot	0.21 ± 0.05	15.9

In enset–vegetables–barley cropping, ~ 62.4% of land was used for the cultivation of cereal crops and grazing land (Table 3). In this home-garden type, the enset crop with vegetables covered ~ 15.5% of land, eucalyptus trees covered 10.1%, and natural forests, including subafroalpine vegetation, had a spatial extent of 7.5%.

Relatively smaller parcels of land were found in the enset–vegetables–barley cropping home-garden type (0.9 ± 0.2 ha). Enset was the only perennial crop in this home garden, and on average, it covered ~ 16.7% of land. Root vegetables such as potatoes and cabbages were the common crops grown next to enset. A large area was used for cereal crops (24.4%) and livestock grazing land (30%). Households cultivated barley as a dominant crop mixed with highland crops such as wheat, peas, and beans. In each household parcel of land, woodlots covered an average of 15.6% of land, dominated by eucalyptus trees.

In the enset–khat–fruit–coffee–mixed–cereal cropping home-garden type, on average, 1.4 ha parcels of land were used for diverse purposes. Enset was the dominant perennial crop, with a land coverage of 14.7%. As a result of agroecology, the production of cereal crops is low. Vegetables such as cabbages and potatoes covered less than 4% of land. The stimulant crops such as khat and coffee were grown in this home-garden type, and on average, they covered 11.8% and 3.1% of the land parcel, respectively. A coffee variety called *Sebatbet* was dominant in this region. Fruit such as avocados and mangoes were also grown and covered 7.9% of land. Some cereal crops such as barley and wheat were grown in this home-garden type mostly for home consumption. Compared with other home-garden types, the spatial extent of woodlots was large (20.6%), mainly because of eucalyptus trees, which could be used as a source of income. On average, the household reared five heads of mixed livestock. The production of coffee was mostly for home consumption.

The fourth home-garden type was enset–khat–fruit–coffee–teff cropping, which was dominated by the indigenous teff crop. Perennial crops such as enset, fruit, and coffee were grown in this home-garden type. While the teff crop covered 41.8% of land, the perennials used 10.5% of this home-garden type landscape. Approximately 16.3% of the average 1.6 ± 0.3 ha of land was used as grazing land, and 4.6 ± 1.5 head of livestock were reared in each household. The cereal crops, khat, fruit, and eucalyptus trees were sold as a source of income.

In the mixed–cereal cropping home-garden type, farmers mainly produced cereal crops such as teff, maize, sorghum, pepper, and red kidney beans. Approximately 78.5% of their parcel of land was used for cereal cropping, and the remainder was used for fruit and woodlots. On average, the farmers had 1.7 ± 0.4 ha of land. An average of four heads

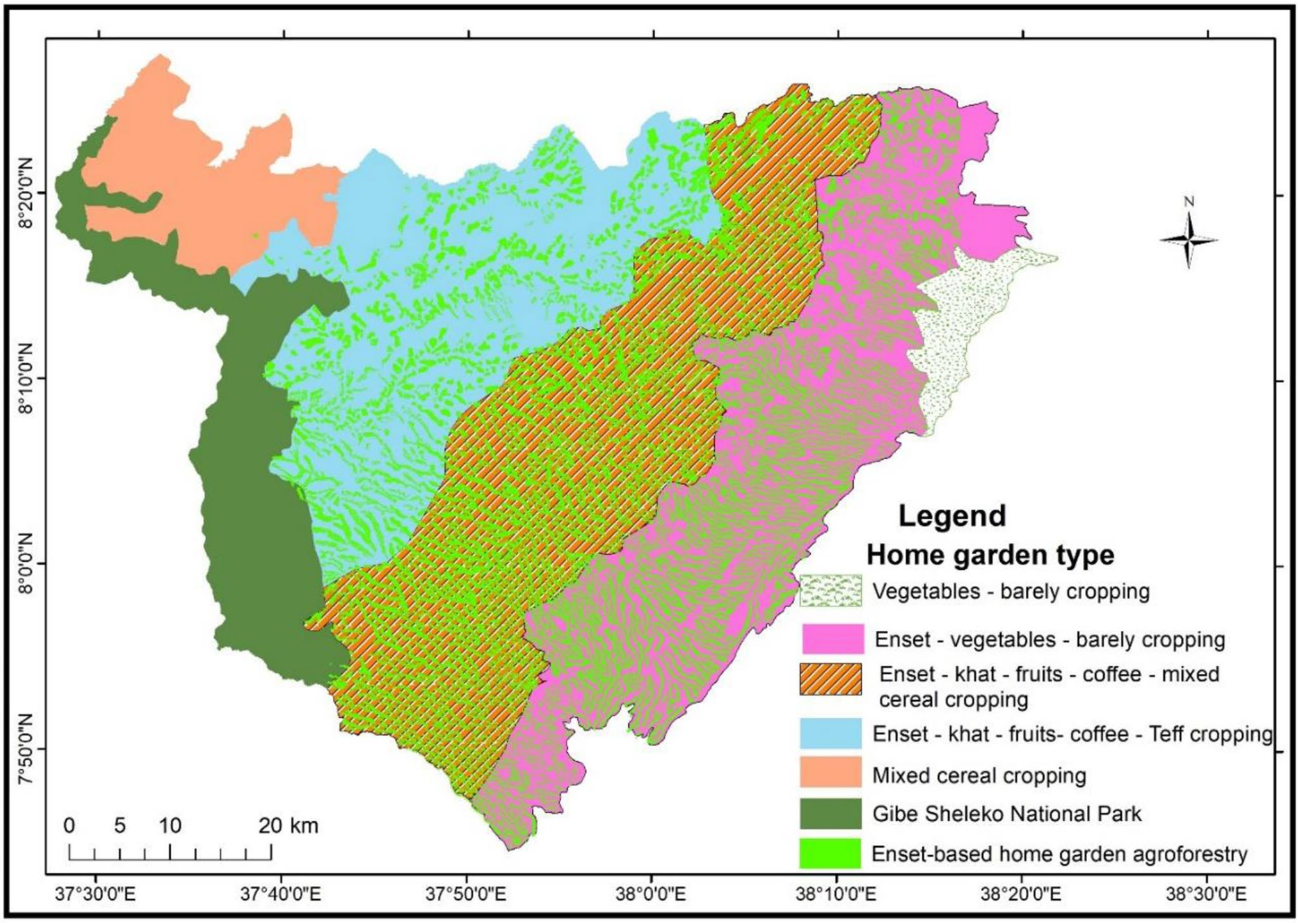

Fig. 5 Home-garden types in the Gurage socioecological landscape

of livestock was reared by some households. The primary source of income was selling cereal crops.

Perceived changes and their drivers in enset-based home-garden crop production

Farmers have observed land use changes in their parcels in the last 50 years. The survey data indicated that ~ 44% of households perceived an increase while 34% observed a decrease in enset crop production (Fig. 6). However, ~ 90% households agreed that the size of each enset plant was decreasing. Farmers raised the issues of diseases, climatic variability, labor force shortages, natural fertilizer limitations (livestock manure), wildlife attacks, and substitution of other foods for the decrease in enset crop production. In several households, the size of the plot assigned for khat and fruit was increasing. Khat crop production increased in 58% of the surveyed households, who were growing the crop. The coffee growing households perceived a change in the production (decrease in 39% of households). The decrease in productivity and diseases was considered as the reason for not producing coffee at a large scale and for the decreasing plot size.

The production of fruit increased among the growers (81%). Approximately 57% of the surveyed households growing potatoes perceived that there is an increase in production. About 50% and 54% of the households perceived that the productions of medicinal plants and vegetables in their home-garden were decreasing, respectively. A majority of farmers (55%) observed a decrease in the extent and type of indigenous tree species in their plots. The decrease could be due to the clearing of trees and shrubs for perennial and cereal crops as well as grazing. Approximately 79% of households perceived that the number of livestock decreased over time. The causes for this decrease were associated with the insufficient feed in their plots, decreased use of communal lands, and labor force shortages. Moreover, the surveyed households reported that cereal crop production was decreasing (83%). Farmers outlined the reductions in the plot size, decreasing productivities, wildlife attacks, and labor force shortages as challenges for crop production in the landscape. Among the farmers who were producing honey,

Table 3 Average LULC (%) of the household land parcels along with different home-garden types

Home-garden type	Enset	Cabbage	Potato	Khat	Coffee	Fruit	Cereal crop	Grazing land	Woodlot	Total area (ha)	Livestock (number)
Vegetables–barley cropping	0	6.8	14.7	-	-	0	28.8	39.7	9.9	1.6±0.5	8±2
Enset–vegetables–barley cropping	16.7	3.3	10	-	-	-	24.4	30	15.6	0.9±0.2	5.3±2
Enset–khat–fruit–coffee–mixed–cereal cropping	14.7	0.7	2.9	11.8	3.1	7.9	8.1	30.1	20.6	1.4±0.3	5±2
Enset–khat–fruit–coffee–teff cropping	9.6	0.6	-	9	1.6	5.1	40.4	17.3	16.3	1.6±0.3	4.6±1.5
Mixed–cereal cropping	-	-	-	-	-	0.6	78.5	13.4	7.6	1.7±0.4	4±1

78% farmers stated that the number of beehives decreased because of a shortage of feed.

Overall, a decrease in the production of the home-garden crops in the landscape was observed except for cash crops such as khat and eucalyptus plantations. The FGD participants and interviewed households identified that a lack of technological innovation was the main reason for the decrease in production and the use of products from home gardens. The long-term agricultural extension service program did not include enset production as the main sector, and therefore, little attention was received for the same from government organizations. Households emphasized that unless they receive technological innovations in the food processing and production systems, the sustainability of the home-garden systems will soon be lost.

Discussion

Enset-based home-garden characteristics in the Gurage socioecological landscape

Enset-based agroforestry, i.e., excluding woodlots, covered ~ 10.2% (44,252 ha) of the western Gurage landscape. Compared with Ethiopia's home-garden agroforestry coverage (2.32 Mha) (Brown et al. 2012) and the southern region of 576,000 ha or 31% of cultivable land (Abebe et al. 2006), the area estimation in the western Gurage is inferior. Moreover, the areal coverage in western Gurage is less than the tropical home-garden agroforestry such as West Java in Indonesia (20%) (Mohri et al. 2013) and Kandy in Sri Lanka (15%) (deHaan et al. 2020). However, there is a major problem in estimating the area under agroforestry, and the area coverage may not show the exact conditions. Mapping the home-garden is challenging because diverse agroforestry systems occur in combination with multiple land use types and the home-garden systems often occur over small land areas (Rosenstock et al. 2019). As we have used high spatial resolution aerial imagery in this study, consideration of advanced geospatial technologies and the development of standard procedures are required to estimate agroforestry areas (Rizvi et al. 2020). The low land coverage in the western Gurage is due to the HHs focusing on the primary staple food source—enset, which can satisfy food in small plots and the remaining parcel of land used for the production of complementary food, cereal, cash crops, and biomass for livestock (Abebe et al. 2013). Improved quantification and mapping of the home-garden coverage help to understand the trends and support for developing appropriate sustainability options that can enhance the material, nonmaterial, and regulating contributions (Rosenstock et al. 2019).

An overview of enset-based home-garden agroforestry looks similar in the Gurage socioecological production

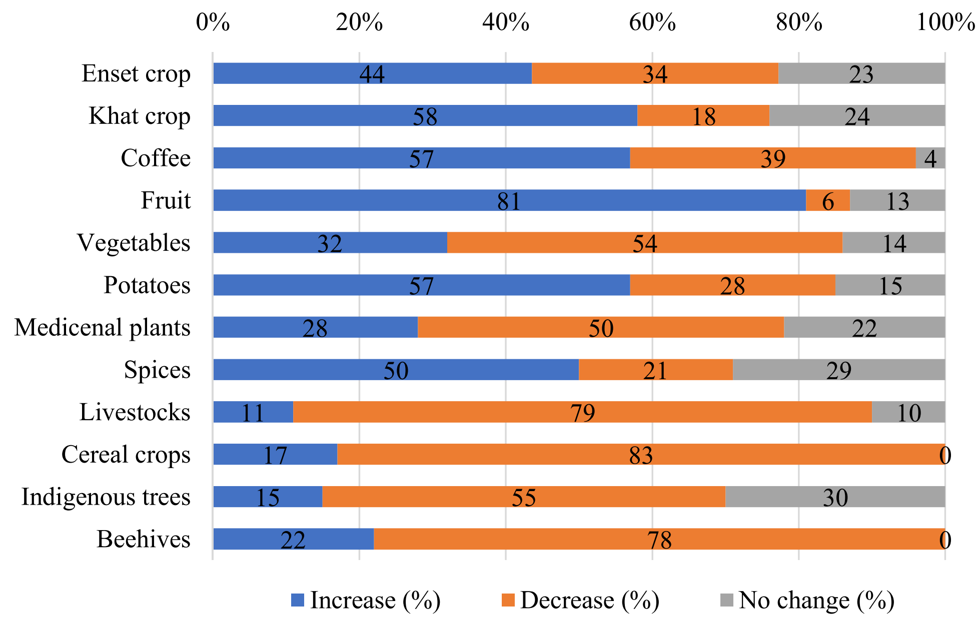

Fig. 6 Perceived changes in the production of home-garden crops in the Gurage socioecological landscape

landscape. However, the detailed characterization of home-garden agroforestry through its spatial and compositional structure led us to identify the differences within the home gardens. We distinguished five types of home gardens. Similar differences within the home-garden agroforestry systems have been observed in tropical regions. In the Gedeo and Sidama agroforestry regions in southern Ethiopia, five home-garden types were identified based on dominant component species (Mellisse et al. 2018). Four types of home gardens were distinguished in Kerala (India) based on the presence and absence of component species (George and Christopher 2020). The differences could relate to the traditional evolution of the home-garden system, where many indigenous people have their own styles (Huai and Hamilton 2009).

The functional structure indicates that perennial-based and parkland types of agroforestry are found in the Gurage home-garden agroforestry system. The home-gardens found in upper and lower catchment areas can be categorized in parkland agroforestry, as areas where staple food crops are grown in the outer farm with trees and vegetable species and fruits are grown in the home garden. Additionally, in perennial-based agroforestry, the three middle catchment home gardens can be categorized as areas similar to the central highland of Ethiopia; perennials are grown on the homestead, while staple food crops are grown in outer fields (Abebe and Bongers 2012). Horizontal type of structure is followed by both types of agroforestry systems. This type of structure could be due to the Gurage landscape households that have a relatively large parcel of land (1.1 ha) compared with the Gedeo (0.70 ha) and Sidama (0.90 ha) agroforestry systems (Mellisse et al. 2018). The variances in settlement patterns, soil fertility, topography, and climatic conditions have an impact for the differences in home-garden types. According to Timsuksai and Rambo (2016), vertical structural design is more efficient in using space and enhancing crop production. Although the vertical structure is rare in the Gurage landscape, with an exception of herbaceous grasses for livestock, integrating trees and other crops with enset could be advantageous. This approach could help households to use their small parcel of land more efficiently while leaving the remaining part for the production of other goods.

The home-garden composition in Gurage includes homesteads, enset gardens, cash crops such as vegetables and khat, grazing and cereal cultivated land, and woodlots, and they were designed in sequential order. Several horizontal structure home-garden systems are randomly arranged without specific geometrical patterns and planted to maximize space utilization while meeting their light, water, and fertility requirements (Siarudin et al. 2019). For example, the Tai gardens are polycentric and mix several species in the same organically shaped planting areas (Timsuksai and Rambo 2016). In addition to various tree species, 10 functional plant groups have been identified in western Gurage. However, the number of functional groups depends on the home-garden types. Although there are pattern differences, the number of functional groups is similar to the Gedeo and Sidama home-garden agroforestry in Ethiopia (Abebe et al. 2006). Enset, a key component of the western Gurage home garden, covers 13.2% area in a given parcel of land, which is less than that in the Sidama case (Abebe et al. 2010). The Gurage home garden is distinguished by its allocation of a large homestead compound that allows conducting social activities and the planting of ornamental trees/fruits.

Most traditional home gardens show high floristic diversities compared with other types of agroecosystems (Salako et al.

2014; Avilez-López et al. 2020). The species diversity (i.e., crops and trees) in western Gurage varies according to the AEZs, and the low and high altitude home-garden types have relatively few species per garden. Similarly, in southern Ethiopia, farm altitude and slope influenced crop species' heterogeneity (Abebe et al. 2013). Although the enset-based home-garden agroforestry in Gurage hosts several edible and woody species, it is less rich in species composition than tropical region home gardens such as Gedeo and Sidama agroforestry in southern Ethiopia (Negash et al. 2012), West Java in Indonesia (Park et al. 2019), and Kerala in India (Peyre et al. 2006; Mohan et al. 2007). The difference can be associated with the variation in geographic location, climate, water availability, garden size, market needs, food culture, and household preferences (Galhena et al., 2013). Because this study only considered food crops and woody species, the low species composition in the western Gurage landscape can be linked with the horizontal home-garden structure (Abebe et al. 2006). Although the existing diversity of species and crop varieties provides various material, nonmaterial, and regulating contributions, an increase in species/variety richness would improve the contributions even further.

Although the explicit characterization of the home-garden system has several advantages, there are no commonly accepted frameworks and methodological procedures (Kumar and Nair 2006; Shin et al. 2020). The most commonly used approaches for characterizing the home-garden agroforestry system are species composition, structure (horizontal and vertical), and management, with limited attention to their scale and layout (Mahato et al. 2016; George and Christopher 2020). This study considered the functional structure of various crops depending on the AEZs, LULC, and the visual interpretation of orthophotomosaic. This approach allowed us to better understand and group the home-garden types and improve their characterization methodology. Although the uniqueness of each home garden hinders the use of a common approach, efforts are required to develop a commonly accepted framework to characterize the home-garden agroforestry systems.

Home-garden agroforestry dynamics and implications for sustainable management

In the Gurage socioecological landscape, the trends indicate that the home-garden production is declining owing to less attention from the government offices in the region and socioeconomic changes. A similar shift in the traditional home gardens, such as enset, coffee, and livestock, is indicated by 20 years of historical analysis in southern Ethiopia's Sidama and Gedeo zones (Mellisse et al. 2018). Although farmers strategically used a given parcel of land for their homesteads and to grew staple food, cash crops, vegetables, cereal crops, pastures, and for woodlots in western Gurage, there was a scope to increase cash crops such as khat and fruit and eucalyptus trees. Currently, coffee is being overwhelmed by khat, and in the future, it may be difficult to find the enset–coffee combinations in the landscape. These dynamics could lead to a loss of an essential *Sebatbet* coffee variety developed by farmers in the area. Cropping patterns in Sidama and Gedeo zones of southern Ethiopia changed most strongly in areas where khat was introduced (Mellisse et al. 2018). In Asia, the historically predominant land use systems, such as home gardens, have been converted to cash crops for land use intensification (Guillerme et al. 2011; Shin et al. 2020). In Sir Lanka, the main constraints for decreasing home-garden crop productions are the access to suitable and sufficient land, capital or credit, water, seeds, and planting materials; poor extension and advisory services; labor access; and market access (Galhena et al. 2013). Labor shortage resulting from out migration is another cause of the decline in home-garden crop production in western Gurage in addition to the use of old-fashioned materials for cultivation, harvesting, food processing, and storage. According to Mellisse et al. (2018), the dynamic changes in the home garden cropping system in the Sidama and Gedeo zones were influenced by variations in population densities, market access, low prices, market liberalization policies, and a decrease in soil fertility.

The proportional use of a given small parcel of land and the diversification of goods has enabled the farmers in the Gurage landscape area to remain resilient for a long time (Sahle et al. 2018). However, the current status does not show the promotion of this valuable ecosystem. Thus, there is a need to promote the diversification of the production system to enhance sustainability in the landscape according to the home-garden type (Jemal et al. 2021). Conservation of the existing species and adoption of other indigenous species suitable for the AEZ are essential for the sustainability of the home garden. Improved varieties of livestock would enhance the production of staple crops such as enset and other complementary food that depend on natural fertilizer, i.e., livestock manure. Introducing mechanical and semidigital machinery that is affordable to low-income households would address labor shortages while contributing to the long-term viability of enset-based home-garden agroforestry. Forming farmer cooperatives and establishing credit and savings schemes would also help farmers stay in the landscape while increasing home-garden agroforestry production.

Past and present evidence indicate that home-garden agroforestry, as part of a multifunctional socioecological landscape, can be a viable land use option and is essential for attaining sustainability (Jose 2009). A home-garden agroforestry system is vital for achieving the first two sustainable development goals (SDG), i.e., no poverty (SDG 1) and zero hunger (SDG 2), and contributes to achieving other targets such as gender equality (SDG 5), climate action (SDG 13), and life on land (SDG 15) (Montagnini and Metzel 2017). In addition, these systems can contribute to several other global goals, such as good health and well-being (SDG 3), clean water and sanitation (SDG 6), affordable and clean energy

(SDG 7), decent work and economic growth (SDG 8), and responsible consumption and production (SDG 12) (Flinzberger et al. 2020). Thus, there is a need for cooperation between regional and global organizations to evaluate home-garden provisions and implement the sustainability goal strategies according to the local context (Plieninger et al. 2020).

The enset-based home-garden agroforestry system in southwestern and central Ethiopia is an example of a multifunctional landscape, and the people in the landscape benefit from its multiple contributions. As a result, expansion in this cultivation system in suitable agroclimatic zones from its current restricted distribution would improve sustainability in Ethiopia and East Africa. The agroforestry system can be scaled up by focusing on farmer adoption, improving extension delivery systems as well as agroforestry technology, and developing markets for agroforestry products (Blaser et al. 2018). An integrated landscape management approach can help to develop strategies for scaling up agroforestry by mobilizing collaborative efforts among multisector stakeholders to address the constraints (Buck et al. 2020).

Conclusion

This study on the characterization of home-garden agroforestry in the Gurage socioecological landscape of southern Ethiopia shows that home-garden composition is not uniform throughout the landscape, and it is mainly affected by AEZ. The home gardens had similar functional pattern where the perennial crops were planted nearest to homesteads mostly without intercropping; annual crops were grown in outer fields; livestock grazing was carried out on the outskirts interchanged with cereal crops; and woodlots were developed at the far end of the home garden. Except for the top of the high mountains in the afroalpine area and lowlands, enset was grown throughout the landscape with or without other perennial crops, such as coffee, khat, and fruit, as a keystone home-garden species on an expansive scale. Five home-garden types with some overlapping were found within this specific landscape. Planners, decision-makers, agricultural input providers, and extension workers should understand the local conditions and develop strategies to support smallholder farmers accordingly to sustain the home garden's place in the landscape.

Researching the comprehensive characteristics of the home-garden system in terms of spatial composition, agrobiodiversity, and structure helped in documenting the traditional knowledge of home-garden management and explore their scientific meaning. An explicit classification of the home-garden type will aid to understand local knowledge and develop strategies for sustainable home gardens using a bottom-up approach. The better we characterize the types of home-garden agroforestry, the more we can understand their differences and develop suitable sustainable management strategies for each of them. Scaling up of home-garden agroforestry needs to be implemented for enhancing productivity and achieve diverse sustainability goals. Site-specific spatial characterization of agroforestry systems by considering a holistic approach to reduce the local challenges supports the development of sustainable landscape management in an altering socioecological landscapes. Similar studies focusing on the spatial characterization of agroforestry systems elsewhere would help to understand their value and support sustainable management.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-17605-0.

Acknowledgements This study's key interviews and FGDs were conducted with the kind cooperation of the Gurage-Zone Tourism and Culture office and Wolkite University in Ethiopia. The authors thank the Japan Society for the Promotion of Science for providing financial support to the overseas researchers and the United Nations University Institute for the Advanced Study of Sustainability and Institute for Global Environmental Strategies in Japan for providing logistic support.

Author contribution Conceptualization, M.S. and O.S.; methodology, M.S.; software, M.S.; validation, M.S. and O.S.; formal analysis, M.S.; investigation, M.S.; resources, O.S.; data curation, M.S.; writing—original draft preparation, M.S.; writing—review and editing, O.S. and S.D.; visualization, M.S.; supervision, O.S.; project administration, O.S.; funding acquisition, O.S. All authors have read and agreed to be published the manuscript.

Funding Financial support was provided by the Japan Society for the Promotion of Science for overseas researchers. This funding organization supported the design of the study; data collection, analysis, and interpretation; and writing the manuscript.

Availability of data and material The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Abbas F, Hammad HM, Fahad S, Cerdà A, Rizwan M, Farhad W, Ehsan S, Bakhat HF (2017) Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios-a review. Environ Sci Pollut Res Int 24:11177–11191. https://doi.org/10.1007/s11356-017-8687-0

Abebe T, Bongers F (2012) Land-use dynamics in enset-based agroforestry homegardens in Ethiopia. In: Arts B, van Bommel S, Ros-Tonen M, Verschoor G (eds) Forest-people interfaces.

Wageningen Academic Publishers, Wageningen. https://doi.org/10.3920/978-90-8686-749-3_4

Abebe T, Sterck FJ, Wiersum KF, Bongers F (2013) Diversity, composition and density of trees and shrubs in agroforestry homegardens in Southern Ethiopia. Agroforest Syst 87:1283–1293. https://doi.org/10.1007/s10457-013-9637-6

Abebe T, Wiersum KF, Bongers F (2010) Spatial and temporal variation in crop diversity in agroforestry homegardens of southern Ethiopia. Agroforest Syst 78:309–322. https://doi.org/10.1007/s10457-009-9246-6

Abebe T, Wiersum KF, Bongers F, Sterck F (2006) Diversity and dynamics in homegardens of southern Ethiopia. In: Kumar BM, Nair PKR (eds) Tropical homegardens: advances in agroforestry 3. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4948-4_8

Avilez-López T, van der Wal H, Aldasoro-Maya E, Rodríguez-Robles U (2020) Home gardens' agrobiodiversity and owners' knowledge of their ecological, economic and socio-cultural multifunctionality: a case study in the lowlands of Tabasco, Mexico. J Ethnobiol Ethnomed 16:42. https://doi.org/10.1186/s13002-020-00392-2

Blaser WJ, Oppong J, Hart SP, Landolt J, Yeboah E, Six J (2018) Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nat Sustain 1:234–239. https://doi.org/10.1038/s41893-018-0062-8

Borelli S, Hillbrand A, Conigliaro M, Olivier A (2017) Agroforestry for landscape restoration—exploring the potential of agroforestry to enhance the sustainability and resilience of degraded landscapes. http://www.fao.org/3/b-i7374e.pdf. Accessed 20 Feb 2021

Borrell JS, Biswas MK, Goodwin M, Blomme G, Schwarzacher T, Heslop-Harrison JSP, Wendawek AM, Berhanu A, Kallow S, Janssens S, Molla EL, Davis AP, Woldeyes F, Willis K, Demissew S, Wilkin P (2019) Enset in Ethiopia: a poorly characterized but resilient starch staple. Ann Bot 123:747–766. https://doi.org/10.1093/aob/mcy214

Brown S, Grais A, Ambagis S, Pearson T (2012) Baseline GHG emissions from the agricultural sector and mitigation potential in countries of East and West Africa. CCAFS Working paper no. 13. CGIAR research program on climate change, agriculture and food security (CCAFS). Copenhagen, Denmark. www.ccafs.cgiar.org. Accessed 10 Sept 2021

Buck L, Scherr S, Trujillo L, Mecham J, Fleming M (2020) Using integrated landscape management to scale agroforestry: examples from Ecuador. Sustain Sci 15:1401–1415. https://doi.org/10.1007/s11625-020-00839-1

Central Statistical Agency (CSA) (2009) Population and house census report of Ethiopia. Addis Ababa, Ethiopia

deHaan R, Hambly OH, Thevathasan N, Nissanka SP (2020) Local knowledge and perspectives of change in homegardens: a photovoice study in Kandy District, Sri Lanka. Sustainability 12(17):6866. https://doi.org/10.3390/su12176866

Descheemaeker K, Ronner E, Ollenburger M, Franke AC, Klapwijk CJ, Falconnier GN, Wichern J, Giller KE (2016) Which options fit best? Operationalizing the socio-ecological niche concept. Exp Agric 55(1):169–190. https://doi.org/10.1017/S001447971600048X

Ethiopian Mapping Agency (EMA) (2017) Aerial photography quality control. Addis Ababa, Ethiopia

Feliciano D, Ledo A, Hillier J, Nayak DR (2018) Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agric Ecosyst Environ 254:117–129. https://doi.org/10.1016/j.agee.2017.11.032

Flinzberger L, Zinngrebe Y, Plieninger T (2020) Labelling in Mediterranean agroforestry landscapes: a Delphi study on relevant sustainability indicators. Sustain Sci 15:1369–1382. https://doi.org/10.1007/s11625-020-00800-2

Galhena DH, Freed R, Maredia KM (2013) Home gardens: a promising approach to enhance household food security and wellbeing. Agric Food Secur 2:8. https://doi.org/10.1186/2048-7010-2-8

Gbedomon RC, Fandohan AB, Salako VK, Idohou AFR, Kakaï RG, Assogbadjo AE (2015) Factors affecting home gardens ownership, diversity and structure: a case study from Benin. J Ethnobiol Ethnomed 11:56. https://doi.org/10.1186/s13002-015-0041-3

Gbedomon RC, Salako VK, Fandohan AB, Idohou AFR, Glèlè Kakaï R, Assogbadjo AE (2017) Functional diversity of home gardens and their agrobiodiversity conservation benefits in Benin, West Africa. J Ethnobiol Ethnomed 13:66. https://doi.org/10.1186/s13002-017-0192-5

George MV, Christopher G (2020) Structure, diversity and utilization of plant species in tribal homegardens of Kerala, India. Agroforest Syst 94:297–307. https://doi.org/10.1007/s10457-019-00393-5

Guillerme S, Barcet H, de Munnik N, Maire E, Marais-Sicre C (2020) Evolution of traditional agroforestry landscapes and development of invasive species: lessons from the Pyrenees (France). Sustain Sci 15:1285–1299. https://doi.org/10.1007/s11625-020-00847-1

Guillerme S, Kumar BM, Menon A, Hinnewinkel C, Maire E, Santhoshkumar AV (2011) Impacts of public policies and farmer preferences on agroforestry practices in Kerala, India. Environ Manag 48:351–364. https://doi.org/10.1007/s00267-011-9628-1

Huai H, Hamilton A (2009) Characteristics and functions of traditional homegardens: a review. Front Biol China 4:151–157. https://doi.org/10.1007/s11515-008-0103-1

IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES secretariat. https://ipbes.net/. Accessed 20 Oct 2020. Bonn, Germany

IPES-food (2016) From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. Brussels. International Panel of Experts on Sustainable Food Systems. https://www.ipes-food.org. Accessed 20 Feb 2021

Jemal OM, Callo-Concha D, van Noordwijk M (2021) Coffee Agroforestry and the Food and Nutrition Security of Small Farmers of South-Western Ethiopia. Front Sustain Food Syst 5:293. https://www.frontiersin.org/article/10.3389/fsufs.2021.608868. Accessed 4 Sept 2021

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agroforest Syst 76:1–10. https://doi.org/10.1007/s10457-009-9229-7

Kumar BM, Nair PKR (2006) Introduction. In: Kumar BM, Nair PKR (eds) Tropical Homegardens. Advances in Agroforestry, 3;1–10. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4948-4_1

Mahato S, Dasgupta S, Todaria NP, Singh VP (2016) Agroforestry mapping and characterization in four districts of Garhwal Himalaya. Energ Ecol Environ 1:86–97. https://doi.org/10.1007/s40974-016-0020-0

Mellisse BT, van de Ven GWJ, Giller KE, Descheemaeker K (2018) Home garden system dynamics in Southern Ethiopia. Agroforest Syst 92:1579–1595. https://doi.org/10.1007/s10457-017-0106-5

Minang P, van Noordwijk M, Freeman O, Duguma L, Mbow C, Leeuw J de, Catacutan D (2018) Climate smart landscapes. https://www.asb.cgiar.org/climate-smart-landscapes. Accessed 17 Mar 2021

Mohan S, Nair PKR, Long AJ (2007) An Assessment of ecological diversity in homegardens: a case study from Kerala State, India. J Sustain Agric 29(4):135–153. https://doi.org/10.1300/J064v29n04_10

Mohri H, Lahoti S, Saito O, Mahalingam A, Gunatilleke N, Irham HVT, Hitinayake G, Takeuchi K, Herath S (2013) Assessment of ecosystem services in home garden systems in Indonesia, Sri Lanka, and Vietnam. Ecosyst Serv 5:124–136. https://doi.org/10.1016/j.ecoser.2013.07.006

Montagnini F, Metzel R (2017) The contribution of agroforestry to sustainable development Goal 2: end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. In: Montagnini F (ed) Integrating landscapes: agroforestry for biodiversity conservation and food sovereignty. Advances in agroforestry, 12. Springer, Cham. https://doi.org/10.1007/978-3-319-69371-2_2

Muschler RG (2016) Agroforestry: essential for sustainable and climate-smart land use? In: Pancel L, Köhl M (eds) Tropical forestry handbook. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-54601-3_300

Negash M, Yirdaw E, Luukkanen O (2012) Potential of indigenous multistrata agroforests for maintaining native floristic diversity in the south-eastern Rift Valley escarpment, Ethiopia. Agroforest Syst 85:9–28. https://doi.org/10.1007/s10457-011-9408-1

Park JH, Woo SY, Kwak MJ, Lee JK, Leti S, Soni T (2019) Assessment of the diverse roles of home gardens and their sustainable management for livelihood improvement in West Java, Indonesia. Forests 10(11):970. https://doi.org/10.3390/f10110970

Peyre A, Guidal A, Wiersum KF, Bongers F (2006) Dynamics of homegarden structure and function in Kerala, India. Agroforest Syst 66:101–115. https://doi.org/10.1007/s10457-005-2919-x

Plieninger T, Muñoz-Rojas J, Buck LE, Scherr SJ (2020) Agroforestry for sustainable landscape management. Sustain Sci 15:1255–1266. https://doi.org/10.1007/s11625-020-00836-4

Rendón-Sandoval FJ, Casas A, Moreno-Calles AI, Torres-García I, García-Frapolli E (2020) Traditional agroforestry systems and conservation of native plant diversity of seasonally dry tropical forests. Sustainability 12:4600. https://doi.org/10.3390/su12114600

Rizvi RH, Handa AK, Sridhar KB, Anil K, Bhaskar S, Chaudhari SK, Arunachalam A, Noyal T, Ashutosh S, Sapra RK, Girish P, Raj Kumar S, Sunil L, Devashree N, Atul D, Rajendra C, Dhyani SK, Javed R, Tor-Gunnar V, Ahmad M, Prabhu R, Biradar C, Gaurav D (2020) Mapping agroforestry and trees outside forest. Jointly published by the ICAR, Central Agroforestry Research Institute (CAFRI), Jhansi and World Agroforestry (ICRAF), South Asia Regional Programme, New Delhi

Rolo V, Hartel T, Aviron S et al (2020) Challenges and innovations for improving the sustainability of European agroforestry systems of high nature and cultural value: stakeholder perspectives. Sustain Sci 15:1301–1315. https://doi.org/10.1007/s11625-020-00826-6

Rosenstock TS, Wilkes A, Jallo C, Namoi N, Bulusu M, Suber M, Mboi D, Mulia R, Simelton E, Richards M, Gurwick N, Wollenberg E (2019) Making trees count: measurement and reporting of agroforestry in UNFCCC national communications of non-Annex I countries. Agric Ecosyst Environ 284:106569. https://doi.org/10.1016/j.agee.2019.106569

Sahle M, Saito O, Fürst C, Yeshitela K (2019) Quantifying and mapping of water-related ecosystem services for enhancing the security of the food-water-energy nexus in tropical data-sparse catchment. Sci Total Environ 646:573–586. https://doi.org/10.1016/j.scitotenv.2018.07.347

Sahle M, Saito O (2021a) Mapping and characterizing the Jefoure roads that have cultural heritage values in the Gurage socio-ecological production landscape of Ethiopia. Landsc Urban Plan 210:104078. https://doi.org/10.1016/j.landurbplan.2021.104078

Sahle M, Saito O (2021) Assessing nature's contributions to people by Jefoure roads for sustainable management in the Gurage socio-ecological production landscape in Ethiopia. Sustainability 13:3806. https://doi.org/10.3390/su13073806

Sahle M, Yeshitela K, Saito O (2018) Mapping the supply and demand of enset crop to improve food security in Southern Ethiopia. Agron Sustain Dev 38:7. https://doi.org/10.1007/s13593-017-0484-0

Salako VK, Fandohan B, Kassa B, Assogbadjo AE, Idohou AFR, Gbedomon RC, Chakeredza S, Dulloo ME, Kakaï RG (2014) Home gardens: an assessment of their biodiversity and potential contribution to the conservation of threatened species and crop wild relatives in Benin. Genet Resour Crop Evol 61:313–330. https://doi.org/10.1007/s10722-013-0035-8

Shin S, Soe KT, Lee H, Kim TH, Lee S, Park MS (2020) A systematic map of agroforestry research focusing on ecosystem services in the Asia-Pacific region. Forests 11:368. https://doi.org/10.3390/f11040368

Siarudin M (2019) IOP Conf. Ser.: Earth Environ. Sci. 250 012043. http://dx.doi.org/10.1088/1755-1315/250/1/012043

Simensen T, Halvorsena R, Erikstad L (2018) Methods for landscape characterization and mapping: a systematic review. Land Use Policy 75:557–569. https://doi.org/10.1016/j.landusepol.2018.04.022

Timsuksai P, Rambo AT (2016) The influence of culture on agroecosystem structure: a comparison of the spatial patterns of homegardens of different ethnic groups in Thailand and Vietnam. PLoS ONE 11(1):e0146118. https://doi.org/10.1371/journal.pone.0146118

van Noordwijk M, Speelman E, Hofstede GJ, Farida A, Abdurrahim AY, Miccolis A, Hakim AL, Wamucii CN, Lagneaux E, Andreotti F, Kimbowa G, Assogba GGC, Best L, Tanika L, Githinji M, Rosero P, Sari RR, Satnarain U, Adiwibowo S, Ligtenberg A, Muthuri C, Peña-Claros M, Purwanto E, van Oel P, Rozendaal D, Suprayogo D, Teuling AJ (2020) Sustainable agroforestry landscape management: changing the game. Land 9(8):243. https://doi.org/10.3390/land9080243

Warnock S, Griffiths G (2020) Landscape characterization: the living landscapes approach in the UK. Landscape Res Landsc Res 40(3):261–278. https://doi.org/10.1080/01426397.2013.870541

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.