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Least concern to endangered: Applying climate change projections profoundly influences the extinction risk assessment for wild Arabica coffee

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Abstract

Arabica coffee (*Coffea arabica*) is a key crop in many tropical countries and globally provides an export value of over US$13 billion per year. Wild Arabica coffee is of fundamental importance for the global coffee sector and of direct importance within Ethiopia, as a source of harvestable income and planting stock. Published studies show that climate change is projected to have a substantial negative influence on the current suitable growing areas for indigenous Arabica in Ethiopia and South Sudan. Here we use all available future projections for the species based on multiple general circulation models (GCMs), emission scenarios, and migration scenarios, to predict changes in Extent of Occurrence (EOO), Area of Occupancy (AOO), and population numbers for wild Arabica coffee. Under climate change our results show that population numbers could reduce by 50% or more (with a few models showing over 80%) by 2088. EOO and AOO are projected to decline by around 30% in many cases. Furthermore, present-day models compared to the near future (2038), show a reduction for EOO of over 40% (with a few cases over 50%), although EOO should be treated with caution due to its sensitivity to outlying occurrences. When applying these metrics to extinction risk, we show that the determination of generation length is critical. When applying the International Union for Conservation of Nature's Red list of Threatened Species (IUCN Red List) criteria, even with a very conservative generation length of 21 years, wild Arabica coffee is assessed as Threatened with extinction (placed in the Endangered category) under a broad range of climate change projections, if no interventions are made. Importantly, if we do not include climate change in our assessment, Arabica coffee is assessed as Least Concern (not threatened) when applying the IUCN Red List criteria.

KEYWORDS
area of occupancy, climate change, coffee, extent of occurrence, generation length, IUCN Red List, population metrics

1 | INTRODUCTION

For the 2015/2016 coffee harvest period, c. 4.3 million tonnes (71.93 million 60 kg bags) of Arabica coffee (*Coffea arabica*) were exported globally, with an estimated export value of US$ 13.8 billion (based on a composite price of US$1.46 per lb) (International Coffee Organization (ICO), 2017). The export value of Arabica coffee is an important, and in some cases critical, component in the economies of several tropical countries (International Coffee Organization (ICO), 2017). Global consumption of coffee (including robusta coffee: *C. canephora*) has had an average annual growth rate of 1.3% since 2012/13 (International Coffee Organization (ICO), 2017).

Despite being a globally distributed tropical crop, wild populations of Arabica are restricted to the humid forests of Ethiopia, and a small area of neighbouring South Sudan (Figure 1) (Davis, Gole, Baena, & Moat, 2012). These wild populations have considerable value as the main storehouse of genetic resources for Arabica coffee (Davis et al., 2012), and have provided fundamental resources for Ethiopia and the global coffee sector (Hein & Gatzweiler, 2006). In Ethiopia, these genetic resources continue to provide an important source of new planting material for coffee-farming, via seed and seedlings, including disease resistant variants, and the intrinsic (genetic) variation associated with the various flavour profiles found across the coffee landscape. Historically, and in recent times, wild Arabica coffee has provided germplasm for the development of the Arabica coffee sector outside Ethiopia. Protection of wild populations of Arabica coffee is therefore viewed as a key part of the long-term sustainability strategy for Ethiopian coffee production and the global coffee sector (Hein & Gatzweiler, 2006).

Despite the importance of wild Arabica populations in Ethiopia and South Sudan, there are serious threats to the survival and genetic integrity of this species. Amongst the most serious of these threats are deforestation (Davis et al., 2012, 2018; Moat et al., 2017a), climate change (Davis et al., 2012; Moat et al., 2017a, 2017b), and genetic erosion (Aerts et al., 2012). Recorded climate data in Ethiopia from the 1960s onwards show an average increase in the mean annual temperature of 0.28°C per decade (Jury & Funk, 2013), a shortening of the wet season, and an increase in the number of hot days (McSweeney, New, & Lizcano, 2010). Given the scale, severity, and potential impact of these threats and other negative influences it is important that the extinction risk of wild Arabica coffee is comprehensively assessed. Until now, no formal extinction risk assessment has been made for Arabica coffee.

The International Union for Conservation of Nature's Red list of Threatened Species (the IUCN Red List (IUCN, 2012)) is a global repository of species and their associated risk of extinction (Rodrigues, Pilgrim, Lamoreux, Hoffmann, & Brooks, 2006). The IUCN Red List is recognized as the most authoritative source on extinction risk; it is widely used and cited, and conservation decisions and actions are increasingly informed by the resulting species-level risk assessments. One of the IUCN Red Lists' main roles is as an "early-warning" system for species that have the most imminent risk of

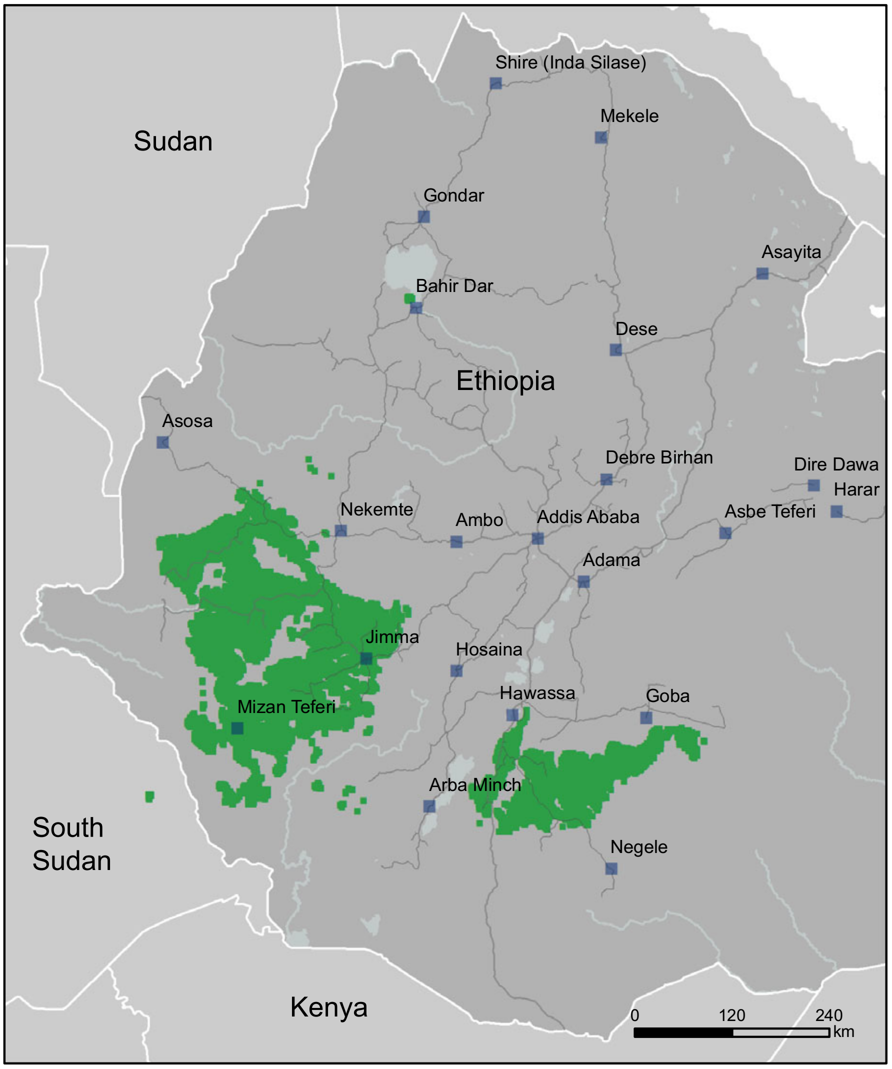

FIGURE 1 Map of potential wild Arabica coffee in Ethiopia and South Sudan. Green areas represent the coverage of the humid forest types* where wild Arabica coffee could occur (where there is ≥1% of forest cover in each km^2). Map generated from species distribution models (SDMs) and remote sensing (Davis et al., 2012 [one SDM]; Moat et al., 2017a [SDMs and remote sensing]). *Humid forest represented by Moist Evergreen Afromontane Forest (MAF) and Transitional Rain Forest (TRF) types (Friis et al., 2010). Agroforestry systems in Sidama (south of Hawassa) are no longer wild habitats but may contain wild type plants originating from this area. Other forest areas may be highly modified compared to primary forest areas

extinction, therefore informing priorities for conservation action (Keith et al., 2014; Vié, Hilton-taylor, & Stuart, 2009).

The central process of assessing extinction risk for a species is the assignment to one of nine categories, which are based on five criteria associated with extinction risk: population decline; geographic distribution; small population size; restricted populations and quantitative analysis of extinction risk (IUCN, 2012).

Within this study we review and address the first four criteria, using: past, present-day, and future projections (based on the projection of accurate present-day occurrence generated from species distribution models (SDMs), using precise ground-point data, and remote sensing of suitable forest type) under various climate change scenarios (Davis et al., 2012; Moat et al., 2017a); combined with demographic and generation length information. We apply three metrics for the present-day and future occurrence (under climate change): (a) Extent of Occurrence (EOO), a measure of risk spread (Gaston, 1991, 1994a, 1994b), using a minimum convex polygon enclosing all known localities, as recommend by Joppa et al. (2016). (b) Area of Occupancy (AOO), a measure of geographic range size (Gaston, 1991, 1994a; Gaston & Fuller, 2009), which uses a simple calculation of the number of 2×2 km cells a species occupies (Moat, Bachman, Fields, & Boyd, 2018). (c) Population size, which is estimated from the SDMs, forest cover (from remote sensing), population demographics and the quality of the niche.

The analyses we present here are focused primarily on exposure (i.e., to climatic suitability), based on climate scenario projections from general circulation models (GCMs). Other aspects of climate change vulnerability, viz., sensitivity and adaptive capacity (Dawson, Jackson, House, Prentice, & Mace, 2011; Foden & Young, 2016), are not directly addressed, although Arabica coffee is identified as a climate-sensitive species with a low adaptive capacity (Davis et al., 2012).

Species distribution models have been widely used in conjunction with other modelling methods to make projections for the potential impact of climate on species ranges (Elith & Leathwick, 2009; Franklin, 2010). As well as giving a prediction for a species range, SDMs can also provide key information on the fundamental biology and ecology of a species. SDM techniques have matured considerably over the last 15 years or more, particularly with the introduction of ensemble modelling approaches (Araujo & New, 2007; Thuiller, Georges, & Engler, 2014; Thuiller, Lafourcade, Engler, & Araújo, 2009). Predicting climate change with certainty is impossible, but we can use multiple models and scenarios to project future trends for species: by comparing the results from these models, we can start to understand the vulnerability of species to climate change and overall trends, at least in terms of exposure. If all models point to a similar (or the same) outcome we can be increasingly confident in our projections. Within this study, we calculate EOO, AOO, and population estimates for Arabica coffee using multiple scenarios and models for climate and migration (Table 1), and then quantify these for the past, present and future.

2 | METHODS AND MATERIALS

2.1 | Overview

Three major spatial datasets were used in our analyses; observational (geo-located) ground-point data, SDMs (which cover present-day to

TABLE 1 Models and scenarios used within this study

Model/scenario	Used in this study	Definitions
Emission scenarios	A2	A very heterogenous world with an emphasis on family values and local traditions, A2 reaching 29.1 giga tonnes of carbon (GtC)
	A1B	Rapid economic growth followed by rapid introductions of new and more efficient technologies. A1B represents a balance across all energy sources. Reaching 13.5 (GtC) by 2099.
General Circulation models[a]	csiro_mk3_5	Centre for Australian Weather and Climate Research Mark, 3.5
	gfdl_cm2_1	Geophysical Fluid Dynamics Laboratory, Coupled Climate Model 2.1
	bccr_bcm2_0	Bjerknes Centre for Climate Research, Bergen Climate Model, Version 2
Migration scenarios (Moat et al., 2017a)	C	Plants can only grow within suitable forest cover, within any suitable niche (i.e., can move within suitable forest).
	D	No Migration. Plants can only grow within suitable forest cover and only in known suitable niche (restricted to present-day forest cover and suitable niche).
	F	Plants can only grow within suitable forest cover and suitable niche, but only if the niche does not drop outside of suitability during any 30-year time-period.
Population size reduction (IUCN Standards & Petitions Subcommittee, 2016)	A3	Population reduction projected, inferred or suspected to be met in the future (up to a maximum of 100 years).
	A4	An observed, estimated, inferred, projected or suspected population reduction where the time-period must include both the past and the future (up to a max. of 100 years in future), and where the causes of reduction may not have ceased OR may not be understood OR may not be reversible.

[a]*Note*. Three out of the 23 GCMs reviewed by Moat et al. (2017a).

future, under various climate change scenarios and multiple GCMs), and forest cover (from remote sensing (Moat et al., 2017a; Davis et al., 2012). The SDMs were combined with forest cover and integrated into a 1 km^2 grid for further analysis. Generation lengths were calculated (see below) and used to predict future and past changes in EOO, AOO, and population size.

2.2 | Data cleaning and preparation

2.2.1 | Point data and ground-truthing

Data for this study are derived from Davis et al. (2012) and Moat et al. (2017a). The data from Davis et al. (2012) were taken and then ground-truthed in Ethiopia during 15 dedicated field missions (2013–2016); four inaccurate records were removed via this process. Ground-point data collected and/or verified as wild Arabica coffee were queried from a database and used for the analyses. In total, this gave 310 unique ground-points for wild Arabica coffee (285 from Ethiopia, and 25 from South Sudan).

2.2.2 | SDM production and preparation

For the present-day modelled distribution of Arabica coffee in Ethiopia (South Sudan was treated separately) we used the final SDM produced by Moat et al. (2017a), which was based on an ensemble SDM approach, with nine selected bioclimatic variables and six modelling methods (Generalized Linear Models, Generalized Boosted Regression Models, Generalized Additive Models, Multiple Adaptive Regression Splines (MARS), Random Forest and Maximum Entropy [Maxent]), processed using the Biomod2 R package, version 3.1–64 (Thuiller et al., 2014). All 19 BIOCLIM variables (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005) were examined and reduced to nine; the nine remaining variables were significant to the model fit, not highly correlated, and represented the ecological requirements of Arabica coffee (Moat et al., 2017a). The nine BIOCLIM variables used were: Annual Mean Temperature, Isothermality, Temperature Seasonality, Annual Temperature Range, Annual Precipitation, Precipitation of the Wettest Month, Precipitation Seasonality, Precipitation of the Driest Quarter and Precipitation of the Warmest Quarter.

For the future projections we used two climate scenarios, A1B and A2, three GCMs (based on 23 GCMs examined and reviewed by Moat et al. (2017a), see Table 1), four date intervals (1960–1990, 2010–2039, 2040–2069, and 2070–2099), and three of the six migration scenarios devised by Moat et al. (2017a). These future projections were downloaded from CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (https://ccafs-climate.org/data_spatial_downscaling/ and https://www.ccafs-climate.org/data/). Both the original SDM and future models were at a resolution of 1 km^2; the future models had been downscaled using the delta method (Ramirez-Villegas & Jarvis, 2010).

The three migration scenarios, C, D, and F (Table 1) are restricted to humid forest (of the Moist Evergreen Afromontane Forest (MAF) and Transitional Rain Forest (TRF) types; classification according to Friis, Demissew, & Breugel, 2010), which was originally derived from Landsat data (United States Geological Survey, 2015) at a resolution of 30 × 30 m, with some manual editing to remove plantations (e.g., tea, mangoes, and forestry) and other non humid forest vegetation (Moat et al., 2017a). The forest cover mask was resampled in R using the aggregate function in the package Raster (Hijmans, 2016) to give the total forest cover per 1 km^2. A typical example of these scenarios (emission, GCM, and migration) is given in Figure 2.

These procedures produced a huge amount of data to process. To make this manageable, and easier to manipulate, we combined all the SDM data into one matrix, with centroids of the cells (x and y position). The raster SDMs were converted to point data using the R package "Raster" (Hijmans, 2016). This matrix is at a resolution of 1 km^2 (using UTM zone 37 Projection) and was stored in R (R Core Team, 2016) as a data frame.

The above dataset only covered Ethiopia, but the wild species extends into a small area close to the Ethiopian border on the Boma Plateau in South Sudan (Davis et al., 2012; Davis, Govaerts, Bridson, & Stoffelen, 2006; Thomas, 1942). The specimen and ground-point data already gathered included the Boma Plateau, but the SDM matrix lacked these data. To resolve this, we imported the South Sudan SDM from Davis et al. (2012), into the 1960–1990 column of the matrix. Davis et al. (2012) show that this location is rapidly lost under climate change projections (by 2020, i.e., representing the time period 2010–2029). This projection was considered realistic on the basis of field survey (Davis et al., 2012): wild Arabica populations on the Boma Plateau are in poor condition, sparsely populated, some of the major canopy trees appear to have been lost through drought, and there is almost no potential for upslope migration. We also reviewed the Boma Plateau area on global forest watch (World Resources Institute, 2014) to determine the area of remaining humid forest (16.8 km^2), and this was added to the forest cover column in the matrix. The locality on Mt. Marsabit in Northern Kenya, which has been suggested as part of the wild distribution of the species is likely to be an area where Arabica has been introduced and cultivated (see review in Davis et al., 2012). Mt. Marsabit is a considerable distance (500 km) from the main populations of Arabica (Davis et al., 2012) and molecular data indicates that the plants growing at this locality are associated with cultivars of Arabica coffee rather than part of the natural genetic range of the wild species (Lashermes, Trouslot, Anthony, Combes, & Charrier, 1996).

2.2.3 | Calculation of EOO and AOO

Using the R software package (R Core Team, 2016), the matrix described above was queried for each of the four time periods (1960–1990, 2010–2039, 2040–2069, and 2070–2099), the three GCMs, the three migration scenarios, and two emission scenarios. We removed any ground-points with very low forest cover (less than 1 hectare), as these would not be viable populations, and many would be due to noise within the satellite imagery.

EOO and AOO were calculated (from cell centroids) using the R package, rCAT (Moat, 2017). In addition, we calculated EOO using

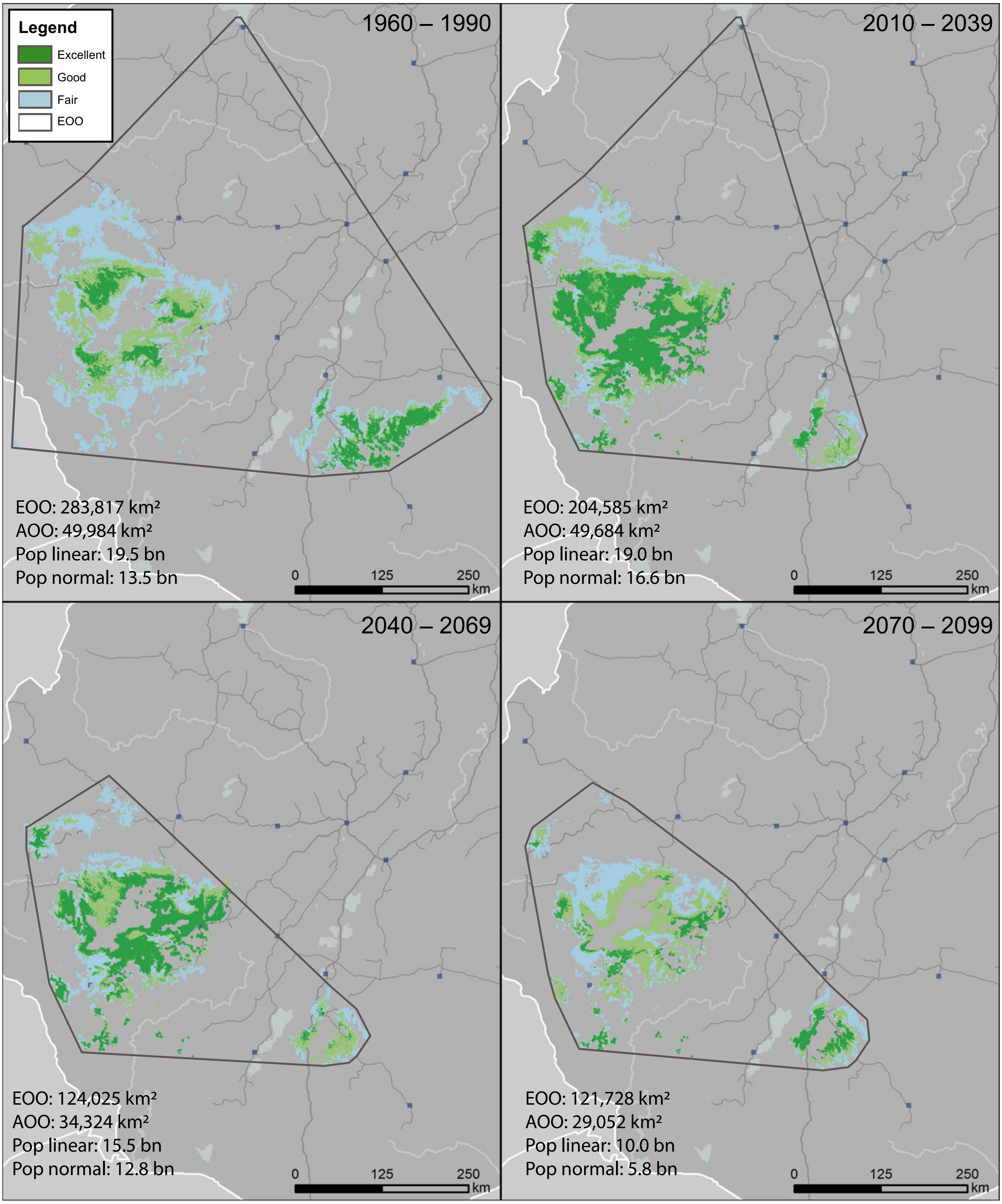

FIGURE 2 Maps and metrics for one example future projection; emission scenario A1b, GCM gfdl_cm2_1 and migration scenario D (see Table 1) showing SDMs and figures for AOO, EOO, and population numbers, for 1960–1990, 2010–2039, 2040–2069, and 2070–2099. The record from Bahir Dar (in the far north, for the time periods 1960–1990 and 2010–2039) is included here, although it is uncertain whether this represents an indigenous population (Davis et al., 2018)

just the ground-point data, and the range of possible AOO values and therefore the minimum AOO using a moving origin and rotating grid as suggested in Moat et al. (2018), with 1,152 iterations.

2.2.4 | Estimating population numbers per unit area

We estimated population numbers using two models of population demographics: (a) that the population is either linearly distributed or (b) normally distributed over elevation, from high to low numbers of plants per unit area (Figure 3). We equated population numbers to the SDM suitability categories used in Moat et al. (2017a); Excellent, Good, Fair, Marginal, and Unsuitable. These categories were derived by examining the present-day SDM values to our ground observations (ground control, absence, and pseudo absences data), by comparing True Skill Statistic, Kappa, specificity versus sensitivity and the cumulative percentage of points to give us thresholds. For the major threshold between Fair and Marginal we used a model value of 353 as a conservative balance between all the thresholds (Kappa: 504, specificity vs. sensitivity: 424, cumulative frequency 99%: 353 and TSS: 324 points). The upper categories (Excellent, Good, Fair), were chosen at equal intervals (see Figure 3 for details). Within our analysis we equate the niche classes to population demographics, that is, under the IUCN criteria A subcriteria b) "an index of abundance appropriate to the taxon" (IUCN Standards & Petitions Subcommittee, 2014).

It should be noted that AOO will be proportional to a constant (i.e., flat) population value. While population numbers for the cultivated species are reported here, there are only a few citations for the demography of wild Arabica. According to Senbeta, Schmitt, Woldemariam, Boehmer, and Denich (2014) the demographic relationship for wild Arabica is a maximum of 800 coffee plants per 400 m^2 in the best areas, reducing to 40 plants per 400 m^2 in the lowest/least suitable (Figure 4). We applied a simple linear relationship, from the Excellent suitability class to zero at the edge of limits of the Fair/Marginal class boundary (Figure 2). This linear relationship is simplistic. Senbeta et al. (2014; Figure 2) and Moat et al. (2017a) show that the population follows a normal distribution. Therefore, we also mapped the niche class to this normal distribution using the mean populations from the elevation classes (Figure 4). We have used both normal and linear demographics within our analysis, where the linear represents a conservative estimate and the normal distribution closer to the actual population distribution of Arabica coffee.

The numbers presented here are similar to: farmed Arabica coffee, where plants are generally spaced around 1 m apart (Wrigley, 1988); spacing distances for Ethiopian coffee cultivation (1.5–2 m between plants, and 2.5–3 m between rows (Davis et al., 2018)); and plot data (16 in situ plots, measured by us), which show densities ranging from 0.04 to 1.2 per m^2.

2.2.5 | Generation length

As with calculations for AOO and EOO, determination of generation length is critical when reviewing any future or past changes in population numbers, and can greatly complicate extinction risk assessments (Fung & Waples, 2017; Willis, Moat, & Paton, 2003). Estimation of generation length is difficult without full population information (Fung & Waples, 2017), which even for a well-studied species is lacking, including Arabica coffee (DaMatta, Ronchi, Maestri, & Barros, 2007). Coffee plants are often referred to as short-lived trees (Davis et al., 2018). Some population information does exist for cultivated Arabica coffee in Ethiopia (see below), but for the wild species the information is poor. For this study we reviewed the generation length for farmed Arabica coffee, for the minimum generation length, and then extrapolated to achieve generation lengths for the wild species. Our generation estimates were reviewed against available observations for wild Arabica coffee, and then used to refine our estimates (see below).

We used three methods to estimate generation length:

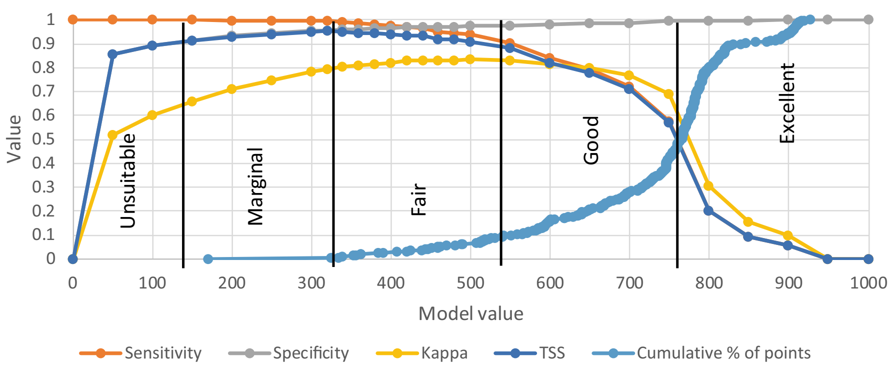

FIGURE 3 Graphs of five threshold statistics versus model values (Moat et al., 2017a). Threshold values and statistics used for SDM classification. Y value = threshold statistic value, X = SDM model value (from 0 unsuitable to 1,000 excellent). Actual categories used for cut-offs are highlighted with vertical black lines. Threshold metrics for categorizing model suitability (statistic type with maximum model threshold values given in parentheses): Kappa (504); True skills statistic TSS (324); Sensitivity = Specificity (424); accumulative percentage of ground observation points 100% (177); 99% (353); 95% (462); 90% (552); 65% (737); 50% (764); 35% (780); 25% (792); 10% (840); 5% (904); 1% (914).

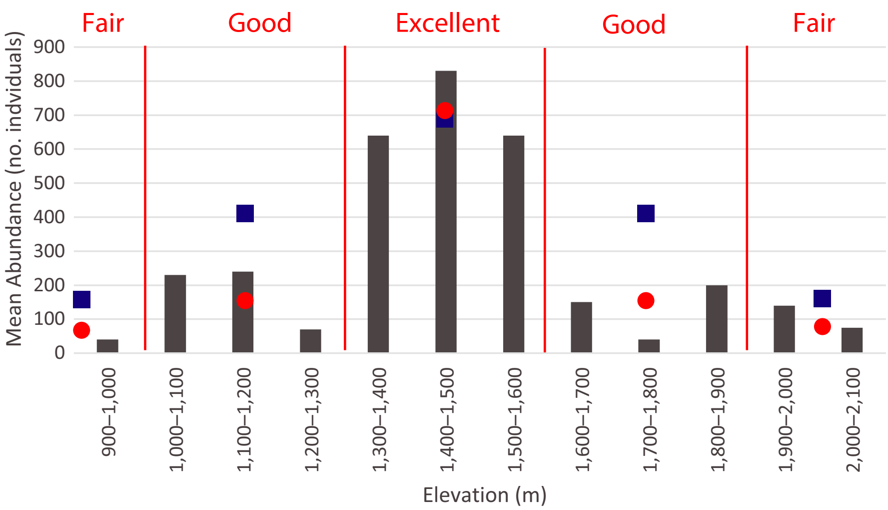

FIGURE 4 Histogram of wild coffee abundance (per 20 × 20 m plot) versus elevation (adapted from Senbeta et al., 2014) and niche classes used in this analysis. Blue squares represent values used for simple linear population demographics, red circles for values of the mean of the elevation classes for each suitability class and equal to the normal distribution.

1. Vitality rates: defined as age of species survival and fecundity. We used the IUCN MS Excel sheet (IUCN, 2017) to calculate generation lengths, with estimates of survival rates and fecundity from expert opinion based on field survey (Davis and Moat pers. observ.).
2. Adult mortality rate: $T_d = \alpha + 1d$ (Fung & Waples, 2017; IUCN Standards & Petitions Subcommittee, 2016).
3. Reproductive life span model: $T_z = \alpha + z * RL$ (Fung & Waples, 2017; IUCN Standards & Petitions Subcommittee, 2016).whereT_d= Generation length (years).

α = Age of first reproduction (years).

d = Adult mortality rate (years).

z = is a constant "that depend[s] on survivorship and the relative fecundity of young versus old individuals in the population" (IUCN Standards & Petitions Subcommittee, 2016). We derived z values by comparison with other woody plant species from (Fung & Waples, 2017)

RL = length of reproductive period (years).

2.3 | Generation length of cultivated Arabica coffee

Cultivated Arabica coffee plants take 3–4 years to reach fruiting stage and 5–8 years to reach maximum reproductive potential (Wrigley, 1988). There are on average 3,000–4,000 fruits per tree (Davis et al., 2018), although productivity drops off significantly as the coffee plant ages (e.g., to 1,000 fruits). To rejuvenate cultivated Arabica coffee, plants are often stumped (coppiced) at an interval of 8–15 years, which usually brings them back to full productivity. Thus, elucidating the age of coffee trees can be difficult, without the cultivation history and dendrochronology. It has been estimated that: at between 7–20 years Arabica coffee trees are at their most productive, senescence is reached at around 25 years, and that 40 years is the average life expectancy (Davis pers. observ.). An Arabica coffee tree will fruit for around 50–60 years, but only if stumped or careful pruned. Cultivated Arabica coffee trees of considerable age are reported, for example up to 140 years old (Tadesse, 2017) but these have not been verified and are likely to have been stumped (coppiced).

Applying this to the three generation length algorithms, gives:

1. Vitality rates model ~ 17 years.
2. Adult mortality model 10–24 years (d values of 0.15 to 0.5 from plants in (Fung & Waples, 2017)).
3. Reproductive life span model ~ 10–16 years (z values for plants of 0.16, 0.21, and 0.33 from plants in (Fung & Waples, 2017)).

2.4 | Generation length of wild Arabica coffee

We extrapolated ages from cultivated plants, but with the following modifications. It is reported that wild Arabica plants in Ethiopia (Meyer, 1965) can be 20 ft (6 m) high and have a trunk diameter of 8 in. (20.3 cm) at ground level; and in South Sudan (Thomas, 1942) 18 ft (5.5 m) high and 6 in. (20.3 cm) at ground level. From these records it is possible to estimate an age of 60–80 years, where 1 in. is roughly equivalent to 10 years growth. It has also been widely reported (e.g., on the Internet and pers. comm.) that wild Arabica coffee plants can for live up to 100 years, but this is not backed up by specific citations. In the wild, Arabica coffee matures (i.e., starts to bear fruit) much later than in cultivation, and we estimate that it will take 8–12 years for wild plants to fruit. Finally, the maximum productivity will be markedly less, probably at a maximum of around 400 fruits per tree (Davis pers. observ.), although this figure could be higher or lower depending on specific environmental conditions (especially light levels) and the amount of competition from surrounding vegetation.

Applying this to the three generation length algorithms, gives:

1. Vitality rates model ~ 21 years.
2. Adult mortality model 16–30 years (d values of 0.15 and 0.5 from plants in (Fung & Waples, 2017)).
3. Reproductive life span model ~ 18–22 years (z values for plants of 0.16, 0.21 and 0.33 from plants in (Fung & Waples, 2017)).

The wild and cultivated models give a generation length of between 10–30 years, with a mean generation length of approximately 16 years for cultivated Arabica, and 21 years for wild Arabica. Estimates for generation length in other perennial plant species have been determined Fung & Waples, (2017) and includes 15.6 years for *Limonium delicatulum* (*Plumbaginaceae*; a pin-cushion plant), 82 years for *Grias peruviana* (Lecythidaceae; sachamangua, a small tropical tree), 169 years for a coniferous species (*Araucaria cunninghamii*; a large, temperate tree). At 21 years this is very much at the lower-end of the generation length for trees. Erring on the conservative side we have used 21 years as our generation length for reporting the metrics in this study, but we also assessed generation lengths of 16, 26, and 30 years, to see how the variation in generation length would influence the assessment of extinction risk under the IUCN Red List assessment criteria.

2.5 | Future and past and future population reduction (A3 and A4)

Future populations (A3) were calculated using three generation lengths as specified by the IUCN (IUCN Standards and Petitions Subcommittee, 2016). For a generation length of 21 years and future reductions (A3), we compared 2010–2039 (2024.5) to 2010–2039 (2087.5); 2010–2039 is where we see coffee suitability peak in Ethiopia (Moat et al., 2017a). For all generation lengths we either extrapolated from the last two periods, if the three generation lengths were beyond the latest models (2070–2099), or interpolated, if between model periods. For the population analysis, each niche class area was either extrapolated or interpolated and the total population recalculated using either the linear or normal population demographics (see above). If any extrapolation gave a negative number (i.e., inferring that the niche would have died out), we defaulted this value to zero. These calculations were performed in R (R Core Team, 2016) using the “approx” and “lm” function, using linear fits. Future and past population reduction (A4) was calculated in a similar way, but with a baseline date of 1975 (1960–1990).

2.5.1 | Application to the Red List criteria and ratings

We calculated all of the metrics in the statistics package R (R Core Team, 2016), using the IUCN thresholds as set out in the IUCN guidelines and criteria (Mace et al., 2008; IUCN Standards and Petitions Subcommittee, 2014; Moat, 2017).

3 | RESULTS

3.1 | Present-day geographic ranges (IUCN Criteria B)

Under IUCN criterion B, the geographic range of variables are relatively simple to measure and calculate.

3.1.1 | B1. EOO

Using the current niche and querying only areas with forest cover of over 1 hectare, we achieved an EOO of 283,817 km^2. Additionally we calculated the EOO from the ground-point data only, in both rCAT (Moat, 2017) and GeoCAT (Bachman, Moat, Hill, Torre, & Scott, 2011), to check that our results were comparable. The EOO value was 107,251 km^2 in rCAT, and 107,785 km^2 in GeoCAT. This metric would fall within the Least Concern extinction risk category.

3.1.2 | B2. AOO

Using the current niche and querying only areas with forest cover of over 1 hectare we achieved a minimum AOO of 49,440 km^2, with a mode of 49,908 km^2, maximum of 50,204 km^2 and mean of 49,874 km^2 (Figure 1). This metric would fall within the Least Concern extinction risk category. We also calculated the AOO from just the ground-point data in both rCAT (Moat, 2017) and GeoCAT (Bachman et al., 2011): the EOO was 512 km^2 in rCAT and 508 km^2 in GeoCAT. We would not expect these AOO values to be accurate as the ground-point data for Arabica coffee is hugely under-representative of population size and extent.

3.1.3 | Present-day population size range (C, D)

Using linear demographic distribution estimates, we arrive at approximately 19.5 billion mature plants for wild Arabica over its indigenous distribution. Using the normalized demographics distribution method, the estimate is 13.5 billion mature plants. This metric would fall within the Least Concern extinction risk category.

3.1.4 | Number of locations

For the number of locations we used the IUCN definition of location: “a geographically or ecologically distinct area in which a single event will affect all individuals” (IUCN, 2012). For wild and cultivated Arabica coffee, climate is the main driver for the distribution of the species (Moat et al., 2017a). The locations covered by the natural distribution of wild Arabica represent different climate regimes (Davis et al., 2018; Moat et al., 2017a), which will affect the species differently under a changing climate. Within Ethiopia there is a major climatic division, east and west of the Great Rift Valley, as discussed in Moat et al. (2017a), giving two locations for wild Arabica coffee. A third would be the Boma Plateau in South Sudan, although this location is projected to fall out of climatic suitability by 2020, representing the time period 2010–2029 (Davis et al., 2012). There is a fourth locality in the north, on the Zege Peninsula (Bahir Dar), located at the southern edge of Lake Tana. Niche models indicate that the Zege Peninsula is potentially part of the wild distribution of Arabica coffee, and forest coffee is cultivated here, but it is uncertain if these are true wild Arabica coffee populations, as the residents of the area say the forest and its coffee was planted around two hundred years ago. This gives three to four locations, but to invoke the number of locations criteria (based on the threshold of less than five locations (IUCN, 2012) this species would need to be pushed to Critically Endangered or Extinct in a very short period, and there is no evidence for this.

3.2 | Population size reduction (IUCN Criteria A)

On analyzing future population reductions (IUCN sub criterion A3) and past to future reductions (IUCN sub criterion A4), we assessed the reductions in EOO, AOO, and estimated population numbers, using both the linear and normal demographic distributions (with generation lengths of 16, 21, 26, and 30 years. The IUCN extinction risk category under Criteria A for future projection scenarios are given in Figures 5 & 6.

4 | DISCUSSION

Reviewing the species using present-day metrics (Criteria B: for AOO, EOO, population size, and number of locations), that is, excluding climate change projections, wild Arabica coffee would be assessed as Least Concern when applying IUCN Red List criteria. It is only when applying climate change to the past to future, and future to future changes, (under IUCN criteria A) that we see the species fall within the higher-level IUCN extinction threat categories. The difference between these two sets of analyses is profound.

We limit most of our discussion below using a generation length of 21 years (Figure 5, see table in top right of figure) but will also comment on the influence of different generation length estimates on the final extinction assessment.

4.1 | Migration scenarios

Our three migration scenarios (Table 1) are taken from Moat et al. (2017a). Migration scenario C allows the species to move anywhere within the present-day forest cover, and we have preserved this scenario for the analysis. However, we think it is unrealistic, due to the following points. (a) The assumption is that the new niche space will have no competition (i.e., that Arabica coffee can readily occupy the new niche), which is unrealistic. (b) If wild Arabica could move into these new niches, in some cases it will need to move hundreds of kilometres from the main population; the probability of the species moving to this space in a short period of time is unrealistic (Davis et al., 2012). (c) The time periods given here for the three generation lengths, would only allow a very short period for: random distributions to a new site, establishment, and breeding. (d) The new niches are often on the lowest part of the niche suitability for Arabica coffee, and so the species will not have optimal conditions to establish and reproduce. (e) That the niche would have the correct soils and microclimate (i.e., humid forest of the correct type and structure). Nonetheless, migration scenario C does serve some purpose, and particularly what could be achieved with intervention (i.e., assisted migration for conservation purposes, including the movement of propagules and establishment of suitable growing conditions, i.e., humid forest). Even with migration scenario C (which represents a best-case scenario) we can see than the species would receive an IUCN risk category of Endangered, using the normally distributed population demographic model and future reductions (IUCN sub criterion A3). This is due to the dramatic reduction (and in some cases loss) of the most suitable niches for Arabica coffee (the "Excellent" niche (Moat et al., 2017a)) for areas by the end of the century (Moat et al., 2017a).

The other two migration scenarios (D and F), either restrict wild Arabica coffee to its current (1960–1990) niche (migration scenario D) or restrict the species to all previous niches (migration scenario F), that is, the niche cannot drop below the threshold during any previous period. For the D and F migration scenarios the IUCN risk categories would be (for 21 years): D = CR (2 metrics), EN (9 metrics), and VU (13 metrics); and for *F* = CR (3 metrics), EN (9 metrics), and VU (17 metrics). Details are given in Figure 5. There is little difference (on average 2%) between the results for these two migration scenarios; with migration scenario F showing the highest reductions.

4.2 | Emission scenarios

There was considerable variability for the two emission scenarios A2 and A1B, with a −30% to + 30% difference in reduction/increase in the niche, between the two. Much of this variation was in EOO, which is not surprising as the EOO metric can be highly variable and sensitive to outlying occurrences (Hartley & Kunin, 2003; Keith, Akçakaya, & Murray, 2018; Keith, Auld, Ooi, & Mackenzie, 2000). The future projections (IUCN sub criterion A3), with emission scenario A2, consistently reports higher loses in AOO and the two population metrics, as expected.

4.3 | General circulation models (GCMs)

We used three GCMs for the future projections under climate change, which provided representative coverage of the variability in climate modelling, without having to process all available (23 or more) GCMs (Moat et al., 2017a). The variability between GCM reductions was not large, and generally below 10%.

4.4 | Past to future versus future reductions (sub criteria A3 and A4)

Predictably, there is a considerable difference between these two metrics, mainly due to the coffee niche coming into its best condition in 2010–2039 (Moat et al., 2017a). This is because A4 (past and future) is always reporting less reduction than A3 (future).

4.5 | Reduction metrics

The AOO metrics, and population numbers with linear demographics and normal demographics, behave consistently. Due to its geometric characteristics, EOO can change dramatically, with substantial changes in the area it reports, due to the loss and gains of outlying

Generation length = 16 years

Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	−4%	24%	32%	43%	11%	−31%	−23%	−42%
C	A1b	csiro_mk3_5	−19%	16%	18%	22%	12%	−27%	−22%	−40%
C	A2	gfdl_cm2_1	−35%	20%	33%	44%	25%	−37%	−40%	−69%
C	A1b	gfdl_cm2_1	6%	20%	25%	35%	0%	−35%	−34%	−61%
C	A2	bccr_bcm2_0	−7%	21%	28%	38%	11%	−51%	−39%	−57%
C	A1b	bccr_bcm2_0	−8%	5%	10%	16%	15%	−24%	−6%	−10%
D	A2	csiro_mk3_5	34%	29%	47%	59%	29%	20%	6%	−15%
D	A1b	csiro_mk3_5	32%	25%	34%	40%	29%	20%	6%	−14%
D	A2	gfdl_cm2_1	10%	23%	46%	57%	52%	18%	−4%	−32%
D	A1b	gfdl_cm2_1	40%	22%	36%	48%	27%	19%	2%	−24%
D	A2	bccr_bcm2_0	19%	19%	32%	42%	29%	17%	−1%	−23%
D	A1b	bccr_bcm2_0	32%	18%	25%	32%	29%	20%	15%	8%
F	A2	csiro_mk3_5	36%	31%	48%	60%	29%	20%	6%	−15%
F	A1b	csiro_mk3_5	34%	28%	35%	41%	29%	20%	6%	−14%
F	A2	gfdl_cm2_1	12%	26%	47%	58%	52%	18%	−4%	−32%
F	A1b	gfdl_cm2_1	41%	25%	37%	49%	27%	19%	2%	−24%
F	A2	bccr_bcm2_0	22%	22%	34%	43%	29%	17%	−1%	−23%
F	A1b	bccr_bcm2_0	40%	20%	26%	32%	29%	20%	15%	8%
		Maximum	41%	31%	48%	60%	52%	20%	15%	8%
		Mean	30%	25%	38%	48%	34%	19%	5%	−15%

Generation length = 21 years

Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	−12%	32%	49%	64%	13%	−24%	−17%	−33%
C	A1b	csiro_mk3_5	−7%	23%	29%	34%	−1%	−22%	−20%	−36%
C	A2	gfdl_cm2_1	−42%	27%	49%	68%	17%	−30%	−33%	−59%
C	A1b	gfdl_cm2_1	−5%	23%	37%	55%	9%	−26%	−28%	−56%
C	A2	bccr_bcm2_0	−7%	26%	39%	57%	9%	−42%	−30%	−48%
C	A1b	bccr_bcm2_0	−12%	10%	25%	40%	14%	−26%	−11%	−17%
D	A2	csiro_mk3_5	33%	40%	68%	82%	41%	26%	16%	1%
D	A1b	csiro_mk3_5	32%	35%	50%	60%	40%	25%	12%	−5%
D	A2	gfdl_cm2_1	18%	35%	65%	80%	53%	22%	6%	−16%
D	A1b	gfdl_cm2_1	41%	29%	50%	69%	41%	25%	10%	−12%
D	A2	bccr_bcm2_0	35%	27%	48%	65%	29%	20%	5%	−15%
D	A1b	bccr_bcm2_0	32%	28%	42%	55%	40%	23%	18%	10%
F	A2	csiro_mk3_5	37%	43%	69%	83%	41%	27%	16%	1%
F	A1b	csiro_mk3_5	35%	37%	51%	61%	40%	26%	12%	−5%
F	A2	gfdl_cm2_1	21%	38%	67%	81%	53%	23%	6%	−15%
F	A1b	gfdl_cm2_1	42%	33%	52%	71%	41%	25%	10%	−11%
F	A2	bccr_bcm2_0	38%	33%	51%	66%	30%	21%	6%	−15%
F	A1b	bccr_bcm2_0	41%	31%	44%	57%	42%	23%	18%	10%
		Maximum	42%	43%	69%	83%	53%	27%	18%	10%
		Mean	34%	35%	56%	70%	42%	24%	12%	−5%

Generation length = 26 years

Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	−20%	40%	61%	79%	15%	−14%	−10%	−20%
C	A1b	csiro_mk3_5	5%	29%	40%	47%	−16%	−17%	−17%	−30%
C	A2	gfdl_cm2_1	−50%	34%	54%	78%	7%	−22%	−24%	−46%
C	A1b	gfdl_cm2_1	−17%	26%	48%	75%	19%	−15%	−21%	−47%
C	A2	bccr_bcm2_0	−6%	31%	46%	72%	6%	−30%	−19%	−35%
C	A1b	bccr_bcm2_0	−16%	16%	41%	65%	12%	−27%	−16%	−24%
D	A2	csiro_mk3_5	32%	52%	71%	84%	54%	33%	27%	18%
D	A1b	csiro_mk3_5	33%	44%	66%	79%	50%	31%	18%	4%
D	A2	gfdl_cm2_1	27%	46%	68%	85%	53%	26%	18%	4%
D	A1b	gfdl_cm2_1	41%	35%	56%	80%	55%	30%	19%	3%
D	A2	bccr_bcm2_0	51%	36%	57%	79%	29%	24%	12%	−6%
D	A1b	bccr_bcm2_0	32%	39%	58%	77%	51%	25%	20%	11%
F	A2	csiro_mk3_5	38%	55%	72%	85%	54%	33%	27%	19%
F	A1b	csiro_mk3_5	36%	46%	68%	80%	52%	33%	19%	5%
F	A2	gfdl_cm2_1	30%	50%	70%	85%	53%	27%	18%	4%
F	A1b	gfdl_cm2_1	43%	41%	58%	81%	55%	32%	20%	3%
F	A2	bccr_bcm2_0	55%	43%	60%	80%	31%	25%	13%	−6%
F	A1b	bccr_bcm2_0	41%	42%	59%	78%	56%	26%	20%	12%
		Maximum	55%	55%	72%	85%	56%	33%	27%	19%
		Mean	40%	45%	64%	81%	50%	29%	20%	7%

Generation length = 30 years

Migration scenario	Emmision senario	GCM	A3 EOO	A3 AOO	A3 Pop linear	A3 Pop normal	A4 EOO	A4 AOO	A4 Pop linear	A4 Pop normal
C	A2	csiro_mk3_5	−26%	47%	61%	79%	11%	−6%	5%	2%
C	A1b	csiro_mk3_5	15%	34%	49%	56%	−10%	−11%	−7%	−18%
C	A2	gfdl_cm2_1	−56%	40%	50%	76%	2%	−14%	−7%	−16%
C	A1b	gfdl_cm2_1	−26%	29%	42%	72%	12%	−11%	−9%	−23%
C	A2	bccr_bcm2_0	−6%	35%	42%	70%	6%	−24%	−7%	−13%
C	A1b	bccr_bcm2_0	−20%	21%	40%	66%	10%	−22%	−5%	−6%
D	A2	csiro_mk3_5	32%	61%	72%	84%	54%	39%	41%	39%
D	A1b	csiro_mk3_5	34%	52%	72%	85%	52%	37%	30%	21%
D	A2	gfdl_cm2_1	34%	55%	68%	84%	56%	33%	33%	27%
D	A1b	gfdl_cm2_1	42%	41%	52%	78%	57%	35%	30%	23%
D	A2	bccr_bcm2_0	64%	43%	53%	77%	37%	29%	24%	14%
D	A1b	bccr_bcm2_0	32%	48%	58%	77%	52%	31%	30%	26%
F	A2	csiro_mk3_5	38%	65%	73%	85%	55%	40%	42%	40%
F	A1b	csiro_mk3_5	37%	53%	72%	85%	53%	39%	31%	22%
F	A2	gfdl_cm2_1	38%	60%	70%	85%	56%	35%	34%	28%
F	A1b	gfdl_cm2_1	44%	47%	54%	79%	57%	37%	31%	23%
F	A2	bccr_bcm2_0	68%	51%	57%	79%	39%	31%	25%	15%
F	A1b	bccr_bcm2_0	42%	50%	59%	78%	58%	32%	31%	27%
		Maximum	68%	65%	73%	85%	58%	40%	42%	40%
		Mean	44%	53%	64%	82%	53%	35%	33%	27%

FIGURE 5 Rates of reduction (percentage) using generation lengths of 16, 21, 26, and 30 years. Green = Least concern (LC), Yellow = Vulnerable (VU), Orange = Endangered (EN), Red = Critically Endangered (CR). Migration scenario C is shown in grey figures as these percentages will only be achieved with considerable intervention (e.g., assisted migration, with replanting of forest). N.B. We would advise caution with the interpation of changes in EOO due to the inclusion of an outlining occurrence in the north (Zege Peninsula, near Bahir Dar) (Figure 2).

areas (Hartley & Kunin, 2003; Keith et al., 2000, 2018). The inclusion (and its loss under future projections) of the uncertain population from the Zege Peninsula (near Bahir Dar, the most northly population in Figure 2), will be driving much of the change in the EOO. On this basis we would advise caution with interpretation of the EOO changes (Figure 5), and we do not use it in our final extinction risk assessment. Nonetheless, the two models for population demographics show the greatest change, with the results from the normal distribution population model showing the most dramatic reductions, which is due to the rapid loss of the Excellent niche category (Moat

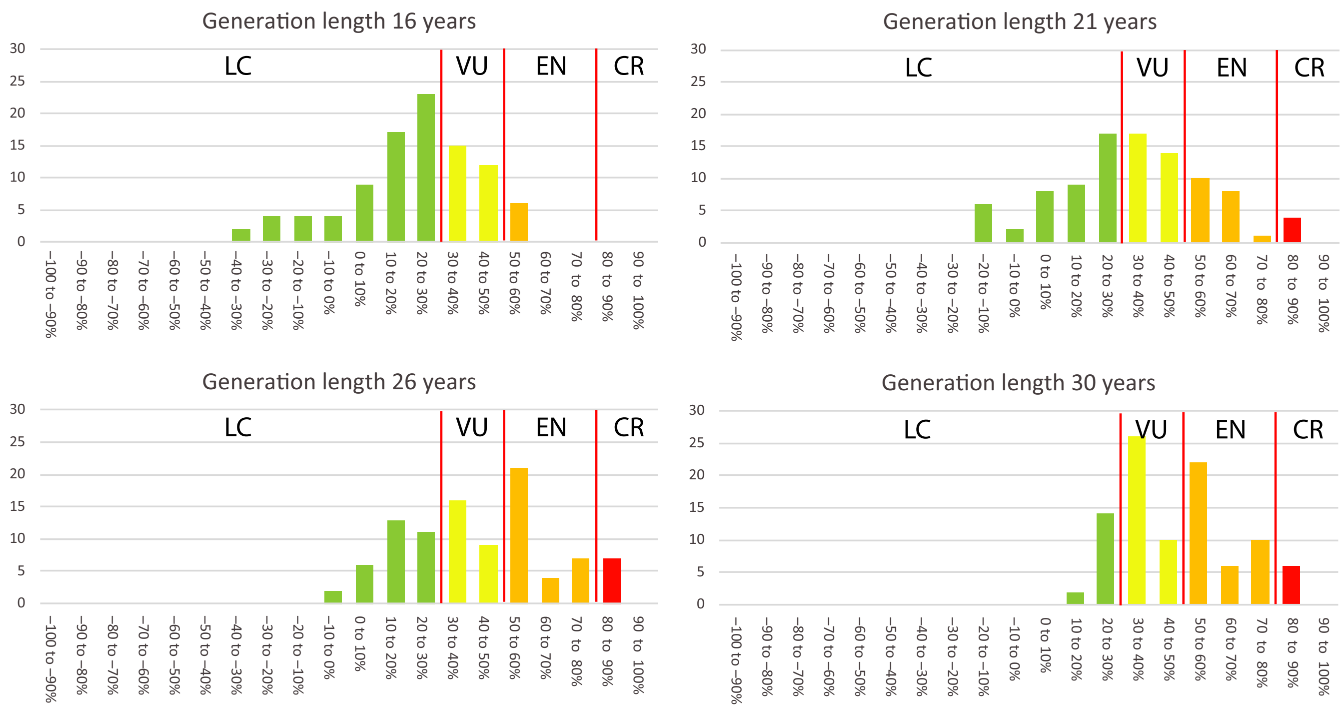

FIGURE 6 Histograms of percentage reduction (AOO, EOO, and population measures), with differing generation lengths. X = percentage change in metric (IUCN thresholds as shown LC = Least Concern, VU = Vulnerable, CR = Critically Endangered. Y = number of measures in the percentage change class.

et al., 2017a) as this century progresses (towards 2099). The linear population model shows the same trend, but with less dramatic changes as the century progresses. Regardless, both show an IUCN extinction risk assessment of Endangered for a generation length of 21 years.

4.6 | Generation length

Based on field observations and published information we estimated a generation length for wild coffee of 16–30 years, with 21 years probably representing a conservative value for the generation length of wild Arabica coffee. A summary of the percentage reductions for different generation lengths is shown in Figure 6. The results for 30 years should be viewed tentatively, as we are projecting far beyond our last time-period (2070–2099 vs. 2,115, which is over 30 years of extrapolation). Even at 16 years, six of the metrics point to Endangered. With our conservative generation length estimate of 21 years, 23 of our metrics point to Endangered and a few (four) point towards the higher category of Critically Endangered. Overall, there is a skew towards higher IUCN extinction risk categories as the generation length increases (Figure 6).

4.7 | In the context of deforestation

Up until this point we have not considered deforestation for the IUCN extinction risk assessment and have assumed forest cover to be static. However, historical deforestation levels in Ethiopia have been dramatically high and are ongoing (Reusing, 2000; World Resources Institute, 2014), as detailed below. Comparing different deforestation studies is difficult, as they use various definitions and classifications for forest types. The original/potential (i.e., without or before the intervention of humankind) extent of forest cover has been given by EFAP (1994) and Friis et al. (2010), as 340,000 and 280,470 km^2, respectively. Although these studies use different classifications and scales, they do give an indication that the original forest cover of Ethiopia is in the region of 25%–31% of Ethiopia's total land surface area. There is no universal agreement on the remaining forest cover (Wakjira, Gole, & Senbeta, 2008), but the majority of studies agree that present-day forest cover is around 4% of the total land surface area of Ethiopia (Reusing, 1998, 2000; Wakjira et al., 2008).

On reviewing studies from (Reusing, 1998, 2000; Wakjira et al., 2008; World Resources Institute, 2014), we can report that the rates of forest loss (Reusing, 1998, 2000) shows reductions of 54% and 61% over 23 and 25 years (from 1971–1975 to 1996–1997 and 1973–1999), respectively, for natural, humid (Afromontane) forest. These values are backed up by Wakjira et al. (2008), who looked in detail at a smaller area of humid coffee forest in south western Ethiopia, and showed that between 1973 and 2005, 32% of the forest cover had been lost, and in some areas there has been a 50% loss in a 32 year period alone. The majority (70%) of the reduction was due to smallholder expansion and forest conversion to agroforestry systems (Wakjira et al., 2008). Finally, forest reduction is still continuing to the present day: between 2001 and 2013 there was a reduction in tree cover of 2,260 km^2, with some (630 km^2) afforestation (Hansen et al., 2013; World Resources Institute, 2014).

It should, however, be noted that all the above metrics cover many forest types in Ethiopia and that the main deforested areas are in the South East and South West (Moat et al., 2017b). It would be very difficult to simply equate and extrapolate these tree-cover loss figures to just the humid forests where wild Arabica coffee occurs; additionally, we would also need to either extrapolate into the future or the past to cover the 63 years (three times generation length) needed. Nonetheless, we would suspect that the reduction figures will be high and possibly comparable to the figures for future reductions from climate change. We have not used the deforestation figures given above in an Arabica extinction risk assessment, due to the uncertainty in forest definitions amongst the various studies and the lack of data over the time period needed, but we suggest that this could be rectified with a dedicated study of the temporal changes in suitable humid forest (Moist Evergreen Afromontane Forest (MAF) and Transitional Forest (TRF) types; Friis et al., 2010) across the region, using remote sensing.

4.8 | CMIP3 versus CMIP5

The projections used here are based on the WCRP CMIP3 (Meehl et al., 2007) multimodel datasets (Moat et al., 2017a). The newer and more developed WCRP CMIP5 multimodel ensemble (Taylor, Stouffer, & Meehl, 2012) has become available as downscaled datasets (at 1 km^2 resolution). Knutti and Sedláček (2012) compared CMIP5 and CMIP3 and stated: "The spatial patterns of temperature and precipitation change are also very consistent. Interestingly, the local model spread has not changed much despite substantial model development and a massive increase in computational capacity." A direct comparison between CMIP3 and CMIP5 is not straightforward, as CMIP3 uses emission scenarios, whereas CMIP5 uses Representative Concentration Pathways (RCPs) (Knutti & Sedláček, 2012). However, Moat et al. (2017a) and Knutti and Sedláček (2012) have compared RCP8.5 with the A2 emission scenario, and report that within Ethiopia the only substantial difference observed was a 0.9°C increase in temperature, but with an increase in the derivation between GCMs, and a small increase in rainfall (in the North and Eastern areas), but again with increasing displacement between GCMs. The increase in temperature observed for RCP8.5 (i.e., 0.9°C) would indicate that both the A2 and A1B scenarios could be more conservative, compared to RCP8.5; the small increase in rainfall (up to 130 mm per annum, but with very high variability between GCMs) would not be enough to negate the change in temperature (Moat et al., 2017a). If temperature change were to follow RCP8.5 (CMIP5), we would see an intensification of the negative changes shown here using CMIP3.

4.9 | Closing remarks

We have shown that climate change could alter the climatic suitability of wild Arabica coffee populations in Ethiopia and South Sudan, resulting in a projected decline in EOO, AOO, and more substantial reductions in population numbers (more than 50% reduction). If we were to apply the precautionary rule (the worst case scenario) this would give coffee the extinction risk value of Critically Endangered (10% of the results, for a generation length of 21 years, IUCN criteria A3 and migration scenarios D and F; Figure 5), but we feel that the assessment of Endangered is more justifiable (50% of the results, for a generation length of 21 years, IUCN criteria A3 and migration scenarios D and F; Figure 5). An IUCN extinction risk assessment for Wild Arabica coffee lacking the inclusion of climate change projections would result in the extinction risk category of Least Concern; applying climate change projections as part of the IUCN Red List criteria methodology results in an assessment of Endangered, under IUCN Criterion A (sub-criteria A3b), which is three categories above Least Concern. The full IUCN extinction risk assessment for Arabica coffee is: Endangered, with population reductions projected to be greater than 70% within a 63-year window (2025–2088), based on a generation length of 21 years and using an index of population abundance (EN A3b).

Generation length is critical when applying the IUCN criteria. Here we have erred here on the side of caution using a generation length of 21 years, but if it can be demonstrated that Arabica coffee has a longer generation length (and 26 years would be sufficient) there is a possibility that the species will be pushed into the extinction risk category of Critically Endangered. We have assumed that forest levels are static, but it is clear that there is a backdrop of rapid and continuing deforestation in Ethiopia and South Sudan. If deforestation metrics were included into the IUCN extinction risk assessment, the outcomes are likely to be even more negative (i.e., climate change plus deforestation), and if deforestation were to remain high and consistent it could impose a stronger driver of extinction risk than climate change alone, at least in short-term. Some locations, such as the Boma Plateau (South Sudan) and wild arabica coffee locations on the eastern side of the Great Rift Valley in Ethiopia (and especially the Bale (Harenna) forest area) are rapidly lost according to climate change projections, a result that receives unanimous agreement across a range of GCMs (Davis et al., 2012; Moat et al., 2017a, 2017b). In Ethiopia and South Sudan both of these areas coincide with high and ongoing rates of deforestation, indicating that there would be a substantial negative compounding influence (i.e., deforestation and climate change). Germplasm from the Boma Plateau (South Sudan) and Bale (Harenna) forest area is thus a high priority for ex situ conservation, and possibly (in situ) assisted migration. The area of coffee forest presently contained within protected areas is small (1,681 km^2; about 4% of the existing wild coffee forest area) and in the future some of these protected areas will need to incorporate higher elevation to ensure the species continued protection at these sites (Davis et al., 2012; Moat et al., 2017a).

The results reported in this paper, shows that intervention could make a substantial difference to the future of wild Arabica coffee. If specific activities are undertaken (particularly assisted migration, forest preservation, and regeneration; see Figure 5 migration scenario C) the chances of the species becoming highly threatened (i.e., Critically Endangered) could be greatly reduced. Focused intervention actions, and especially forest preservation and reestablishment, could have a positive outcome for the species, humid forest cover, and ecosystem services, and the long-term sustainability of the Ethiopia coffee economy.

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