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Species diversity and vegetation structure of woody plants in regenerating *Juniperus* forest replacing *Eucalyptus* in the conservation area of Gullele Botanic Garden, Addis Ababa, Ethiopia

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Abstract. The Gullele Botanic Garden (GBG), on the slope of the Entoto hills, adjoins the north-western limit of the city of Addis Ababa, capital of Ethiopia. The forested area of GBG is home to a mixture of semi-natural forest and *Eucalyptus* plantations with *Eucalyptus* having been removed in the recent past. The floristic composition, species diversity and vegetative structure of the woody plant species in the forested area are here presented from 81 plots (20 × 20 m). A total of 104 woody plant species (90% native, the rest planted or naturalised) of 83 genera and 47 families are recorded; a species richness higher than what researchers have found in nearby natural forests, though the definitions of woody species have varied between studies. The number of individuals of the dominant species, *Juniperus procera*, decreases with increasing DBH and height class, which indicates a healthy regeneration inside the GBG; the appearance of seedlings and young plants of *Juniperus* after the removal of *Eucalyptus* is comparable to the regeneration of *Juniperus* forests described from East Africa after forest fires or clear-felling. Clustering analyses on the floristic data result in four partly overlapping clusters, but the distribution of the plots on clusters changes notably if data on *Eucalyptus* is in- or excluded. Many woody species in nearby natural or semi-natural forests, where *Juniperus procera* is dominant, occur also in GBG but plant communities defined for those forests are not identified in the plot data from GBG. The findings in this paper can serve as a baseline dataset to follow the regeneration of the conservation area towards natural forest, useful for future management and sustainable utilization of Ethiopian forest species at local and national levels.

Keywords: Baseline study, Central Ethiopian Plateau, conservation of biodiversity, conservation of vegetation, Dry Afromontane Forest, frequency, *Juniperus procera*, plant community analyses, population structure.

INTRODUCTION

Ethiopia has a very diverse flora with a high number of endemic species particularly in the Shewa Uplands (SU) floristic region (Demissew et al. 2021). Just north of Addis Ababa is the Entoto mountain chain and the Gullele Botanic Garden (GBG) with remains of previously continuous dry mountain forest. In the central Ethiopian highlands, only fragmented forests remain (Bekele 1993; Darbyshire et al. 2003). The conservation challenges are significant (Egziabher 1989; Shibru and Balcha 2004; Lemenih and Teketay 2004; Asmelash and Rannestad 2022). Efforts to study and restore the forests have been gaining momentum since the late 1980s (Demissew 1988; Bekele 1993; Hylander and Hylander 1995; Reusing 1998; Institute of Biodiversity Conservation 2005; Shibru and Woldu 2006; Woldemariam et al. 2016; Aerts et al. 2016; Kindu et al. 2022; Masresha and Melkamu 2022), and research on forest structure and composition is being encouraged to guide the restauration of forests (Tesfaye et al. 2002). Asmelash and Rannestad (2022) provide a list of forests and associated vegetation studies in the central Ethiopian highlands. The present study of the forested area in the Gullele Botanic Garden (GBG) intends to contribute to such studies and the conservation efforts.

The natural forests around Addis Ababa

The potential natural vegetation of the central highlands of Ethiopia between 1800 and 3000 (upper limit 3400) m a.s.l. was described and mapped by Friis et al. (2010, 2011, 2022). The natural vegetation is characterised by a mosaic of montane woodland and wooded grassland and dry Afromontane forest (referred to as DAF). One of the first scholarly studies of DAF forests near Addis Abeba was of Menagesha Suba Forest (Demissew 1988). A detailed study of forest remnants on the central Ethiopian plateau around Addis Ababa was produced by Bekele (1993) and covered Jibat Forest south of Gedo in the west (a more humid forest with a somewhat different species composition), Chilimo Forest north of Ginchi, Menagesha Forest west of Addis Ababa, and Wof-Washa Forest to the east of Debre Birhan. In the three drier of these forests, *Juniperus procera* occurs as the dominant woody species in three phytosociological communities out of ten (Bekele 1993).

Regeneration of Juniperus forests in East Africa and Ethiopia

Regeneration of forest is important in connection with the conservation efforts of the central Ethiopian plateau (Asmelash and Rannestad 2022). The regeneration of trees in dry Afromontane forest, particularly of *Juniperus procera*, has been studied in East Africa. Gardner (1926) found that the nearly complete destruction of the old *Juniperus procera* forest was necessary before any natural regeneration with that species took place. This was confirmed from both Kenya and Tanzania by Wimbush (1937) and Hall (1984). Hall summarised the typical life cycle for a *Juniperus procera* forest following clear felling or a major forest fire: "*J. excelsa* [= *Juniperus procera*] has been reported to assume dominance at around 20 years, when it reaches a height of about 8 m. The trees reach full height – 30 m or more in favourable sites – by the time they are 80-90 years old [and] are believed to remain the dominant canopy constituent for a further 200-300 years before showing signs of senescence, … allowing more light into the forest and favouring vigorous growth of late-successional broad-leaved species. These replace the dying *J. excelsa* and constitute the climax forest [which] includes *Ekebergia*, *Olea*, *Olinia* and *Rapanea* [*Myrsine*]." Bussmann (2001) confirmed that these observations applied to *Juniperus* forests in both East Africa and southern Ethiopia, and Bussmann and Beck (1995) had previously provided experimental evidence for poor germination of *Juniperus procera* seeds in the dark or when covered by humus.

Lack of regeneration has been observed in the Wof Washa forest in central Ethiopia, where Teketay and Bekele (1995) saw very few *Juniperus procera* seedlings in *Juniperus* dominated forest. They concluded that this species did not regenerate under the canopy of mature parent trees. And this despite the presence of abundant viable seeds of *Juniperus procera* in the soil seed bank of DAF forests (Teketay and Granström, 1995). Wassie (2007) studied the regeneration of Ethiopian church forests and found that the number of germinated seeds of *Juniperus procera* was very low under closed canopy and in canopy gaps.

The DBH classes for *Juniperus procera* from the hill with the Menagesha Amba Mariam forest, between the main Menagesha Suba forest and the GBG indicate a regenerating forest with trees of comparable age (Tilahun et al. 2015). In Tigray a study on the regeneration from the soil seed bank of *Juniperus procera* and *Olea europaea* subsp. *cuspidata* after disturbance in fenced and unfenced areas found that fencing made no change for the regeneration of *Juniperus procera*, while there was a significantly better regeneration of *Olea europaea* subsp. *cuspidata* in the fenced areas (Aynekulu et al. 2009).

General objectives of this study

The objectives of the present study are:

(1) To present an image of the current woody species composition, diversity, and population structure (DBH, height, density, frequency) in the forested area in GBG and to see this in the light of the history of the area.

(2) To provide a preserved baseline dataset with floristic and structural data on the woody species from the GBG conservation area for future monitoring and analyses of the changes in the vegetation.

(3) To illustrate the replacement of *Eucalyptus* plantations with regenerating native forest and to briefly discuss this process in relation to nearby dry Afromontane forests and their phytosociological plant communities.

MATERIALS AND METHODS

History, geographical location, geology and soil of the GBG on the slope of the Entoto hill; establishment and removal of Eucalyptus

It is not customary to study vegetation in managed botanic gardens, but the removal of the *Eucalyptus* trees from the forested area in GBG presents an opportunity to study the succession of the vegetation and compare this with findings from *Juniperus* forests elsewhere. The process was initiated slightly more than 10 years ago, when the GBG was officially established with the signing of a memorandum of understanding between the town authorities and the Addis Ababa University on October 9th 2009, ensuring the allocation of 705 hectares of land for a botanic garden with a conservation area of ca. 621 ha and approximately 100 ha of cultivated garden (Reeder 2013). A legal proclamation on the GBG, No. 18 in the official Addis Negari Gazeta (2009), appeared soon after the signing of the memorandum.

The GBG was established on the site of a mosaic of regenerating forest patches and *Eucalyptus* plantations. The planting of *Eucalyptus* on the slopes of the Entoto hill began soon after the foundation of Addis Ababa in 1885, when Emperor Menelik II in 1895 ordered the planting of *Eucalyptus* imported from Australia to provide wood and fuel for the growing Addis Ababa population (Pohjonen and Pukkala 1990; Pankhurst 2001). In the first years after this introduction, tax relief for land planted with *Eucalyptus* and free distribution of seed rapidly increased planting. During the Italian occupation in 1935-1940, Italian foresters estimated that over 5000 ha around Addis Ababa were covered with *Eucalyptus*. A study of aerial photographs in 1:20,000 allowed Horvath (1968) to draw a map of the *Eucalyptus* plantations, which then extended over 24,500 ha around the city, particularly on Entoto and the western side of the city, and of this area 13,500 ha were densely planted with *Eucalyptus*. Horvath further pointed out that the intensive cultivation of *Eucalyptus* caused serious erosion on the slopes of Entoto, where there was no undergrowth. The major objectives of the GBG, are now conservation, research, education, and ecotourism (Seta and Belay 2021; Borsch and Löhne 2014). Some non-native species have been introduced in the conservation area during tree planting initiatives (Ayele 2020), including the "green legacy programs".

The outer limits of the GBG boundary are between latitudes 9°03'36"(= 9.060°) and 9°05'42" (= 9.095°) N and between longitudes 38°41'24" (= 38.69°) and 38°44'24" (= 38.740°) E and the altitude range is between 2575 and 2950 m a.s.l. The rock type and soil of GBG (silicics) is described in Agonafir and Worku (2017). The southern half of the GBG is comparatively flat while the northern half is quite mountainous. Two perennial watercourses originate from the mountainous area and flow southwards towards the city centre (Figure 1).

Beginning before 2019 and continuing after the field work for this study, stumps and coppices of *Eucalyptus* were being debarked until the trees were dead, and native trees were allowed to regenerate naturally. Images from different stages in the removal of *Eucalyptus* are presented here. Figure 2 and 3 show views of the upper part of the GBG conservation area before the systematic removal of *Eucalyptus* began. Figure 2 shows the upper boundary road of GBG. Figure 3 shows a view from a prominent rocky outcrop slightly lower down with the line of sight towards Entoto. Figure 4 shows an early stage in the regeneration of the natural vegetation after removal of the *Eucalyptus*. Figure 5 shows a slightly later stage after removal of the *Eucalyptus* with older specimens of *Juniperus procera*.

Previous studies of the vegetation in the GBG and adjacent vegetation on Mt Entoto

An open vegetation in which young regenerating *Juniperus procera* (Debushe 2008) make up 95.16% of the Basal Area (Debushe et al. 2015) is described from Entoto. Data from the *Eucalyptus* plantations with regeneration of natural vegetation on Mt. Entoto were gathered and analysed by Atinafe et al. (2020). By then, Entoto was still dominated by *Eucalyptus* in terms of number of individuals; with 952 individuals/ha for *Eucalyptus globulus*, 369 individuals/ha for *Juniperus procera* and 304 individuals/ha for *Carissa spinarum*.

In a study of the conservation area of GBG (Reeder 2013), it was attempted to provide a baseline dataset

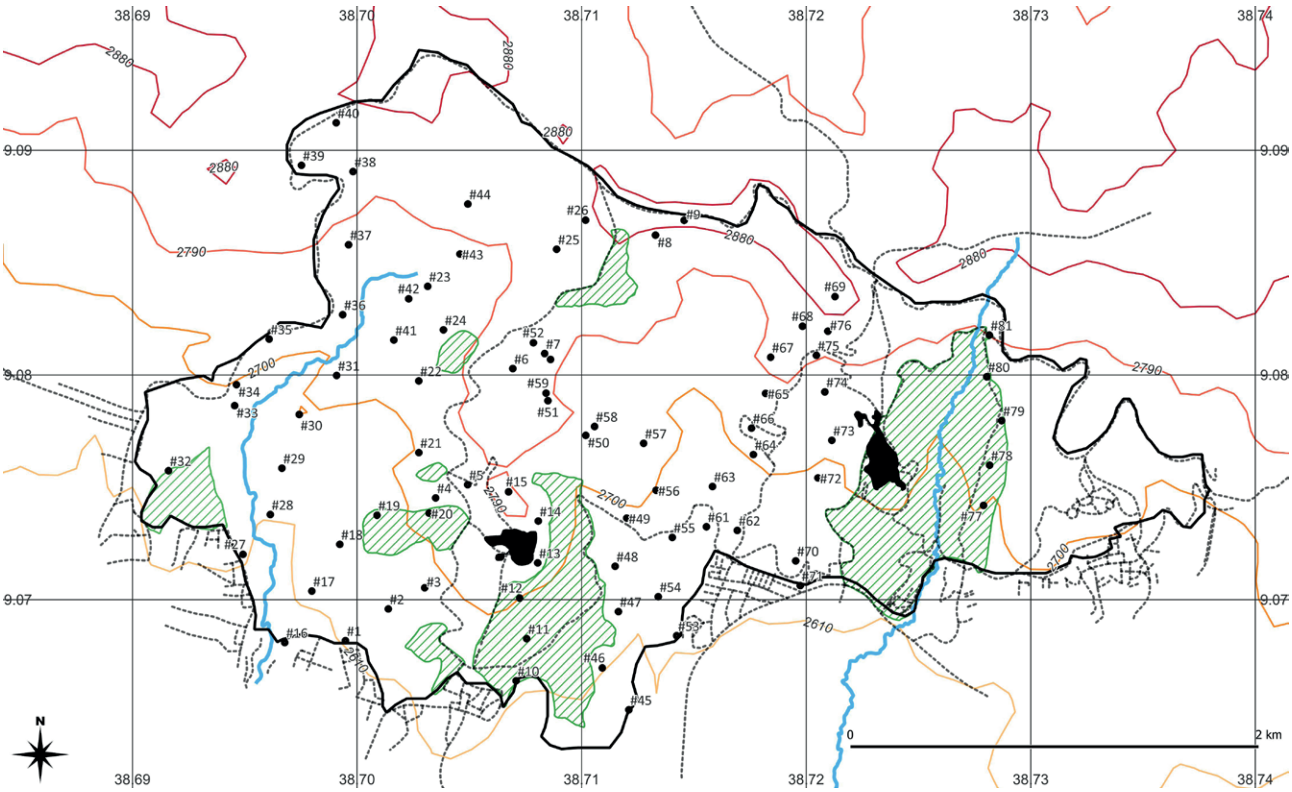

Figure 1. Map of the Gullele Botanic Garden, showing altitude as contour lines (90 m spacing), management areas (green hashed polygons) and the location of the plots (with numbering). The two permanent steams are represented by blue lines; the roads network is represented by dashed lines. The areas in black are the visitor centre in the eastern part of the GBG and the Kalu Beterara Abune Habtemariam Monastery and church in the centre-south-western part. The contour lines are derived from CGIAR-CSI SRTM 90m Digital Elevation Database on https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/. The management areas have had work or combination of works carried out in them including terracing, planting and/or enclosure and mulching of seedlings.

Figure 2. Trail along the upper boundary of the GBG with mixture of *Eucalyptus* and indigenous trees before the systematic removal of *Eucalyptus* began. Young plants of *Eucalyptus globulus* with characteristic glaucous leaves are seen in the background to the left of the trail and nearer the foreground to the right. (Ca. 9.0939° N, 38.7028° E; ca. 2900 m a.s.l.). Photo by Ib Friis, 2005.

Figure 3. View towards forests and plantations on the Entoto towards the east from the rocky ledge above 2790 m a.s.l. that divides the upper part of GBG. Photo taken before the removal of *Eucalyptus* began. A few tall trees of *Eucalyptus globulus* can be seen to the left in the foreground and underneath these trees there is prolific regrowth of glaucous resprouting from tree stumps. (Ca. 9.0892° N, 38.7042° E). Photo by Ib Friis, 2005.

Figure 4. An early stage in the regenerating forest in the rocky western part of GBG being reclaimed by *Juniperus procera*. The image was taken some time after cutting and debarking of *Eucalyptus*. Older trees of *Juniperus* are seen in the background surrounding stipes of *Eucalyptus*. [9.0702° N, 38.6999° E; ca. 2650 m a.s.l. Photo by Ergua Atinafe, April 2023].

Figure 5. Later stage of regenerating *Juniperus* forest in an area previously with *Eucalyptus*. In the background the westernmost part of Addis Ababa can be seen. Also visible is the isolated volcanic hill with the Menagesha Amba Mariam Forest, a northern outlier of the much larger Menagesha Suba Forest on Mt. Wuchacha (9.0693° N, 38.7005° E; ca. 2650 m a.s.l.). Photo by Ergua Atinafe, April 2023.

for future research and management practices, but the main focus was on biomass and carbon storage, and floristic analyses or a classification into local community types was not presented. Based on trees with a DBH above 5 cm, *Eucalyptus globulus* (the only *Eucalyptus* species mentioned) accounted for 63% of the number of trees per hectare (with average DBH of 16.6 cm and on average 14.6 m tall) compared to 25.1% of the number of trees per hectare for *Juniperus procera* (with average DBH of 24.9 cm and on average 9.3 m tall) (Reeder 2013). A later study confirmed the finding by Reeder that *Eucalyptus* was the most important taxon for carbon storage in GBG (Woldegerima et al. 2017).

Sampling design

In the present study a total of 81 vegetation plots the size of 20 × 20 m (400 m^2) were positioned across GBG to cover almost the whole extent of the area (Figure 1). Systematic sampling design used to collect vegetation data and topographic variables followed the methods used by previous authors of similar studies (Bogale et al. 2017; Yineger et al. 2008). Altitude and geographical position were recorded for each plot with a Garmin GPSMAP 62. Woody species inside and outside the plots were recorded to produce a complete inventory of the woody plants in GBG. Nomenclature and taxonomy of all species followed the Flora of Ethiopia and Eritrea (with exception of *Osyris lanceolata* Hochst. & Steud.). The identification of the material was confirmed against specimens at the National Herbarium (ETH), Addis Ababa University, and duplicates of herbarium specimens were deposited at ETH, and at the GBG Herbarium. In addition, the presence of different disturbance types (e.g. grazing/browsing, erosion and anthropogenic disturbance) in and around each quadrate were recorded, following Asefa et al. (2015). Data collection took place from October to November 2019 and February to April and June 2020.

Vegetation data collection

The number of individuals per species (of tree, shrub, and woody climber) were counted in each plot. Diameter at Breast Height (DBH) was measured at about 1.3 m from the ground using a tree calliper and recorded if the trees or shrubs had a DBH > 2.5 cm or a height above 3m. Individual trees and shrubs with multiple stems which forked below 1.3 m height were treated as a single individual (Ayanaw and Dalle 2018) by summing up the DBH of the stems; this is particularly relevant in the cases where stumps of *Eucalyptus* have regenerated by producing stubble shoots or suckers. The tree height (from ground level to the top of the crown) was measured using a clinometer.

Structural data analysis

The DBH and height measurements were compiled into an Excel file to calculate the sum DBH per plot, the Basal Area (BA), the number of individuals that had a

DBH and height measurement, plot DBH against height and to calculate the ratio of small sized individuals (< 10 cm) to bigger sized individuals (> 10 cm) for selected species. The BA of the plot and per ha was calculated from the sum of all measured trees (using the DBH as the diameter in assumed circular trunks). The structural data of DBH and height are summarised per plot and per selected species, and these findings were compared to findings by Reeder (2013).

Species and number of individuals per species per plot were compiled into an Excel file in preparation for the clustering and ordination analyses. The frequency (F, the number of quadrats in which the species is encountered in %) of species, including singletons, was calculated from this dataset.

Plant Community Analyses: clustering and ordination

The Excel file with the number of individuals per species was imported into PC-ORD7 (McCune and Mefford 1999; McCune et al. 2002). The resulting plot/species matrix (matrix1) was used to calculate for each plot the number of species; number of individuals; Shannon–Wiener diversity index ($H' = -\Sigma p_i \times (\ln p_i)$, where p_i is the proportion of each species in the sample); Simpson's reciprocal diversity index ($DS = N \times (N-1) / \Sigma ni \times (ni-1)$, where N is the total number of individuals and n is the number of individuals of each species), and Simpson evenness index, calculated by dividing the Shannon diversity index by its maximum value ($=H'/H'_{max}$). A second data matrix (plot/factor matrix; matrix2) was set up with these data in addition to topographical parameters for each plot: altitude; latitude; longitude; and disturbance types recorded in the field. The number of individuals and sum of DBH were added for the dominant species (*Eucalyptus* spp. and *Juniperus procera*).

The clustering for the plant community analysis is based on the number of individuals per species per plot for species occurring in at least three plots. The space conserving linkage method flexible beta (with a beta value of -0.25 and -0.80) was used in combination with Sørensen's compatible distance measure. The high negative value of flexible beta is space expanding, it groups plots more intensely and reduces chaining in relation to the more commonly used group average or nearest neighbour methods (McCune et al. 2002).

Senbeta (2006) stated that in community analysis, a common goal is to detect and describe the value of different species for indicating environmental conditions. An indicator species of a particular group should be faithful to that group. An indicator species analysis (ISA) was carried out in PC-ORD7 (quantitative or binary response, ISA eqn. 1 in Dufrêne & Legendre 1997) on the previously identified clusters. A Monte Carlo test of significance with 4999 permutations was carried out. The average p-values from the Monte Carlo test for different numbers of clusters were used to determine the optimal number of clusters and to identify possible significant indicator species for those clusters.

The non-metric multidimensional scaling (NMS) facility in PC-ORD7 was used to produce ordinations based on a matrix1 with two versions of the same plots, once with and once without data on *Eucalyptus*. The default settings of the autopilot on slow speed and thoroughness with 250 runs on the real data were selected in the setup in PC-ORD7. The stability of the final solution was confirmed by looking for a flat line when plotting stress versus iteration number, and the number of iterations was selected accordingly. The NMS ordination method was preferred since it can handle data that has no known parametrical distribution. We chose the Sørensen distance measure to express floristic dissimilarity, as it gives no weight to species with double absence in plot pairs and because Sørensen distance was used in the clustering. The species included in our ordinations are those present in at least three plots. Species occurring in one or two plots only were considered statistically meaningless.

Vegetation types in nearby natural forests as identified by previous authors were compared to the plots in GBG by running an NMS ordination based on presence/absence data of 32 species. The species data for the different vegetation types were extracted from Table 1 in Bekele (1993) and Table 4 in Beche (2011). The number of axes was set to 2, with 250 runs.

RESULTS AND DISCUSSIONS

Floristic composition and life forms of woody species

In the course of this study, 104 woody plant species belonging to 84 genera and 47 families were recorded in GBG, of which 79 were recorded inside the 81 plots. A species-area curve was constructed in order to see if the plots adequately represented the diversity of the vegetation, and the curve levelled out within the number of plots studied in this paper. The average number of species per plot is 17.4 with a minimum of 4 (plots 19 and 20) and a maximum of 30 species (plot 81). There are 18 species that occur in one plot only. These singletons and species occurring in only two plots were omitted from the ordination and clustering analyses. Appendix 1 provides recorded and derived information about the plots including, altitude, slope, number of species, number of individuals (all, *Juniperus* only, other native species, individuals with a DBH and height measurement), ratio of smaller to bigger individuals, DBH (sum, maximum, for *Juniperus*), BA, height of the tallest tree, diversity indices and disturbances recorded in the field. Appendix 2 lists the species recorded in GBG and provides additional information derived from the data collected for this study or found in the literature. The values obtained for the Simpson Diversity index are shown in Figure 6 – the most diverse plots are located in the north western part of the garden where the old *Eucalyptus* stands had not yet been destroyed when this study was made. The life form distribution of the species is 38 trees (36.54 %), 50 shrubs (48.1 %), 10 tree/shrubs (9.6 %), and 6 climbers (5.77 %). Eleven species are endemic to Ethiopia, and 14 are non-native species that have been introduced to Ethiopia. Fabaceae and Asteraceae are the most dominant families with 11 and 10 species respectively, followed by Myrtaceae and Rosaceae with 6 and 5 species respectively. One *Acacia*, one *Helichrysum* and one *Indigofera* species could not be determined to species level. There may be a doubt about the identity of the *Pittosporum* species in GBG, but it is either *P. abyssinicum* Del. or *P. viridiflorum* Sims (See Appendix 2).

Table 1. Number of native woody species from forests on the highland plateau. The species lists provided in the studies were reassessed to follow the same concept for woody species. Species considered as woody by one author may not have been recorded by a different author. Climbers are only counted if they are shared with GBG.

Forests and studies	Shrubs and/or trees	Climbers shared with GBG	Cumulative total	Shared with the 87 species in GBG
Wof Washa			**126**	**68**
Bekele 1993	28	0	28	21
Teketay & Bekele 1995	54	4	58	37
Fisaha et al. 2013	57	0	57	40
Tilahun 2018	90	7	97	61
Yirga et al. 2019	72	4	76	47
Menagesha			**113**	**71**
Demissew 1988	47	2	49	39
Bekele 1993	30	0	30	27
Fetene et al. 2010	72	8	80	58
Beche 2011	80	5	85	57
Tilahun et al. 2015	32	0	32	30
Chilimo			**81**	**57**
Bekele 1993	28	0	28	24
Soromessa & Kelbessa 2014	71	6	77	55
Siraj & Zhang 2018	40	1	41	31
Entoto			**69**	**61**
Debushe et al. 2015	30	4	34	30
Atinafe et al. 2020	58	9	67	60

GBG shares many of its native woody species with nearby natural and semi-natural forests (Table 1). On one hand, the percentage of species that nearby regenerating or mature forests share with GBG are in decreasing order: 88% for Entoto (61 out of 69 species), 70 % for Chilimo, 63% for Menagesha (both Suba and Amba Mariam) and 54% for Wof Washa. On the other hand GBG shares 82% of its species with Menagesha (71 out of 87), 78% with Wof Washa, 70% with Entoto and 65% with Chilimo.

Density of woody species

The plant species in GBG with the highest density is *Juniperus procera* (with 405.9 individuals/ha) and the least dense species for which DBH data was recorded are the singletons (with less than one individual/ha). The ten woody species with the highest abundance of individuals based on the floristic analysis data and in order of decreasing density are: *Juniperus procera*, *Eucalyptus globulus*, *Rosa abyssinica*, *Eucalyptus camaldulensis*, *Olinia rochetiana*, *Myrsine africana*, *Vernonia leopoldii*, *Sideroxylon oxyacanthum*, *Smilax aspera* and *Carissa spinarum*. See Appendix 2 for the density of the species.

Frequency

The frequency gives an approximate indication of the homogeneity and heterogeneity of a forest stand. A high number of species with high frequency values and few species with low frequency values show homogeneity in forest composition (Ayanaw and Dalle 2018; Mahajan and Fatima 2017). Conversely, a low number of species with high frequency values shows heterogeneity. Our data shows a high number of species with low values for frequency (many not-common species; 33 species occur in less than 5% of plots) and relatively few species have a high frequency (few common species; only two species occur in more than 75% of the plots). These results suggest a high degree of floristic heterogeneity in GBG. *Juniperus procera* and *Rosa abyssinica* are the two most frequent species, followed by *Maytenus arbutifolia*, *Myrsine africana*, *Maytenus addat*, and *Olinia rochetiana*. The species with the lowest frequency (1.2%) were often species that according to Friis et al. (2010, 2011: 81-88 & 103) are characteristic of forest margins of both DAF forests and to some extent also margins of Moist evergreen Afromontane Forest (MAF), such as *Calpurnia* *aurea*, *Erythrina brucei*, *Leonotis ocymifolia*, *Phytolacca dodecandra*, *Salix subserrata*, and *Vernonia adoensis*. See data for frequencies in Appendix 2.

Diameter at Breast Height (DBH), size-structure and Basal Area (BA)

The sum of DBH measurements is presented per plot in Appendix 1, and per species in Appendix 2. The sum of DBH per plot for all species and the sum of DBH of the *Eucalyptus* per plot is shown in the map in Figure 6. The population structure of *Juniperus procera*, *Eucalyptus* and 34 native woody species in all plots in the GBG is presented in Figure 7 in terms of the number of individuals in different DBH classes. A high number of individuals was observed in the lowest DBH class (≤10 cm) with consecutive reduction towards the highest DBH class for both *Juniperus procera*, for *Eucalyptus* and for the group of 34 native species. This trend with many young and few old and large trees depicts healthy populations with good recruitment (Wassie et al. 2005; Siraj and Zhang 2018). Some species have a naturally low DBH and do not grow further once they reach the maximum limit of trunk-size for the species, this is for example the case with *Maytenus arbutifolia*, *Olinia rochetiana* and *Rosa abyssinica*. The results presented by Reeder (2013) based on data collected 10 years ago show a different trend in the distribution of DBH classes for *Juniperus procera*, *Eucalyptus* (only one species of *Eucalyptus* mentioned) and 12 other native species. Reeder reports more individuals per unit area in the 10.1-20 cm DBH class than in the ≤10 cm DBH class for *Juniperus procera* and *Eucalyptus*. It is difficult to assess if this is due to a different sampling protocol or reflects real changes in the population structure of these species. Reeder may have started to measure individuals from 5 cm in diameter and above (not from 2.5 cm) and he did not study the more disturbed parts of the forest where young specimens of *Juniperus procera* are most prominent (the present study covers nearly all parts of GBG). The predominance of small sized individuals in plots can be due to

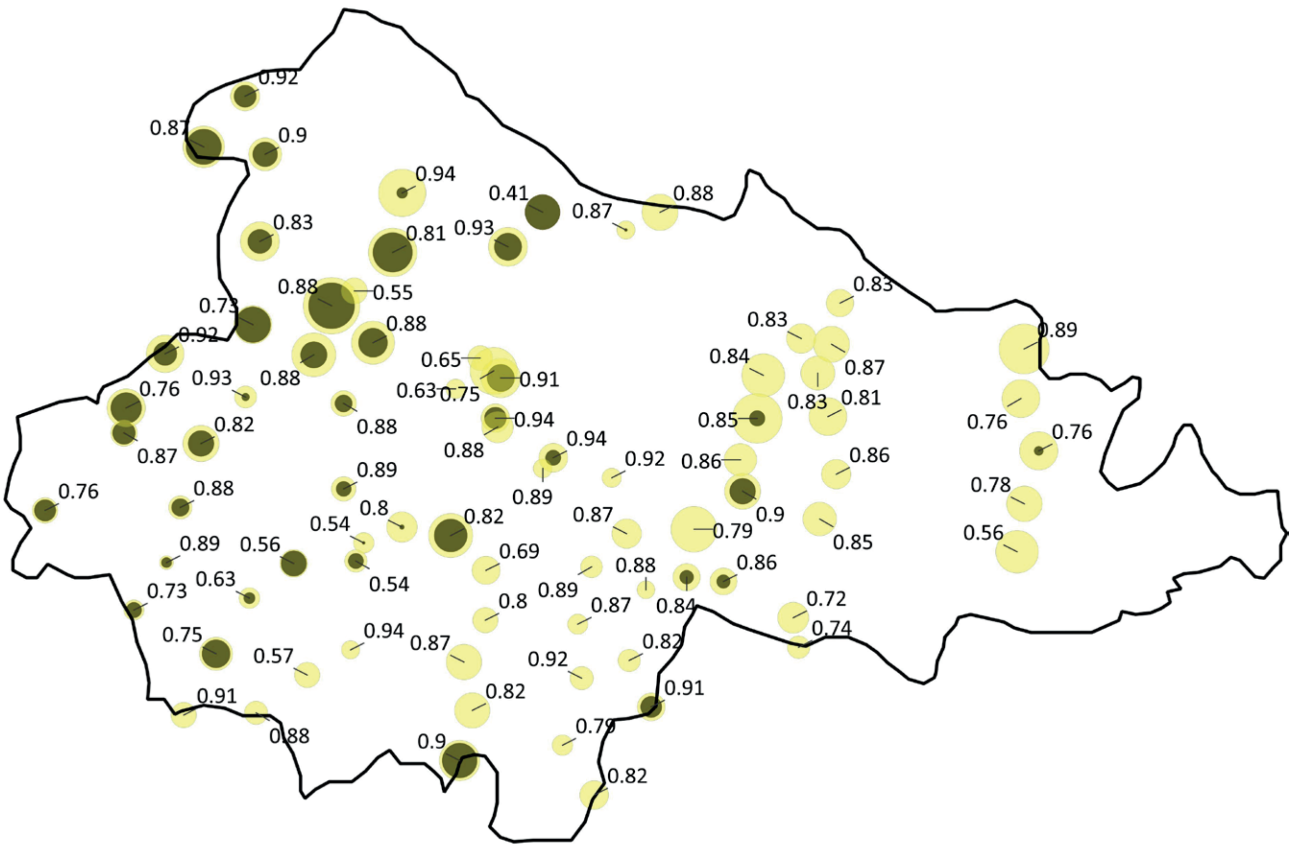

Figure 6. Map showing DBH and the Simpson Diversity index per plot (numbers next to the plots). The size of the plot symbol is relative to the total DBH of all species measured in the plot (open yellow circles) and of the two species of *Eucalyptus* in the plot (filled darker circles). Some plots in the eastern part of the GBG already had all *Eucalyptus* removed at the time of data collection.

recruitment of individuals from the soil seed bank or to the removal of bigger trees in the past (Siraj and Zhang 2018). More native woody species were recorded during this study than were recorded by Reeder (2013) and by Woldegermia et al. (2017) (see Appendix 2), but it is difficult to say if there has been a progressive addition of species to the study area or if species have been missed in previous studies.

Basal Area (BA) per plot for trees that have DBH > 3 cm is listed in Appendix 1, and the total basal area (BA) of woody plants in GBG is 12.91 m^2/ha, which is much lower compared with what has been reported from natural forests in the highlands, suggesting a large number of young individual trees. In the central Ethiopian plateau Chilimo Gaji forest has a BA of 27.3 m^2/ha, and Menagesha Suba forest has a BA of 32.4 m^2/ha (Bekele 1993). Chilimo Gaji forest is reported to have a BA= 454.52 m^2/ha (Siraj & Zhang 2018), but this seems unlikely, because it is about 17 times as high than the figure given elsewhere (Bekele 1993; Table 10) for individuals with a DBH > 10 cm. The BA/ha is dependent on what size of woody plants is included in the calculation of the BA (all individuals or individuals above a certain DBH) and what part of the forest is studied. The BA in the GBG is greater than that of other ecologically similar areas on Mt Entoto where Debushe et al. (2015) report a BA of 4.9 m^2/ha. The BA of species is thought to provide a better measure of the relative importance of the species than simple stem count (Endris et al. 2017). In this study, BA analysis across individual species revealed that there was high dominance in the woody vegetation by either very few and large individuals or by small and numerous individuals of different species. Differences in growth forms could be important; the shrubby and slender species *Maytenus addat* is quite dense but its contribution to the basal area is minimal, the same result is reported by Ayanaw & Dalle (2018). The following four species make the largest contribution to the basal area: *Juniperus procera* has the largest BA with 8.8 m^2/ha, followed by *Eucalyptus globulus* 2.6 m^2/ha, *Eucalyptus camaldulensis* 0.9 m^2/ha and *Olinia rochetiana* 0.11 m^2/ha. The remaining 35 species have a cumulative BA of 0.48 m^2/ha.

Height class distributions

Woody plant height measurements provide valuable insight into the vertical structure of forest stands (Stepper et al. 2015). Height can be used as an indicator of the age of the forest (Hall 1984; Boz and Maryo 2020). In GBG the density of individuals gradually decreases with increasing height. The individuals measured for height, excluding *Eucalyptus*, count 280 individuals/ha that are up to 9 m tall, 246.3 individuals/ha that are up to 21 m tall and only 5.5 individuals/ha that are over 21 m tall. Similar results were reported from natural forests by Bogale et al. (2017) and Bekele (1993). Plots sampled across the entire GBG show a fair amount of variability in average DBH and height as can be seen in Figure 8, where the average height/DBH ratios are shown for all woody species, *Juniperus procera* native woody species excluding *Juniperus procera* and *Eucalyptus*. Most plots have an average height for *Juniperus procera* that is much lower than the maximum height of 30 m or more indicated by Hall (1984). The variation in DBH and height between the different parts of GBG is almost certainly due to difference in history.

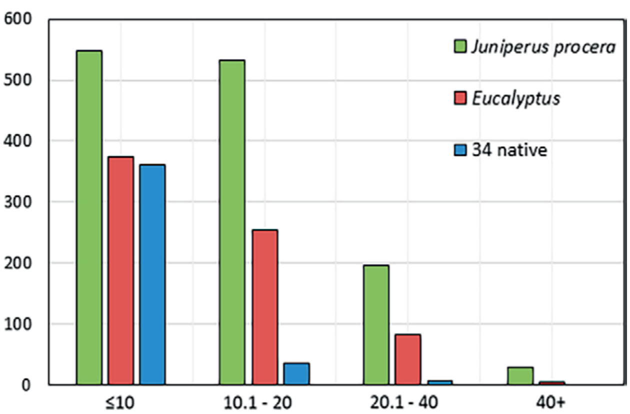

Figure 7. Population structure showing the DBH in cm of *Juniperus procera*, *Eucalyptus* and a group of 34 native species. The y axis represents the number of individuals from all 81 plots (= 3.24 ha).

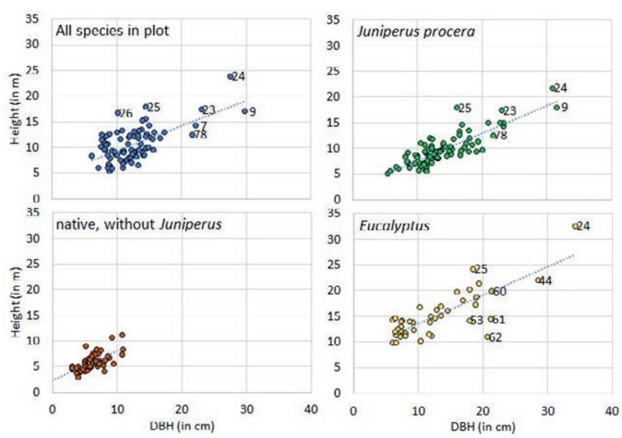

Figure 8. Average height against average DBH by plot. The plotnumbers for plots with high DBH and/or height are given.

Plant Community Analyses: clustering and ordination; influence of removal of Eucalyptus

Plant community analysis is done as a standard procedure in many forest studies. The floristic records from 81 plots in GBG were initially analysed with various clustering and ordination methods and there was notable variation in the resulting clusters. It must be an important part of a community analysis to decide if the clusters reflect natural groups. The clustering method (beta flexible linkage) was selected because this combination gave the lowest amounts of chaining.

None of the species that occur in at least three plots were identified as outliers in the outlier analysis in PC-ORD7. For the study units, plots 19, 26 and 48 were identified as outliers. Clustering including and excluding data from these plots didn't change the overall architecture of the dendrograms, but all three plots featured on very long branches as singleton-sister to a cluster of several other plots.

The best number of high-level clusters was identified by an Indicator Species Analysis (ISA). The lowest average p-value was obtained for four clusters when flexible beta was -0.80 and for 10 cluster when flexible beta was -0.25. The solution with few plots and low average p-values was selected. The four clusters are hierarchically arranged like this: first dichotomy between 1 and 2; second dichotomy between 1.1 and 1.2, and third dichotomy between1.1a and 1.1b.

The ISA yields values for relative frequency, relative abundance, and significance (p-value in the Monte Carlo test) for all the species used in the analysis. Although some species scored as significant in the Monte-Carlo test, none of them were specific to a particular cluster. This suggests that the woody vegetation in the plots across GBG is heterogeneous and without well-defined plant communities, and we have therefore not named the clusters 1.1a, 1.1b, 1.2 and 2 with plant names derived from Indicator Species. Figure 9 shows that in some parts of the study area some plots belonging to the same cluster are found in proximity to each other, for example a row of plots belonging to cluster 1.2 (plots 17-20) in the southwestern part of the GBG and the plots around the visitors' centre (plots 65-81) belonging to cluster 2, but there is no consistent pattern.

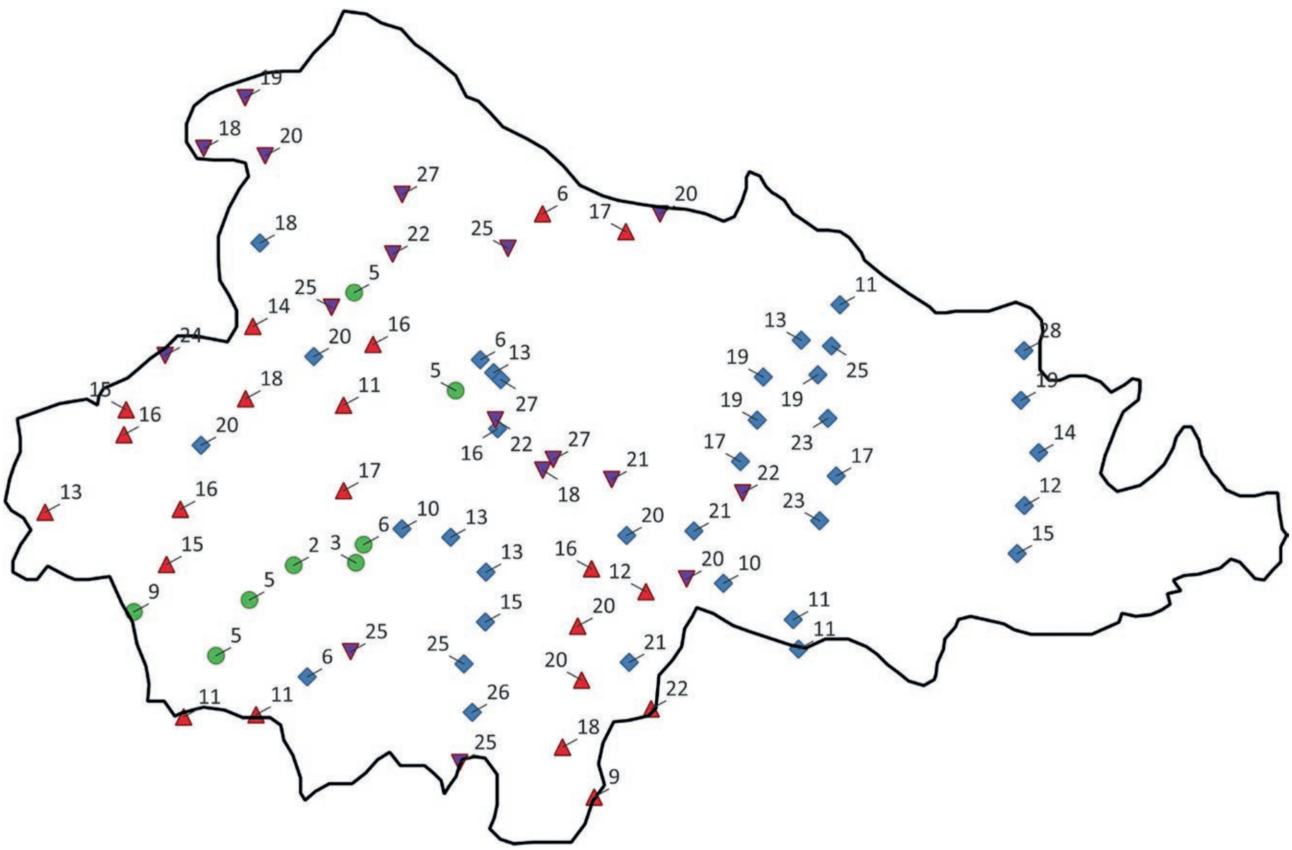

Figure 9. Map with assignment of the plots to the four clusters in our analysis (red triangles to cluster 1.1a, purple inverse triangles to cluster 1.1b, dark green circles to cluster 1.2, dark blue diamonds to cluster 2). The figures at each plot indicate the number of species that were used in the clustering and ordination (only species present in at least three plots and without data for *Eucalyptus*).

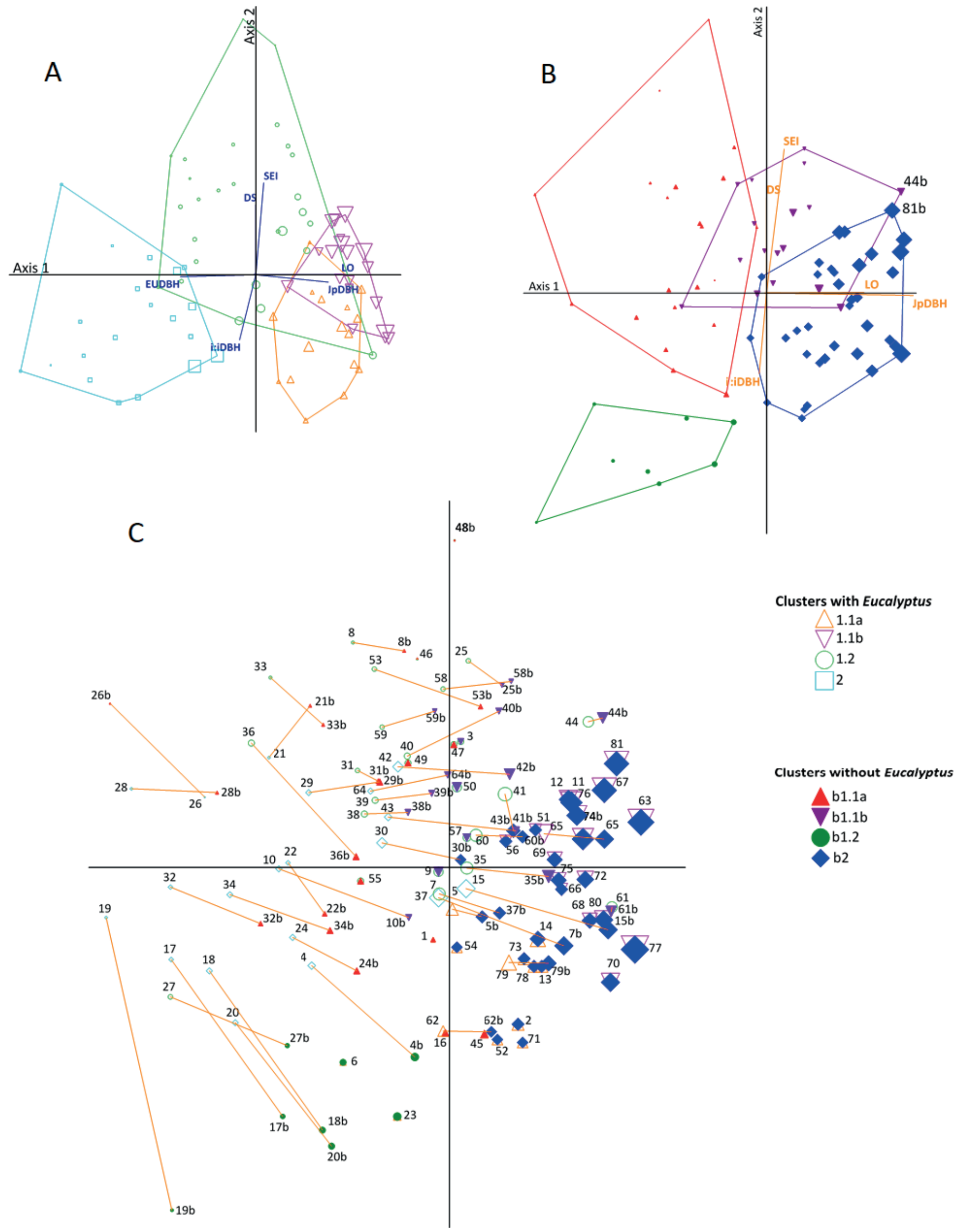

Figure 10. NMS ordination graphs based on numbers of individuals of species present in three plots or more. The points represent plots, the symbols indicate assignment to clusters (with convex hulls around the clusters in A and B). The size of the symbols is proportional to the number of individuals of *Juniperus procera* present in the plots. The axes are rescaled proportionate to the axis with the maximum range, and axis 1 has been rotated to be parallel with the vector longitude (LO). The vector EUDBH represents the sum DBH from *Eucalyptus* spp.; other vector abbreviations are explained in Appendix 1 (not all vectors with a cutoff r^2 value of 0.200 are shown). 10-A: Plot data including *Eucalyptus globulus* and *Eucalyptus camaldulensis*. The final stress for 2-dimensional solution is 23.179, and for 3-dimensional solution: 16.368. The average initial stress is 34.6118. MEASURES OF FIT R^2n (nonmetric fit): 0.9732. 10-B: Plot data excluding all records of *Eucalyptus*. The final stress for 2-dimensional solution is 20.629, and for 3-dimensional solution: 14.976. The average initial stress is 34.9922. MEASURES OF FIT R^2n (nonmetric fit): 0.9776. 10-C: Change in NMS ordination graph caused by the removal of Eucalyptus data. The plots are represented twice in the ordination: plots with numbers only represent all species data, plots with numbers marked with "b" represent the plots without data for *Eucalyptus*. Note that some plots, mainly to the right in the graph, were without *Eucalyptus* when the study was made and are only represented with plots with "b" numbers. For the other plots, the orange lines represent "pseudo-successional vectors" between the plots with *Eucalyptus* and those with the data on *Eucalyptus* removed. The initial stress in the real data is 38.502. The final stress for 2-dimensional solution is 24.100 and for 3-dimensional solution: 14.976. The average initial stress is 34.9581. MEASURES OF FIT R^2n (nonmetric fit): 0.9712.

An NMS calculation yields a graph of the cloud of plot points in 2 or 3 dimensions. The results in PC-ORD7 (autopilot settings) consistently recommend a three-dimensional representation. For the sake of brevity, only axes 1 and 2 are shown here (Figure 10A-C). The NMS point cloud clusters relatively uniformly around its centroid for the graph with *Eucalyptus*, the graph without *Eucalyptus* and the combined graph showing both versions of the plots when the *Eucalyptus* data was removed from the data. Given the results from the ISA a strong division of the cloud is not expected. *Juniperus procera* is particularly prominent in cluster b1.1b and cluster b2 (Figure 10-A and 10-B respectively). The comparison of the cluster analysis with the result of the ordination was carried out because in the study of Ethiopian forests cluster analyses are standard procedure, leading to designation of plant communities named from the names of the indicator species. It is relevant to document that in the GBG we did not find clearly defined vegetation types by clustering. The changes to the position of the plots to be expected by the physical removal of *Eucalyptus* across the GBG is illustrated by Figure 10-C.

The plots with high diversity and evenness (DS and SEI vectors in Figure 10A and 10B) may represent the oldest parts of the forest in GBG. The identical left to right direction of the vectors LO and JpDBH suggests higher dominance of *Juniperus procera* in the eastern part of the GBG (Figure 10-B), and the opposite trend is indicated by the direction of vector EUDBH (Figure 10-A). The exclusion of *Eucalyptus* in the dataset provoques a shift of the plots from the left side of the graph to the right (Figure 10-C). High values of the parameter i:iDBH suggest regenerating vegetation with many young plants in the lower strata and fewer in the canopy.

Comparison of GBG clusters and of nearby forest types of Tamrat Bekele and Dinkissa Beche

As indicated in the paragraph on the natural forests around Addis Ababa and in combination with Table 1, many of the species present in GBG are shared with forests nearby. As shown by the community and Indicator Species Analysis, the clusters identified in GBG are deeply influenced by the removal of *Eucalyptus*. We wanted none the less to comment on the similarity of GBG plots and clusters to the community types identified by Bekele (1993) and Beche (2011). The floristic contents of their vegetation types are here compared via an ordination of presence or absence of 32 species shared with GBG plots, as shown in Figure 11. This crude method does not take into account differences in sampling methodology and analysis. A number of GBG plots from different clusters (25, 44 and others) have a species composition similar, but not identical to that of vegetation type D3 described by Tamrat Bekele (*Erica arborea-Myrica salicifolia*). These are from the upper limit of the Afromontane forests, with a well-defined layer formed by *Erica arborea* up to 8 m and a discontinuous, presumably emergent layer formed by *Juniperus*). Plot 35 is closest to vegetation type C3 – *Dovyalis abyssinica-Myrsine africana* described by Dinkissa Beche. It is notable that the vegetation types of Tamrat Bekele have a species assemblage different from those described by Dinkissa Beche (though this may be due to incomplete data used in this analysis). D8 (*Juniperus procera-Maytenus arbutifolia-Peucedanum winkleri*) with plots from Wof-Washa is most similar to C2 *Sideroxylon oxyacanthum-Dovyalis verrucosa*) from Menagesha. The convex hull surrounding Tamrat Bekele's communities has only marginal overlap with the hulls surrounding the GBG clusters from the present study and there is no overlap of Dinkissa Beche communities with GBG plots. This agrees with our previous observation that the clusters found in the GBG data do not represent natural plant communities.

CONCLUSIONS AND RECOMMENDATIONS

Our findings on the distribution of DBH classes and height of trees suggest that *Juniperus procera* is recruiting well following the removal of *Eucalyptus* and that the recruitment appears to be similar to that happening after clear-felling or forest fires described in studies in East Africa (Gardner 1926; Wimbush 1937; Hall 1984; Bussmann 2001). Although some plots have trees of *Juniperus procera* that are more than 20 m high, very many *Juniperus* trees are currently much smaller and will according to the stated growth rates (Hall 1984; Pohjonen and Pukkala 1992) reach 8-10 m around or just before 2030. The diagram for *Juniperus procera* in Figure 8 shows an almost equal proportion of plots with *Juniperus* trees above and below ca. 10 m high, whereas the average height of other native species is nearly always less than 10 m. The following part of the life cycle of *Juniperus procera* until the trees reach their maximal height will (again according to Hall 1984; Pohjonen and Pukkala 1992) take another ca. 60 years and several hundred years before broad-leaved angiospermous trees gradually take over and more mixed forests with more broad-leaved species appear. If it is possible to find control plots in areas elsewhere on Entoto with a species composition similar to plots in GBG, it might be possible to evaluate the development in GBG better. Future studies would show how quickly more species get added to the

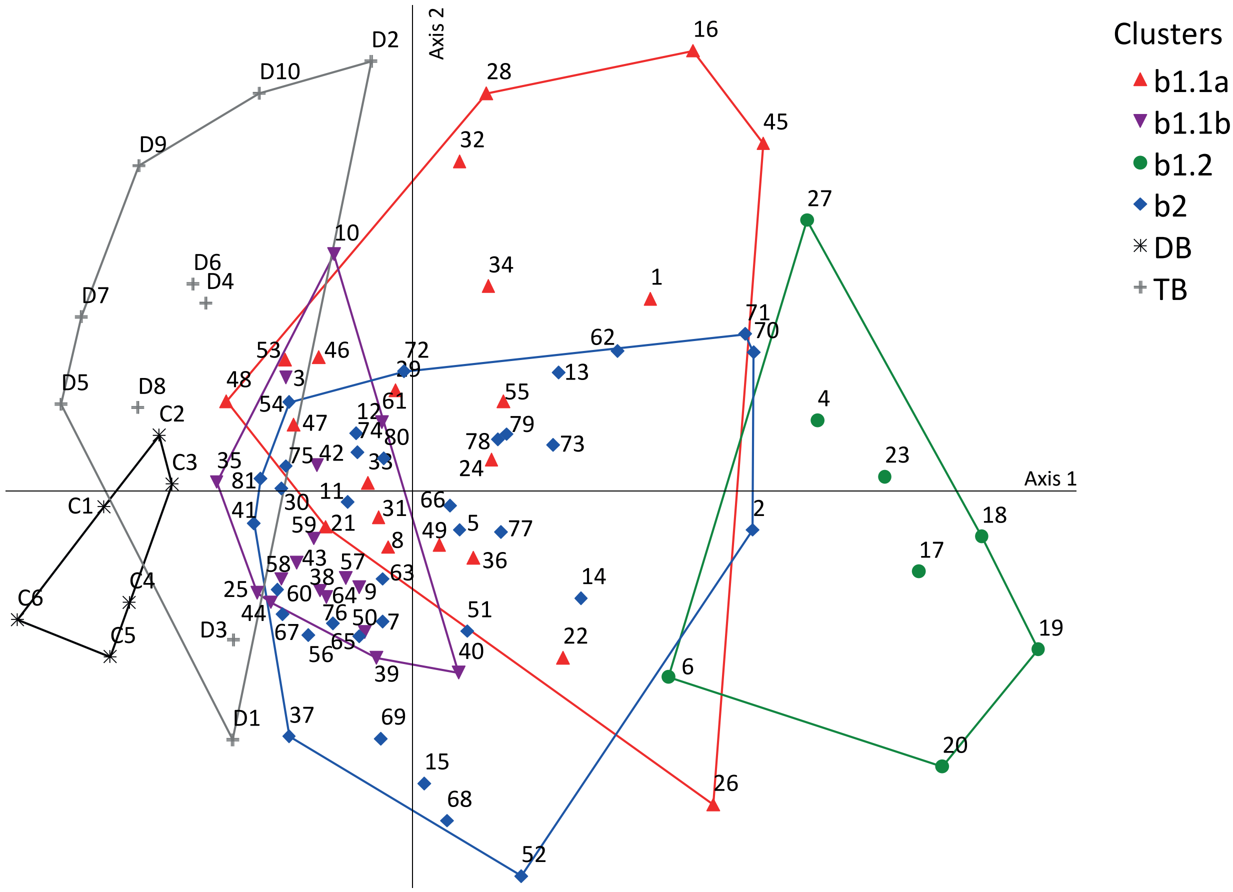

Figure 11. NMS ordination graph of the 81 plots (without *Eucalyptus* data) in the GBG and representative data from nearby natural forests studied by Tamrat Bekele and Dinkissa Beche (see text). The matrix used in the analysis is based on presence/absence data from 32 species. To the left, the grey clusters and the grey hull line represent vegetation types from the studies by Tamrat Bekele (TB = Bekele 1993) and the black clusters and the black hull line represent the vegetation types from Dinkissa Beche (DB = Beche 2011). The final stress for the 2-dimensional solution is 21.8079 from an average initial stress of 42.7674.

floristic mix in the plots that are currently dominated by *Juniperus procera* or if species disappear as more *Juniperus* specimens grow to taller height. It is well known from forests in other tropical countries that the species diversity is usually higher in regenerating forests than in mature forests (Eggeling 1947; Catford et al. 2012).

Currently, the vegetation of GBG is very heterogeneous, probably due to the history with *Eucalyptus* plantations being felled and the reclaiming of cleared areas by *Juniperus* at different times. Attempts in this paper to identify local community types gave the result that groups found by clustering analyses change very notably when the data on *Eucalyptus* are removed, and the clusters found inside the study area are not well defined and different from those found in nearby natural forests. The repositioning of the plots between clusters when *Eucalyptus* is removed, in combination with the life cycle of *Juniperus*, suggests that the conservation area will continue to see notable changes before a more stable equilibrium is reached, but the known life-spans for *Juniperus procera* forests (Hall 1984; Pohjonen and Pukkala 1992) suggest that these changes will take a long time. In order to follow the development in floristic composition, density, frequency, BDH, height class distribution and distribution of the plots on clusters, we suggest that repeat studies like the one documented in this paper be carried out at regular intervals, and with methods and plots closely comparable to those used in this study. Such repeat studies would provide valuable data both on the vegetation and the behaviour of the individual species. For these studied to be useful, it is necessary that the floristic dataset in the Appendices is preserved.

Unfortunately, we have no observations about the original vegetation of the GBG or data about older *Juni-*

perus trees from before the destruction of *Eucalyptus*, but it is known from other sources. when *Eucalyptus* was introduced around Addis Ababa in order to compensate for the destructive cutting of natural fuelwood, and we know that areas with *Eucalyptus* continued to expand until very recently (Horvath 1968). From the available information, we assume it likely that the situation at Gullele and Entoto sometime after 1895 was comparable to clear-felling of the forest, that very little natural forest can have regenerated while the *Eucalyptus* plantations expanded, and therefore most current populations of *Juniperus* on Entoto and at Gullele are much less than 100 years old.

We consider that a few recommendations derived from our practical experience with this project but not directly derived from our plot data are important for the sustainability of the biodiversity in the conservation area of the BGB. This is also in agreement with an established tradition in Ethiopian environmental studies:

(1) Although 70% of the GBG is set aside as a conservation area and basically left to natural regeneration, there are areas where forest management activities are being implemented, as shown in Figure 1. The management measures consist of terracing, planting and/or enclosure and mulching of planted seedlings, and activities necessary for soil conservation on sloping terrain. The management measures should be monitored, and planting of trees should only involve species belonging to the natural forest. In future studies of the development of the vegetation in GBG, special note should be taken of the development in the plots at the managed areas.

(2) Conservation is dependent on ecological, economical and related knowledge, so staff in scientific centres involved in conservation should continue utilizing their field knowledge and experience to conduct research and follow up on previous studies.

(3) As the conservation area inside the GBG is intended for conservation and research on natural forests, the GBG should discourage planting of non-indigenous species inside the conservation area of GBG. Planting during the “green legacy programs” should be done in degraded and unprotected areas around the city.

(4) Awareness on the executive and community levels should be promoted through programs informing about the objectives, goals, ecological and economical value of the garden and the result of research relevant to conservation, including results of studies such as this. In order to raise awareness of the resources in natural forests it is suggested that ethnobotanical studies of the plants in the GBG be carried out to explore the wealth of indigenous knowledge on the diversity of plants, thereby raising awareness of the uses of these plants.

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APPENDIX 1 – INFORMATION ABOUT PLOTS

The altitude was recorded in the field. Slope is derived from a GIS-layer provided by Reeder (2013) **SP** is the number of species and **i** is the number of individuals recorded for the floristic analysis and used to calculate the Shannon-Wiener diversity index (**H'**), the Shannon-Wiener evenness index (**SEI**) and the Simpson's reciprocal diversity index (**DS**). It includes species that occur in 2 or one plot. **iJp**, **inat** and **iDBH** are the numbers of individuals of *Juniperus procera*, of native species other than *Juniperus procera* and individuals with DBH measurements, respectively. The ratio **i:iDBH** is indicative of the number of small individuals in the shrub stratum in relation to number of bigger individuals. **Σ DBH** is the sum DBH of all DBH individuals in the plot. **Max DBH** and **Max H** are measurements of the thickest and tallest tree respectively measured in the plot. Values in brackets of Max H are for *Juniperus procera*, if the tallest species is a different species. **JpDBH** is the sum DBH from *Juniperus procera*. **BA** is the basal area. Erosion **(Er)**, grazing/browsing pressure by wildlife (**Gr/br**) and Anthropogenic factors (**Anthro.**) are types of disturbance recorded during the field work.

Plot	Altitude (m)	Clusters with *Eucalyptus*	Clusters without *Eucalyptus*	Slope	SP	i	iJp	inat	iDBH	i:iDBH	Σ DBH (cm)	Max DBH (cm)	JpDBH	BA	Max H (m)	H'	SEI	DS	Er	Gr/br	Anthro.
1	2611	1.1a	b1.1a	14	11	53	6	17	23	0.43	205.5	18	68	0.17	11 (9)	2.22	0.72	9.37	yes		
2	2644	1.1a	b2	7	6	32	20	0	20	0.63	238	32	238	0.29	20	1.2	0.39	2.43		yes	yes
3	2665	1.2	b1.1b	17	25	73	10	5	15	0.21	134.4	14	95	0.1	10	2.98	0.97	20.69			
4	2713	2	b1.2	4	7	68	13	0	14	0.21	165.4	20	158	0.17	15	1.1	0.36	2.19		yes	yes
5	2756	1.1a	b2	18	11	51	19	1	21	0.41	331	41	312	0.53	19	1.94	0.63	5.52			yes
6	2820	1.1a	b1.2	1	5	18	9	1	10	0.56	151	26	148	0.22	16	1.19	0.39	3		yes	yes
7	2822	2	b2	8	15	102	30	0	32	0.31	711.9	60	697	1.65	19	1.75	0.57	4.2		yes	
8	2858	1.2	b1.1a	23	18	67	4	6	11	0.16	135.3	33	93	0.21	18	2.4	0.78	8.54			
9	2980	1.2	b1.1b	27	21	49	14	1	15	0.31	447	65	442	1.3	26	2.64	0.85	10.32			
10	2623	2	b1.1b	11	29	70	10	1	36	0.51	543	32	112	0.76	29 (8)	1.82	0.59	12.08	yes		yes
11	2650	1.1b	b2	19	26	93	37	11	48	0.52	427.5	24	378.5	0.39	9	2.48	0.8	5.86			
12	2695	1.1b	b2	12	26	100	31	17	48	0.48	432.3	21	347.8	0.38	15	2.61	0.85	8.15	yes		yes
13	2737	1.1a	b2	7	15	50	20	2	22	0.44	238	19	232	0.25	15	2.1	0.68	5.37	yes		
14	2757	1.1a	b2	14	13	49	26	0	26	0.53	287.5	27	287.5	0.36	20	1.79	0.58	3.44	yes		yes
15	2795	2	b2	8	15	99	31	0	68	0.69	633.5	54	249.5	0.77	20	2.05	0.66	5.71	yes		yes
16	2575	1.1a	b1.1a	12	16	69	8	15	29	0.42	238.2	24	43	0.21	20 (6)	2.56	0.83	12.51			yes
17	2575	2	b1.2	9	9	48	7	3	43	0.9	383.1	65	59.75	0.56	26 (12)	1.64	0.53	4.19	yes		
18	2646	2	b1.2	6	7	49	9	1	20	0.41	167.2	19	100.3	0.14	22 (17)	1.27	0.41	2.78			
19	2685	2	b1.2	9	4	37	4	0	35	0.95	280.1	20	34	0.21	17 (10)	1	0.32	2.36	yes		
20	2735	2	b1.2	8	4	27	9	0	25	0.93	193.1	18	90	0.15	20 (15)	0.92	0.3	2.25			
21	2743	2	b1.1a	13	18	57	4	9	28	0.49	225.3	25	84	0.22	20 (16)	2.55	0.83	10.57			
22	2765	2	b1.1a	17	13	50	7	0	24	0.48	242.6	22	118	0.26	22	2.31	0.75	9.8	yes		
23	2780	1.1a	b1.2	7	5	17	11	0	11	0.65	254	36	254	0.51	21	1.12	0.36	2.39		yes	

Plot	Altitude (m)	Clusters with *Eucalyptus*	Clusters without *Eucalyptus*	Slope	SP	i	iJp	inat	iDBH	i:iDBH	Σ DBH (cm)	Max DBH (cm)	JpDBH	BA	Max H (m)	H'	SEI	DS	Er	Gr/br	Anthro.
24	2780	2	b1.1a	7	17	42	9	4	22	0.52	607.4	62	278	1.78	42 (32)	2.44	0.79	10.01			
25	2839	1.2	b1.1b	9	26	96	7	13	35	0.36	509.4	25.5	113	0.7	29 (22)	2.97	0.96	18.1			
26	2887	2	b1.1a	9	7	54	0	0	41	0.76	420.5	20	0	0.4	30 (0)	0.97	0.31	1.73	yes		yes
27	2620	1.2	b1.2	3	11	37	7	2	26	0.7	160.1	13	49	0.09	13 (8)	1.75	0.57	4.06			
28	2618	2	b1.1a	20	16	45	3	0	11	0.24	83.6	16.5	31.5	0.06	14	2.48	0.8	11	yes		
29	2660	2	b1.1a	19	17	72	8	0	27	0.38	207.3	16	77.5	0.14	20 (11)	2.46	0.8	9.4	yes		
30	2702	2	b2	9	21	96	16	1	52	0.54	448.7	21	194.5	0.35	17 (15)	2.31	0.75	5.95			
31	2727	1.2	b1.1a	11	19	53	7	7	19	0.36	186.3	42	120.5	0.27	16	2.74	0.89	17.67	yes		
32	2630	2	b1.1a	15	14	51	6	0	29	0.57	242.7	19	59.5	0.19	24 (12)	1.99	0.64	4.51	yes	yes	yes
33	2671	1.2	b1.1a	10	17	48	3	0	18	0.38	260	23	57.5	0.33	24 (10)	2.44	0.79	8.61	yes	yes	yes
34	2681	2	b1.1a	11	17	63	8	0	41	0.65	493.5	32	110	0.61	22 (18)	2.03	0.66	4.31			
35	2707	1.2	b1.1b	8	26	98	19	1	36	0.37	478	55	244	0.97	28 (20)	2.93	0.95	15.14	yes	yes	yes
36	2739	1.2	b1.1a	8	15	75	8	0	45	0.6	487.5	20	46	0.48	20 (8)	1.92	0.62	3.83	yes	yes	yes
37	2772	1.2	b2	8	19	63	20	6	40	0.63	509.5	27	255	0.65	25 (17)	2.28	0.74	6.47			
38	2809	1.2	b1.1b	12	21	60	9	5	27	0.45	379.2	23	111.2	0.51	25 (20)	2.66	0.86	12.04	yes		
39	2851	1.2	b1.1b	13	19	81	9	8	41	0.51	570.3	37	75	0.82	25 (14)	2.52	0.82	8.71	yes		
40	2874	1.2	b1.1b	11	20	89	9	5	29	0.33	306.5	20	60	0.3	22 (10)	2.77	0.9	15.3			
41	2776	1.2	b2	11	21	90	23	6	47	0.52	627.3	41	322.8	0.91	24 (20)	2.53	0.82	8.69	yes		
42	2775	2	b1.1b	10	27	138	17	5	73	0.53	982.4	40	260.5	1.26	24 (18)	2.68	0.87	8.99	yes	yes	
43	2784	2	b1.1b	7	24	105	13	4	59	0.56	748.5	37	186	0.92	22 (16)	2.37	0.77	5.5			
44	2812	1.2	b1.1b	9	28	133	18	23	43	0.32	717.4	51	409.2	1.28	24 (22)	3.04	0.98	18.56	yes		
45	2579	1.1a	b1.1a	3	10	51	12	7	19	0.37	297.8	35	232	0.49	18	1.97	0.64	6.25	yes		yes
46	2612	1.2	b1.1a	6	19	69	2	17	19	0.28	164	18	36	0.14	12	2.22	0.72	4.95	yes	yes	
47	2621	1.2	b1.1a	11	20	83	9	8	17	0.2	205.5	28.5	161.83	0.27	12	2.68	0.87	13.72	yes		
48	2641	1.2	b1.1a	20	20	76	0	22	22	0.29	159.5	22	0	0.12	9 (0)	2.5	0.81	8.61			
49	2691	1.2	b1.1a	21	16	68	9	12	21	0.31	183	27	105.5	0.19	16	2.42	0.78	9.9			
50	2781	1.2	b1.1b	16	18	58	12	1	13	0.22	142.2	16.5	137.2	0.13	9	2.51	0.81	10.53			
51	2801	1.1b	b2	24	16	65	19	1	20	0.31	348.6	34	341.6	0.6	20	2.48	0.8	9.24			
52	2852	1.1a	b2	1	6	29	16	1	17	0.59	232.2	24	223.7	0.29	18	1.37	0.44	3.05			
53	2619	1.2	b1.1a	12	23	86	7	11	28	0.33	281.9	29	61	0.37	20 (14)	2.74	0.89	12.1			yes
54	2630	1.1a	b2	40	21	41	16	1	17	0.41	192.1	27	184.1	0.21	12	2.37	0.77	6.07	yes		

Plot	Altitude (m)	Clusters with *Eucalyptus*	Clusters without *Eucalyptus*	Slope	SP	i	iJp	inat	iDBH	i:iDBH	Σ DBH (cm)	Max DBH (cm)	JpDBH	BA	Max H (m)	H'	SEI	DS	Er	Gr/br	Anthro.
55	2660	1.2	b1.1a	14	12	36	9	5	14	0.39	129.5	20	109	0.13	10	2.28	0.74	10	yes		
56	2696	1.1b	b2	21	20	67	21	1	22	0.33	311	35	305	0.45	17	2.56	0.83	8.67	yes	yes	yes
57	2734	1.2	b1.1b	16	21	57	11	6	17	0.3	146.5	18	114	0.13	10	2.8	0.91	15.96	yes		
58	2774	1.2	b1.1b	5	28	103	6	14	31	0.3	300.5	33	111	0.33	15 (12)	3.09	1	20.68	yes		yes
59	2789	1.2	b1.1b	27	23	76	6	4	20	0.26	293	26	78	0.43	20 (15)	2.94	0.95	19.93	yes		
60	2806	1.2	b2	14	29	91	19	4	36	0.4	520	34	221	0.77	26 (15)	2.89	0.94	13.08			
61	2630	1.2	b1.1b	11	21	70	17	2	23	0.33	271	26	180	0.35	16 (11)	2.37	0.77	6.94			
62	2655	1.1a	b2	6	14	53	16	0	20	0.38	266	35	183	0.37	18 (10)	2.3	0.74	8.15			
63	2686	1.1b	b2	10	21	101	43	18	61	0.6	674	42	565	0.83	14	2.24	0.72	4.97	yes		
64	2703	2	b1.1b	20	23	82	10	9	40	0.49	443	37	152	0.53	15 (12)	2.72	0.88	10.85			
65	2765	1.1b	b2	19	20	96	30	16	55	0.57	780	46	599	1.47	15 (13)	2.4	0.78	7.3			
66	2732	1.1b	b2	21	17	70	20	10	30	0.43	370	44	333	0.66	13	2.37	0.77	7.84			
67	2802	1.1b	b2	13	19	114	41	12	53	0.46	603	44	542	0.83	13	2.4	0.78	6.54	yes		yes
68	2832	1.1b	b2	13	13	68	24	0	24	0.35	313	45	313	0.46	21	2.2	0.71	6.55			
69	2903	1.1b	b2	3	12	69	25	0	25	0.36	274	26	274	0.31	12	2.13	0.69	6.14	yes		yes
70	2639	1.1b	b2	0	13	63	31	0	31	0.49	340	24	340	0.35	10	1.82	0.59	3.73			
71	2644	1.1a	b2	7	11	34	16	0	16	0.47	194	25	194	0.22	12	1.82	0.59	4.19			yes
72	2686	1.1b	b2	13	23	83	28	2	30	0.36	389.7	44	378.7	0.62	16	2.5	0.81	7.26			yes
73	2703	1.1a	b2	6	17	60	20	0	20	0.33	310.5	43	310.5	0.51	20	2.42	0.78	7.7			
74	2744	1.1b	b2	11	23	84	35	3	38	0.45	481	27	470	0.59	15	2.43	0.79	5.48	yes		yes
75	2767	1.1b	b2	23	19	67	25	4	29	0.43	400	40	373	0.56	20	2.36	0.76	6.39	yes		yes
76	2814	1.1b	b2	12	25	103	33	9	42	0.41	444	31	391	0.51	15	2.68	0.87	8.36	yes		yes
77	2683	1.1b	b2	3	16	72	47	1	48	0.67	596	49	592	0.87	20	1.52	0.49	2.32	yes		yes
78	2707	1.1a	b2	7	12	49	20	0	20	0.41	434	50	434	0.99	22	1.97	0.64	5.03	yes		yes
79	2723	1.1a	b2	10	15	54	25	4	34	0.63	492	54	420	0.89	20	2.02	0.65	4.39	yes		yes
80	2749	1.1b	b2	8	19	64	30	6	36	0.56	485	34	450	0.67	16	2.13	0.69	4.34	yes	yes	yes
81	2772	1.1b	b2	17	30	136	41	12	53	0.39	787	55	717	1.43	22	2.83	0.91	9.29	yes		yes

APPENDIX 2 – INFORMATION ABOUT SPECIES

List of all woody plant species recorded from GBG, with family, growth habit, several metrics from this study, characteristic vegetation type (based on Friis et al. 2010, 2011) and mention if the species has not been reported in previous studies (Reeder 2013; Woldegerima et al. 2017). The nomenclature follows the *Flora of Ethiopia and Eritrea*. Frequency and Density is based on the floristic dataset used in the clustering and ordination analysis. Diameter at breast height (DBH) was measured on individuals with a minimum diameter at breast height of 2.5 cm. Species with individuals too small to be measured for DBH have no value in the DBH column; other values are very small. T = tree, Sh = Shrub, Cl = Climber; * = planted in GBG.

Scientific name and family	Habit	status	Frequency (%)	Density (i/ha)	DBH (m/ha)	Vegetation type	Prior studies
Acacia abyssinica Hochst. ex Benth. (Fabaceae)	T	native	35.8	22.8	1.1	DAF; MAF	
Acacia decurrens (J.C.Wendl.) Willd. (Fabaceae)	T	introduced	1.2	1.5	0.1		absent
Acacia melanoxylon R.Br. (Fabaceae)	T	introduced	2.5	1.9	0.2		absent
Acacia negrii Pic.Serm. (Fabaceae)	T	endemic	1.2	0.6	0.0	DAF	absent
Acacia saligna (Labill.) H.L.Wendl. (Fabaceae)	T	introduced	1.2	0.3	0.0		absent
Acacia sp. (Fabaceae)	T		recorded outside plots				
Albizia schimperiana Oliv. (Fabaceae)	T	native	1.2	1.2		DAF; MAF; TRF	absent
Allophylus abyssinicus (Hochst.) Radlk. (Sapindaceae)	T	native	recorded outside plots			DAF; MAF; RV	absent
Apodytes dimidiata E.Mey. ex Arn. (Icacinaceae)	T	native	9.9	8.0	0.3	DAF; MAF; RV	
Arundinaria alpina K.Schum. (Poaceae)	T	native*	recorded outside plots			DAF; EB; MAF	absent
Arundo donax L. (Poaceae)	Sh	introduced	recorded outside plots				absent
Asparagus africanus Lam. (Asparagaceae)	Sh	native	69.1	42.0		ACB; DAF; EB	
Azadirachta indica A.Juss. (Meliaceae)	T	introduced	recorded outside plots				absent
Bersama abyssinica Fresen. (Melianthaceae)	T	native	19.8	11.1	0.2	DAF; MAF; RV	
Buddleja polystachya Fresen. (Loganiaceae)	Sh	native	4.9	2.5		DAF; EB	
Callistemon citrinus (Curtis) Skeels (Myrtaceae)	T	introduced	recorded outside plots				absent
Calpurnia aurea (Aiton) Benth. (Fabaceae)	Sh	native	1.2	1.9		DAF; MAF	absent
Carissa spinarum L. (Apocynaceae)	Sh	native	48.1	42.3	0.1	ACB; DAF; MAF; RV	
Clematis simensis Fresen. (Ranunculaceae)	Cl	native	4.9	1.9		DAF; EB; MAF	
Clerodendrum myricoides (Hochst.) R.Br. ex Vatke (Lamiaceae)	Sh	native	2.5	1.2		CTW; DAF	absent
Clutia abyssinica Jaub. & Spach (Euphorbiaceae)	Sh	native	4.9	3.1		DAF	
Coffea arabica L. (Rubiaceae)	T	native*	recorded outside plots			MAF; TRF	absent
Conyza pyrrhopappa Sch.Bip. ex A.Rich. (Asteraceae)	Sh	native	16.0	4.0		ACB; DAF	absent
Crotalaria exaltata Polhill (Fabaceae)	Sh	endemic	recorded outside plots			DAF; EB	absent
Cupressus lusitanica Mill. (Cupressaceae)	T	introduced	2.5	1.2	0.0		
Discopodium penninervium Hochst. (Solanaceae)	Sh	native	7.4	8.6		AA; DAF; EB	
Dodonaea angustifolia L.f. (Sapindaceae)	Sh	native	recorded outside plots			DAF	absent
Dombeya torrida (J.F.Gmel.) Bamps (Sterculiaceae)	T	native	3.7	2.5	0.0	DAF; MAF	absent
Dovyalis abyssinica (A.Rich.) Warb. (Flacourtiaceae)	Sh	native	54.3	16.4	0.1	DAF; RV	
Dovyalis caffra (Hook.f. & Harv.) Warb. (Flacourtiaceae)	Sh	introduced	1.2	0.3			absent
Dovyalis verrucosa (Hochst.) Lign. & Bey (Flacourtiaceae)	Sh	native	38.3	15.4	0.0	DAF; EB	absent
Dracaena steudneri Engl. (Dracaenaceae)	T	native*	recorded outside plots			DAF; MAF; TRF	absent
Echinops longisetus A.Rich. (Asteraceae)	Sh	endemic*	recorded outside plots			AA; DAF; EB	absent
Ekebergia capensis Sparrm. (Meliaceae)	T	native	9.9	4.0	0.2	DAF; MAF	
Embelia schimperi Vatke (Myrsinaceae)	Cl	native	recorded outside plots			DAF; RV	
Erica arborea L. (Ericaceae)	Sh	native	32.1	24.1	0.0	AA; DAF; EB	
Erythrina brucei Schweinf. (Fabaceae)	T	endemic	1.2	1.2	0.0	DAF; MAF	
Eucalyptus camaldulensis Dehnh. (Myrtaceae)	T	introduced	19.8	70.1	6.9		absent
Eucalyptus citriodora Hook. (Myrtaceae)	T	introduced	recorded outside plots				absent
Eucalyptus globulus Labill. (Myrtaceae)	T	introduced	42.0	196.3	19.9		
Euphorbia abyssinica J.F.Gmel. (Euphorbiaceae)	T	native	recorded outside plots			DAF	absent
Ficus exasperata Vahl (Moraceae)	Sh	native*	recorded outside plots			RV; TRF	absent

Scientific name and family	Habit	status	Frequency (%)	Density (i/ha)	DBH (m/ha)	Vegetation type	Prior studies
Ficus sur Forssk. (Moraceae)	T	native*	1.2	0.3	0.1	DAF; MAF; RV; TRF	absent
Ficus vasta Forssk. (Moraceae)	T	native*	recorded outside plots			DAF; RV	absent
Galiniera saxifraga (Hochst.) Bridson (Rubiaceae)	Sh	native	21.0	11.7	0.0	DAF; MAF	
Grevillea robusta A.Cunn. ex R.Br. (Proteaceae)	T	introduced	recorded outside plots				absent
Grewia ferruginea Hochst. ex A.Rich. (Tiliaceae)	Sh	native*	recorded outside plots			CTW[1]	absent
Hagenia abyssinica (Bruce) J.F.Gmel. (Rosaceae)	T	native	1.2	0.9	0.1	DAF; EB	
Halleria lucida L. (Scrophulariaceae)	Sh	native	2.5	1.2		DAF; EB	
Helichrysum schimperi (Sch.Bip. ex A.Rich.) Moeser (Asteraceae)	Sh	native	4.9	1.2			
Helichrysum sp. (Asteraceae)	Sh		11.1	2.8			
Hypericum revolutum Vahl (Guttiferae)	Sh/T	native	34.6	32.7		AA; DAF; EB	
Indigofera sp. (Fabaceae)	Sh		1.2	0.3			
Inula confertiflora A.Rich. (Asteraceae)	Sh	endemic	29.6	20.1		AA; DAF; EB	
Jasminum abyssinicum Hochst. ex DC. (Oleaceae)	Cl	native	55.6	32.7		DAF	
Jasminum stans Pax (Oleaceae)	Sh	endemic	46.9	40.7		DAF	
Juniperus procera Hochst. ex Endl. (Cupressaceae)	T	native	100	405.9	56.6	DAF; EB	
Laggera tomentosa (A.Rich.) Sch.Bip. ex Oliv. & Hiern (Asteraceae)	Sh	native	12.3	9.9			
Leonotis ocymifolia (Burm.f.) Iwarsson (Lamiaceae)	Sh	native	1.2	0.3		AA; CTW; DAF; EB	
Lippia adoensis Hochst. ex Walp. (Verbenaceae)	Sh	native	29.6	19.8		DAF	
Maerua aethiopica (Fenzl) Oliv. (Capparidaceae)	Sh	native	recorded outside plots			CTW	absent
Maesa lanceolata Forssk. (Myrsinaceae)	Sh/T	native	40.7	24.7	0.4	DAF; MAF; RV	
Marsdenia abyssinica (Hochst.) Schltr. (Asclepiadaceae)	Cl	native	6.2	1.5			absent
Maytenus addat (Loes.) Sebsebe (Celastraceae)	Sh	endemic	74.1	32.1	0.0	DAF; MAF	
Maytenus arbutifolia (Hochst. ex A.Rich.) R.Wilczek (Celastraceae)	Sh	native	74.1	32.7	0.3	DAF	
Millettia ferruginea (Hochst.) Hochst. ex Baker (Fabaceae)	T	endemic*	1.2	0.3		DAF; MAF; RV	absent
Myrica salicifolia Hochst. ex A.Rich. (Myrtaceae)	T	native	6.2	4.6	0.5		absent
Myrsine africana L. (Myrsinaceae)	Sh	native	71.6	60.2	0.0	AA; DAF; EB	
Myrsine melanophloeos (L.) R.Br. ex Sweet (Myrsinaceae)	Sh/T	native	8.6	6.8	0.1	AA; DAF; EB	
Nuxia congesta R.Br. ex Fresen. (Loganiaceae)	Sh/T	native	49.4	29.9	0.4	DAF; MAF; EB	
Olea europaea subsp. *cuspidata* (Wall. & G.Don) Cif. (Oleaceae)	T	native	53.1	16.4	0.1	DAF	
Olinia rochetiana A.Juss. (Oliniaceae)	Sh/T	native	67.9	63.3	2.0	DAF; EB	
Osyris quadripartita Salzm. ex Decne. (Santalaceae)	Sh	native	49.4	30.6	0.2	DAF	
Pentas schimperi (Hochst.) Wieringa (Rubiaceae)	Sh	native	30.9	20.7		DAF; EB; MAF	
Phoenix reclinata Jacq. (Arecaceae)	T	native	recorded outside plots			DAF; MAF; RV; FLV	absent
Phytolacca dodecandra L'Hér. (Phytolaccaceae)	Sh	native	1.2	1.2		DAF	absent
Pinus patula Schiede ex Schltdl. & Cham. (Pinaceae)	T	introduced	recorded outside plots				absent
Pittosporum abyssinicum Delile (Pittosporaceae)	T	native	23.5	10.5		DAF; EB	absent
Pittosporum viridiflorum Sims (Pittosporaceae)	T	native	3.7	0.9	0.3	DAF; MAF	
Podocarpus falcatus (Thunb.) Endl. (Podocarpaceae)	T	native	1.2	0.3		DAF; MAF	absent
Prunus africana (Hook.f.) Kalkman (Rosaceae)	T	native	11.1	3.7	0.1	DAF; MAF	
Rhamnus prinoides L'Hér. (Rhamnaceae)	Sh	native	4.9	1.2		DAF; EB; MAF; RV	
Rhamnus staddo A.Rich. (Rhamnaceae)	Sh	native	37	17.9	0.0	DAF; MAF	
Rhus glutinosa Hochst. ex A.Rich. (Anacardiaceae)	Sh/T	endemic	14.8	8.3	0.0	DAF; EB	
Rhus vulgaris Meikle (Anacardiaceae)	Sh/T	native	6.2	2.5	0.1	ACB; CTW; DAF	
Ricinus communis L. (Euphorbiaceae)	Sh	native	1.2	1.2			absent
Rosa abyssinica R.Br. ex Lindl. (Rosaceae)	Sh	native	88.9	79.3	0.0	DAF; EB	

Scientific name and family	Habit	status	Frequency (%)	Density (i/ha)	DBH (m/ha)	Vegetation type	Prior studies
Rubus apetalus Poir. (Rosaceae)	Sh	native	28.4	19.4		DAF	absent
Rubus steudneri Schweinf. (Rosaceae)	Sh	native	3.7	4.0		DAF	
Rumex nervosus Vahl (Polygonaceae)	Sh	native	recorded outside plots				absent
Salix subserrata Willd. (Salicaceae)	Sh	native*	1.2	1.2		RV	absent
Satureja punctata (Benth.) R.Br. ex Briq. (Lamiaceae)	Sh	native	16	5.2			
Scolopia theifolia Gilg (Flacourtiaceae)	Sh	native	3.7	1.5	0.0	DAF	absent
Sida schimperiana Hochst. ex A.Rich. (Malvaceae)	Sh	native	22.2	5.6			
Sideroxylon oxyacanthum Baill. (Sapotaceae)	Sh/T	native	34.6	53.1	1.2	ACB; DAF	
Smilax aspera L. (Smilacaceae)	Cl	native	51.9	46.0		DAF	
Solanecio gigas (Vatke) C.Jeffrey (Asteraceae)	Sh	endemic	2.5	0.9		DAF; EB; MAF	
Solanum incanum L. (Solanaceae)	Sh	native	recorded outside plots				absent
Syzygium guineense (Willd.) DC. (Myrtaceae)	T	native*	recorded outside plots			DAF; MAF; CTW; RV; FLV	absent
Tacazzea conferta N.E.Br. (Asclepiadaceae)	Cl	native	1.2	0.6		DAF; MAF; RV	absent
Vernonia adoensis Sch.Bip. ex Walp. (Asteraceae)	Sh	native	1.2	0.3			absent
Vernonia amygdalina Delile (Asteraceae)	Sh/T	native	3.7	2.8		DAF; MAF; RV	
Vernonia leopoldii Vatke (Asteraceae)	Sh	endemic	49.4	59.3		DAF	
Washingtonia filifera (Rafarin) H.Wendl. ex de Bary (Arecaceae)	Sh/T	introduced	recorded outside plots				absent

[1] Vegetation type according to Friis et al. (2010, 2011, 2022): **AA** = Afroalpine belt, **DAF** = Dry evergreen Afromontane forest and grassland complex, **EB** = Ericaceous belt, **ACB** = *Acacia-Commiphora* woodland and bushland, **RV** = Riverine vegetation, **CTW** = *Combretum-Terminalia* woodland and wooded grassland, **MAF** = Moist evergreen Afromontane forest, **FLV** = Fresh-water lakes, lake shores, marsh and floodplain vegetation, and **TRF** = Transitional rainforest.