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# Resilience potential of the Ethiopian coffee sector under climate change

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**Coffee farming provides livelihoods for around 15 million farmers in Ethiopia and generates a quarter of the country's export earnings. Against a backdrop of rapidly increasing temperatures and decreasing rainfall, there is an urgent need to understand the influence of climate change on coffee production. Using a modelling approach in combination with remote sensing, supported by rigorous ground-truthing, we project changes in suitability for coffee farming under various climate change scenarios, specifically by assessing the exposure of coffee farming to future climatic shifts. We show that 39–59% of the current growing area could experience climatic changes that are large enough to render them unsuitable for coffee farming, in the absence of significant interventions or major influencing factors. Conversely, relocation of coffee areas, in combination with forest conservation or re-establishment, could see at least a fourfold (>400%) increase in suitable coffee farming area. We identify key coffee-growing areas that are susceptible to climate change, as well as those that are climatically resilient.**

Arabica coffee (*Coffea arabica*) provides Ethiopia with its most important agricultural commodity, contributing around one quarter of its total export earnings[1]. In 2015/16, Ethiopia exported around 180,000 metric tonnes of coffee[2] at a value in excess of 800 million USD, making it Africa's largest coffee producer and the world's fifth largest coffee exporter[2], despite the fact that around half of the coffee produced each year is consumed in-country[3]. Coffee farming provides a livelihood income for around 15 million Ethiopians (16% of the population), based on four million small-holder farms[2,4].

In Ethiopia, coffee is produced within specific agro-ecological zones, over numerous geographical and political boundaries. At least 80% of Ethiopia's coffee comes from forests, forest-like habitats, or farms with shade (canopy) cover, representing land coverage of around 19,000 km$^2$ (Fig. 1) with around another 4,000 km$^2$ (c. 20%) grown in small plots in partial shade or full sun. Most of the coffee is grown in areas that are covered, or were previously covered[5], with humid evergreen forest: Moist Afromontane Forest (MAF) and Transitional Rain Forest (TRF)[6]. MAF and TRF are found at 650–2,600 m (450–3,000 m including extremes), although coffee is mostly confined to 1,200–2,200 m. Coffee farming is also undertaken in association with a drier type of vegetation, classified as Dry Afromontane Forest[6], such as that found in the Harar Zone (Fig. 1). The main coffee-growing areas of Ethiopia are found within the south-west and south-east (Oromia Region and Southern Nations, Nationalities and Peoples' Region), with modest and minor production in the north (Amhara Region and Benishangul–Gumuz Region, respectively) (Fig. 1).

Coffee farmers and other coffee sector stakeholders in Ethiopia and East Africa report that coffee production has been negatively influenced by changes in climate. These changes include: an increase in the uncertainty of yearly weather patterns, particularly in precipitation variability and timing of the wet season; an extension of the dry season (shortening of the wet season); a more extreme (drier and hotter) end to the main dry season; more intense (extreme) weather (heavier rain, hotter days); and warmer nights[7,8].

Historical climate data shows that the mean annual temperature of Ethiopia has increased by 1.3 °C between 1960 and 2006, at an average rate of 0.28 °C per decade[9] and by 0.3 °C per decade in the south-west[10] and Amhara in the north[11]. These temperature increases have been most rapid in the main wet season (July to September) at a rate of 0.32 °C per decade[9]. Analyses of extreme temperature changes in various coffee-growing areas indicate positive trends for maximum temperature, warm days, warm nights and warm spell duration; and negative trends for cool days, cool nights, and cold spell duration across different eco/agricultural environments (pastoral, agro-pastoral and highland), although some of the trends are not statistically significant[12]. The strong variability within Ethiopia's annual and decadal rainfall makes it difficult to detect long-term, country-wide trends[13]. Despite these limitations, studies show: that February to May[14] and June to September rains have declined[13,15,16]; a 15–20% reduction in rainfall since the mid-1970s[17] and late 2000s in southern, south-western and south-eastern Ethiopia, particularly in the period of the initial early (February to March) rains in the south-east and east[18,19], with an increase in drought frequency in all parts of Ethiopia during the last 10–15 years[16]; a decrease in June to September precipitation in the Greater Horn of Africa by approximately 1 s.d. during the period 1950–1989, corresponding to decreases of over 30 mm per decade throughout much of the Ethiopian Highlands[20]; and a downward trend in rainfall of 0.4 mm per month per year over the south-western region in the period 1948–2006[10].

The mean annual temperature of Ethiopia is projected to increase by 1.1–3.1 °C by the 2060s, and 1.5–5.1 °C by the 2090s, depending on the emission scenario[9]. Climate model projections under the emission scenarios A2 and B1 show Ethiopia warming in all four seasons across the country[21]. Projections from different General Circulation Models (GCMs) are broadly consistent in

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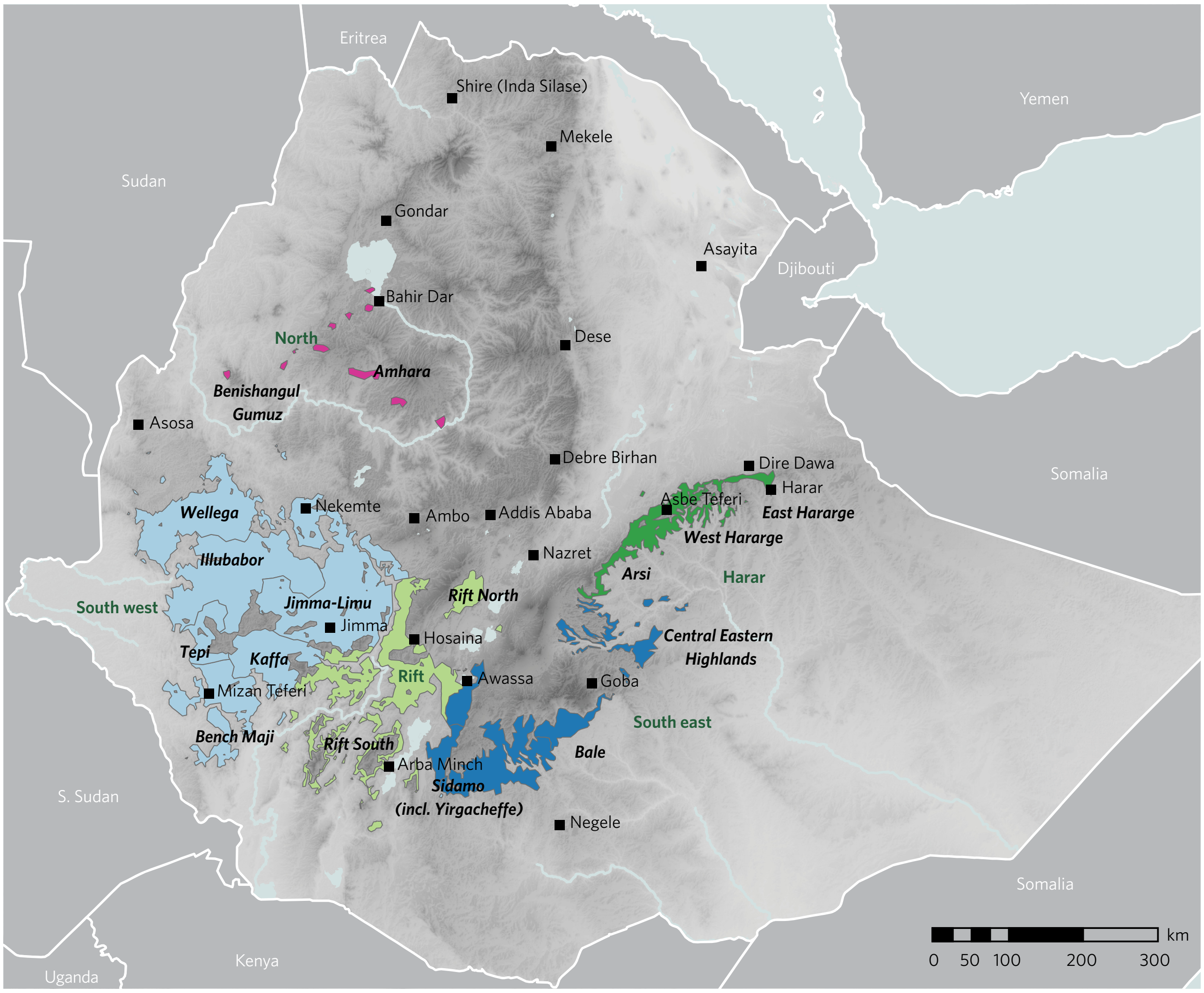

**Figure 1 | The main coffee growing zones and areas of Ethiopia.** The coffee zones represented by coloured polygons: red/pink, North Zone (coffee areas: Amhara and Benishangul Gumuz); light blue, South West Zone (coffee areas: Wellega, Illubabor, Jimma-Limu, Kaffa, Tepi and Bench Maji); light green, Rift Zone (coffee areas: Rift North and Rift South); dark blue, South East Zone (coffee areas: Sidamo, Yirgacheffe, Bale and Central Eastern Highlands); dark green, Harar Zone (coffee areas: Arsi, West Hararge and East Hararge).

indicating slight increases in annual rainfall in Ethiopia[22,23]. However, it should be made very clear that precipitation projections vary considerably in their agreement; some increases are negligible; the variability for GCM change is extremely high[24]; and for some regions of Ethiopia GCMs do not agree on the direction of change[21].

It is imperative to better understand the influence of climate change on coffee farming in Ethiopia, given the importance of coffee production and consumption for this country. The impacts of observed and projected changes in climate on coffee farming in Ethiopia are largely unknown. The only available climate change study for Ethiopian coffee is for native populations of Arabica coffee, using a single species distribution model (SDM), forest-only data and one GCM[25].

In order to quantify the influence of climate change on coffee farming in Ethiopia, we collated and collected high-quality ground-point data, from across the Ethiopian coffee landscape and beyond, then modelled using an ensemble SDM approach, which was overlaid with Landsat 8 satellite imagery[26] to accurately delimit the main coffee production areas (humid forest). This approach, in conjunction with the use of multiple migration scenarios, fine-level suitability thresholding, multiple GCM appraisal and rigorous ground-truthing (of models and remote sensing outputs), constitutes a significant advancement over previous coffee climate change analyses generally[25,27–33]. Nine environmental variables (from BIOCLIM[34]) were used to understand the current climate conditions for coffee farming, and to project suitable growing areas for the future. Using these data and methods we quantify the potential outcomes of climate change on coffee production across the coffee landscape of Ethiopia until 2099. Our analyses are primarily focused on exposure (based on climate scenario projections from GCMs). The two other aspects of climate change vulnerability, sensitivity and adaptive capacity[35,36], have not been directly addressed, although it should be noted that Arabica coffee is identified as a climate-sensitive species with a low adaptive capacity[25]. The potentially beneficial influence of elevated $CO_2$ and compounding negative influences (for example, pests, diseases and deforestation) were not included in our analyses, but are discussed.

## Results

**Model projections overview.** We modelled Arabica coffee suitability for Ethiopia using the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3)[37], across four time intervals (1960–1990, 2010–2039, 2040–2069 and 2070–2099; Supplementary Fig. 1), using

### Box 1 | Migration scenarios.

Six migration scenarios used in the modelling (see Supplementary Fig. 5 for further details, and Methods for processing details).

(A) Full Migration. Plants can grow in any suitable niche (can move anywhere).
(B) Plants can only grow within known niche (can only move within presently predicted niche).
(C) Plants can only grow within suitable forest cover, within any suitable niche (can move within suitable forest).
(D) No Migration. Plants can only grow within suitable forest cover and only in suitable known niche (restricted to present-day forest cover and suitable niches).
(E) Plants can only grow within suitable niche but only if niche does not drop outside of suitability during any 30-year time period.
(F) Plants can only grow within suitable forest cover and suitable niche, but only if niche does not drop outside of suitability during any 30-year time period.

### Box 2 | Niche classifications.

Environmental niche (coffee suitability) categories (see Supplementary Fig. 2, Methods and Supplementary Information for category threshold visualization and statistics).

1. Unsuitable. Coffee farming is barely possible to impossible.
2. Marginal. Coffee farming is possible but often problematic, with poor and very inconsistent yields.
3. Fair. Coffee farming possible and sometimes good but may require additional inputs (for example, irrigation, good shade and pruning). Yields poor in years with low rainfall.
4. Good. Coffee farming good, with the potential for consistent, high-quality yields. Yield and quality may be negatively affected in some years (during adverse weather conditions, especially low rainfall and high temperatures).
5. Excellent. Coffee farming good to excellent, with the potential for consistent, high-quality yields. Yields and quality can be negatively affected by adverse weather conditions, but less likely.

**Table 1 | Total suitable niche area change for three selected GCMs.**

| Scenario (migration – emission) | Area change for low: middle: high outcomes (km$^2$ with percentage area remaining in parentheses) | | | |
|---|---|---|---|---|
| | 1960–1990 | 2010–2039 | 2040–2069 | 2070–2099 |
| A – A1B | 44,820: 44,820: 44,820<br>(100: 100: 100) | 60,996: 66,158: 74,873<br>(136: 148: 167) | 50,387: 58,036: 72,033<br>(112: 129: 161) | 42,247: 51,280: 61,230<br>(94: 114: 137) |
| B – A1B | 44,820: 44,820: 44,820<br>(100: 100: 100) | 29,192: 35,270: 41,195<br>(65: 79: 92) | 27,110: 29,838: 35,597<br>(60: 67: 79) | 19,553: 24,379: 26,809<br>(44: 54: 60) |
| E – A1B | 44,820: 44,820: 44,820<br>(100: 100: 100) | 29,192: 35,270: 41,195<br>(65: 79: 92) | 26,287: 29,079: 34,923<br>(59: 65: 78) | 18,427: 23,389: 26,110<br>(41: 52: 58) |
| A – A2 | 44,820: 44,820: 44,820<br>(100: 100: 100) | 62,774: 74,272: 90,527<br>(140: 166: 202) | 54,722: 57,118: 68,728<br>(122: 127: 153) | 42,004: 50,498: 56,371<br>(94: 113: 126) |
| B – A2 | 44,820: 44,820: 44,820<br>(100: 100: 100) | 31,245: 34,904: 42,046<br>(70: 78: 94) | 28,054: 32,138: 33,438<br>(63: 72: 75) | 19,101: 22,468: 27,647<br>(43: 50: 62) |
| E – A2 | 44,820: 44,820: 44,820<br>(100: 100: 100) | 31,245: 34,904: 42,046<br>(70: 78: 94) | 27,617: 31,717: 33,091<br>(62: 71: 74) | 17,648: 21,415: 26,577<br>(39: 48: 59) |
| C – A1B | 19,142: 19,142: 19,142<br>(100: 100: 100) | 17,451: 20,575: 23,855<br>(91: 107: 125) | 17,330: 19,588: 22,082<br>(91: 102: 115) | 14,479: 17,139: 20,378<br>(76: 90: 106) |
| D – A1B | 19,142: 19,142: 19,142<br>(100: 100: 100) | 11,370: 14,319: 17,130<br>(59: 75: 89) | 12,131: 12,897: 14,335<br>(63: 67: 75) | 8,604: 11,256: 12,311<br>(45: 59: 64) |
| F – A1B | 19,142: 19,142: 19,142<br>(100: 100: 100) | 11,370: 14,319: 17,130<br>(59: 75: 89) | 11,817: 12,556: 14,100<br>(62: 66: 74) | 8,377: 10,464: 12,058<br>(44: 55: 63) |
| C – A2 | 19,142: 19,142: 19,142<br>(100: 100: 100) | 19,111: 21,072: 25,040<br>(100: 110: 131) | 18,092: 20,264: 20,742<br>(95: 106: 108) | 14,189: 17,781: 19,225<br>(74: 93: 100) |
| D – A2 | 19,142: 19,142: 19,142<br>(100: 100: 100) | 13,257: 14,177: 16,319<br>(69: 74: 85) | 11,295: 12,983: 14,964<br>(59: 68: 78) | 8,584: 9,933: 13,013<br>(45: 52: 68) |
| F – A2 | 19,142: 19,142: 19,142<br>(100: 100: 100) | 13,257: 14,177: 16,319<br>(69: 74: 85) | 11,105: 12,789: 14,858<br>(58: 67: 78) | 7,910: 9,502: 12,622<br>(41: 50: 66) |

Percentage and km$^2$ change (that remaining) in surface area for coffee niche suitability, against 1960–1990, for low, middle and high outcomes (see Methods for explanation) for migration scenarios (A–F) and emission scenarios A1B and A2. GCMs: GFDL-CM2.1, CSIRO-MK3.5 and BCCR-BCM2.0. The table is split: the top section contains niche-only scenarios (A, B, E), while the bottom section consists of forest and niche scenarios (C, D, F).

two emission scenarios (A1B and A2), six migration (coffee area movement) scenarios (Box 1; Supplementary Fig. 5), two biological/climatic coffee groups/areas and 23 GCMs, selecting three GCMs for our final analysis (see Methods). Coffee growing suitability was divided into five categories, based on statistical thresholding: Unsuitable, Marginal, Fair, Good and Excellent (see Methods; Box 2; Supplementary Fig. 2). We restrict our narrative here to two migration scenarios: A and D (Box 1), which we refer to as 'Full Migration (A)' and 'No Migration (D)'. The Full Migration (A) scenario represents the (maximum) potential niche (suitability) for coffee in Ethiopia, invoking an assisted migration scenario, where coffee areas can move to newly available niches, regardless of whether there is forest or not (Fig. 2). This scenario would require considerable intervention, including the provision of canopy cover (tree planting) in many places. The No Migration (D) scenario represents the actual (near-minimum; where scenario F is the minimum) coffee-growing surface area, based on the recent past (1960–1990) (Fig. 3). It assumes non-migration of coffee areas, either natural[25] or assisted (by planting coffee and shade cover) and also that there is zero forest loss or gain, but allows for climate change within the niche. Summary data for other migration scenarios are supplied in Table 1 and

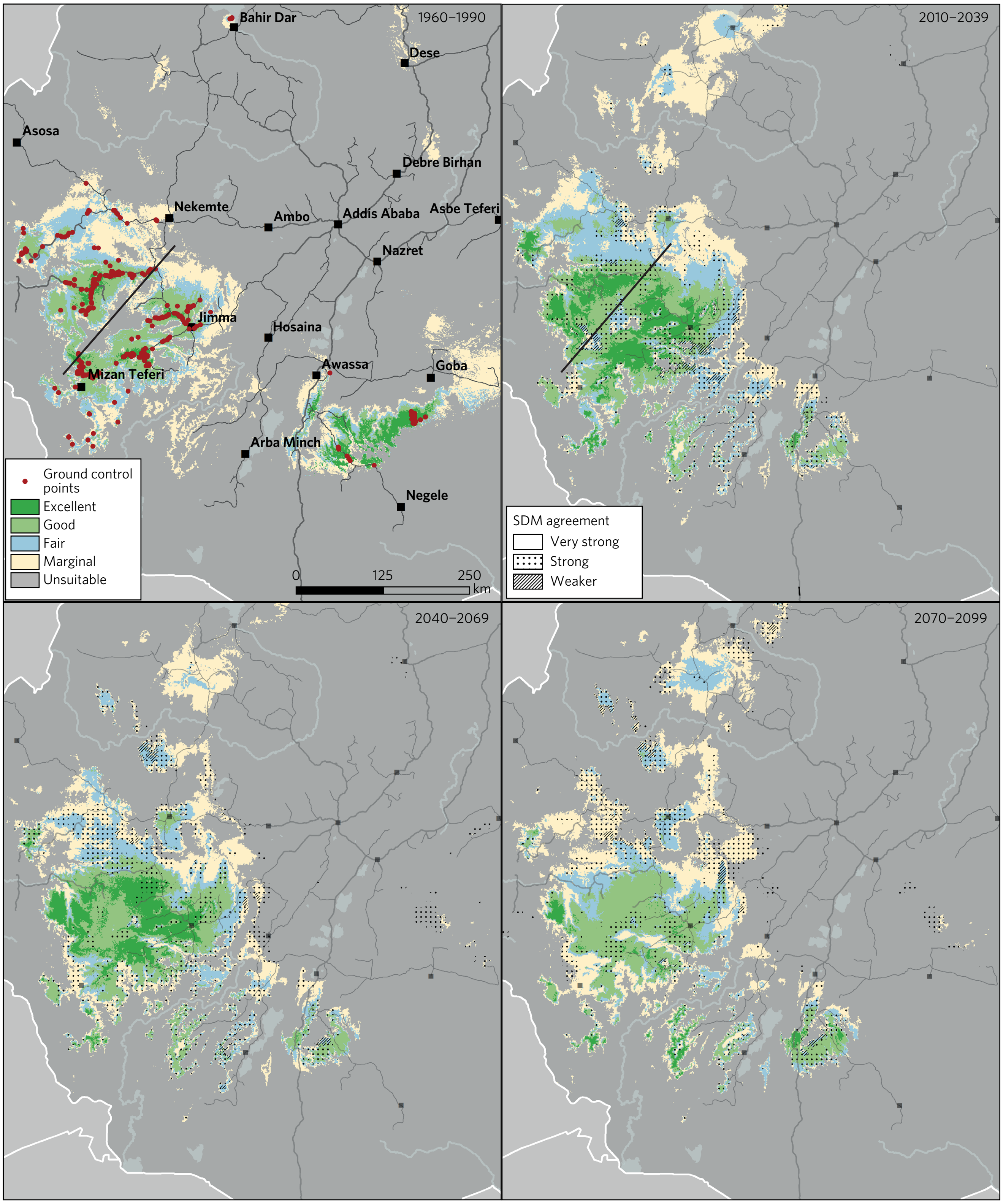

**Figure 2 | Future projections for coffee suitability under Full Migration (A) and emission scenario A1B.** Median of the three GCMs was used to colour niche suitability. SDM modelling agreement: very strong (average of 86% across study area, for all time periods), solid colour with no overlay; strong (13%), dots overlaid; weaker (1%), diagonal hatching overlaid. The 1960–1990 map shows the ground control data points used in this study and major place names (removed for clarity in subsequent maps). All maps show major roads (as dark lines) for navigation. Diagonal lines on 1960–1990 and 2010–2039 maps show the location of the elevation profile given in Fig. 6.

Supplementary Figs 7 and 8. In our modelling, there were no considerable differences between A1B and A2 (CMIP3 (ref. 37)), and so we restrict our main narrative to scenario A1B, which is the lower emission scenario of the two; results from the A2 analysis and migration scenarios B, C, E and F are supplied (Table 1; Supplementary Figs 7 and 8). We also review the more

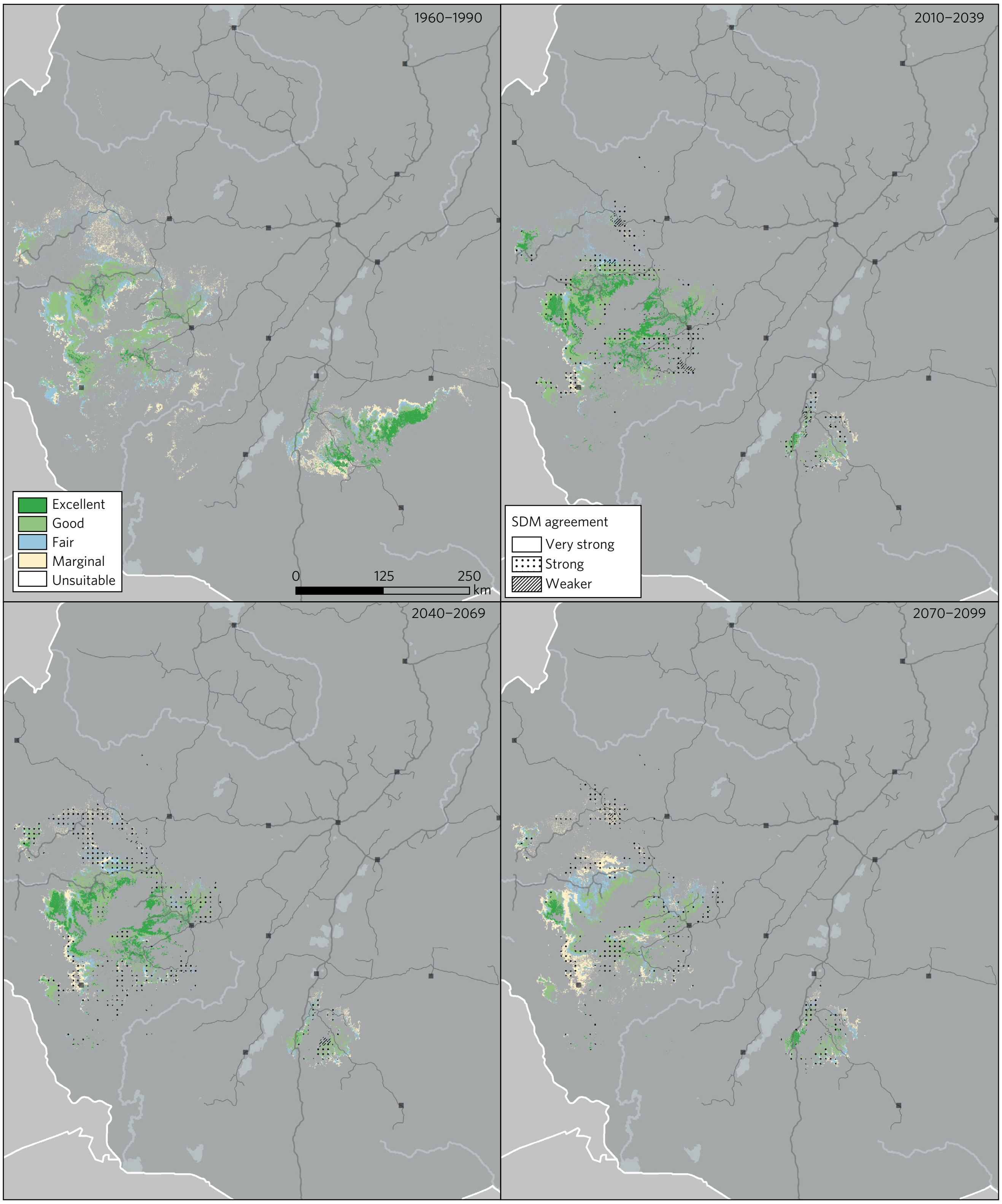

**Figure 3 | Future projections for coffee suitability under the No Migration scenario (D) and emission scenario A1B.** Median of the three GCMs used. All maps show major roads (as dark lines) for navigation. SDM agreement symbolism as in Fig. 2.

recent Coupled Model Intercomparison Project phase 5 (CMIP5)[38] Representative Concentration Pathway (RCP) Scenario 8.5 (RCP8.5) emission scenarios, following Knutti & Sedláček[39] (see Methods and Discussion). In the following two sections, we provide percentages for the middle range projections and their area (coffee niche suitability in km$^2$), based on the three selected GCMs (Bjerknes Centre for Climate Research, Bergen Climate Model, Version 2 (BCCR-BCM2.0); Centre for Australian Weather and Climate Research Mark, 3.5 (CSIRO-MK3.5); and Geophysical Fluid Dynamics Laboratory, USA, Coupled Climate Model 2.1 (GFDL-CM2.1)). The range of values for low and high range outcomes, which are also based on the above three GCMs, are given in Table 1.

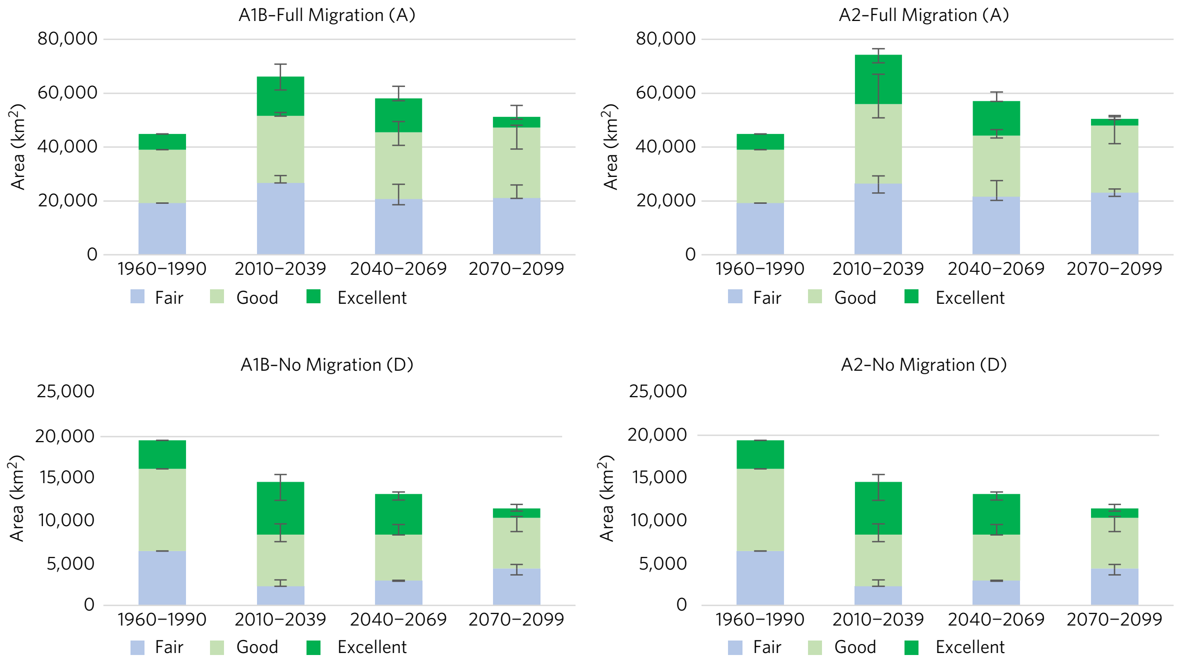

**Figure 4 | Future projections for coffee suitability under the scenarios of Full Migration (A) and No Migration (D) across emission scenarios A1B and A2.** Error bars represent the SDM area (km$^2$) model variability (low and high model outcome) within the three GCMs (GFDL-CM2.1, CSIRO-MK3.5 and BCCR-BCM2.0). See Methods (section 'Selection of GCMs') and Table 1 for further details. A1B–A is the scenario used in the Results and Discussion.

**Projections 1960–1990 to 2010–2039.** We see a large increase (Figs 2, 4 and 5) in coffee area suitability under the Full Migration (A) scenario within the present/near future (2010–2039), compared to the recent past (1960–1990). This is due to a dramatic increase in the area available (and suitable) for coffee at higher elevation, as temperatures increase, particularly in the South West Zone and to a lesser extent the North Zone (see Fig. 1 for zone localities). The overall shift for each time period is shown in Fig. 6. If we look at the south-western plateau (South West Zone) there is a vast area (in excess of 15,000 km$^2$) that comes into suitability in 2010–2039,

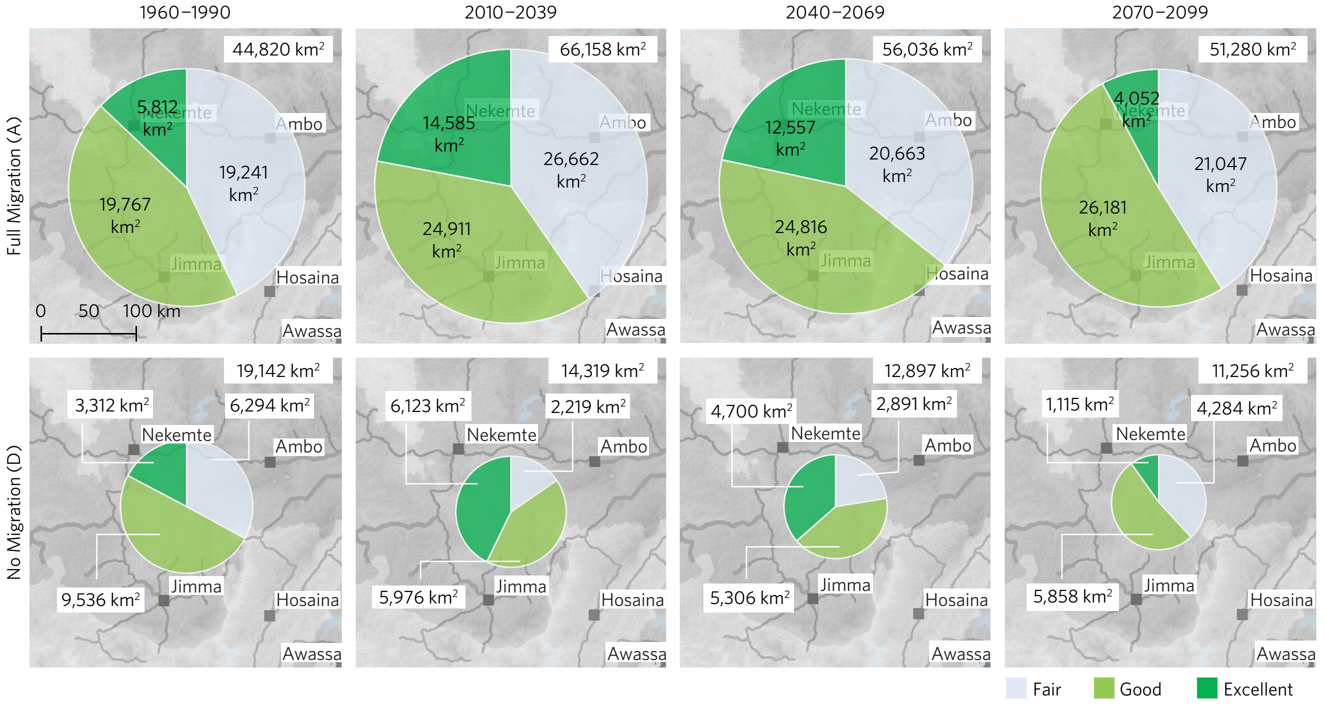

**Figure 5 | Availability of suitable coffee niche in km$^2$ for migration scenarios of Full Migration (A) and No Migration (D).** Total suitable area is given in the top right of each pie chart box. See Table 1 and Supplementary Table 1 for all metrics. Scenario A: coffee plants can grow in any suitable niche (can be moved anywhere); scenario D: coffee plants can grow only within suitable forest cover and only in a suitable known niche (restricted to movement within present-day forest cover and suitable niches). See Supplementary Fig. 5 for further details. The background is part of south-eastern Ethiopia, and is given to provide a scale for the ground area.

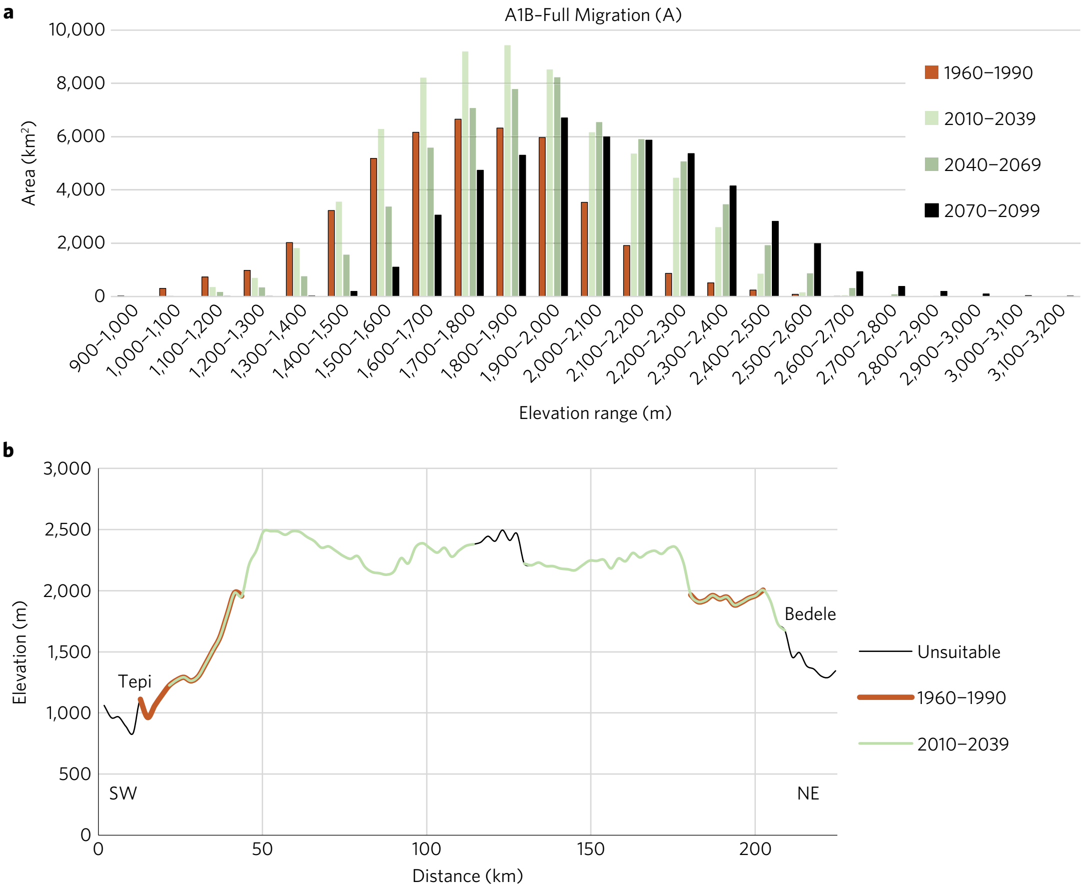

**Figure 6 | Histogram and profile for elevation shifts.** **a**, Histogram of elevation range for Full Migration (A) scenario, under emission scenario A1B. The change in ranges shows a potential shift of 32 m in elevation per decade (see Methods). **b**, Elevation profile of the South West Zone with coffee suitability for 1960–1990 and 2010–2039. Location of profile across the south-western plateau, running from south-west corner (SW) to north-east corner (NE), as shown in Fig. 2.

but which declines as the century progresses (Fig. 6). We originally considered the possibility that this expansion in suitability might be due to the 'East African Climate Paradox'[14], where forecasts (from GCMs) show an increase in rainfall for East Africa compared to actual declines in rainfall (from the 1980s to present day)[14,40]. We do not see this in our data or analyses; the increase in suitable area for 2010–2039 is as a result of the interaction between climate change and the topology of Ethiopia (see Discussion).

Under the No Migration (D) scenario (Figs 3–5) and the middle range projection, from 1960–1990 to 2010–2039 there is a decrease of 25% (19,142 km$^2$ to 14,319 km$^2$) across the Fair to Excellent coffee suitability niche categories. Over the same period there is an increase of 85% (from 3,312 km$^2$ to 6,123 km$^2$) in the Excellent category, which accounts for the corresponding decreases in the Fair and Good categories (Figs 4 and 5; Supplementary Figs 7 and 8). Under Full Migration (A) there is a 48% increase (44,820 km$^2$ to 66,158 km$^2$) in the Fair to Excellent categories over this period (Box 2; Table 1; Figs 4 and 5). A projection with profound implications is the early loss (2010–2039) of almost the entire Bale coffee area and eastern parts of the Sidamo coffee area (Figs 2 and 3). This outcome is consistent across all three GCMs, and all migration and emission scenarios (Figs 2 and 3). This result appears dramatic given that much of this area currently falls within the Excellent coffee niche suitability category. In the Discussion, we offer a possible explanation for this critical finding.

**Projections 2010–2039 to 2070–2099.** Over the rest of this century (until 2099), the models forecast a general reduction (km$^2$) in coffee niche suitability, but the degree of reduction is highly dependent on the migration scenario (Box 1; Table 1; Figs 4 and 5; Supplementary Figs 5, 7 and 8). Under the No Migration (D) scenario and the middle range projection (Fig. 5) there is a 21% decrease (from 14,319 km$^2$ to 11,259 km$^2$) in the suitable coffee niche, from 2010–2039 to 2070–2099. We also see a similar reduction under the Full Migration (A) scenario, where there is a 22% decrease (from 66,158 km$^2$ to 51,280 km$^2$) over the same period (Fig. 5). For both No Migration (D) and Full Migration (A), the most obvious difference is the substantial decrease in the Excellent category: 82% (from 6,123 km$^2$ to 1,115 km$^2$) for No Migration (D), and 72% (from 14,585 km$^2$ to 4,052 km$^2$) for Full Migration (A) (Table 1; Figs 4 and 5), from 2010–2039 to 2070–2099. During 2040–2069, coffee suitability holds quite well, due to niche potential at higher elevations (as the higher ground provides suitability for coffee), for Full Migration (A) and No Migration (D) and most of the other migration scenarios (Figs 2–5). Most of the increases and stabilities in suitability are distributed in the main South West Zone (Figs 1–3 and 6). The Arsi, East Hararge and West Hararge coffee areas (Harar Zone) do not show any niche suitability, for any of the modelling, for any future time period, and this result receives strong model agreement. Environmentally, they are ill suited to coffee growing now and do not improve in the future (Figs 1–3 and 6). Under the Full Migration (A) scenario, new areas of suitability develop, especially in the Amhara, Benishangul–Gumuz and Rift South coffee areas (Figs 1–3), mostly in the Fair and Good categories, but with lower model agreement (Figs 2 and 3).

**Full Migration versus No Migration.** Comparing Full Migration (A) to No Migration (D) over the three future time periods, the percentage differences in the potential coffee niche area are substantial: 2010–2039, 462% (44,820 km$^2$ to 14,319 km$^2$); 2040–2069, 450% (58,036 km$^2$ to 12,897 km$^2$); and 2070–2099, 455% (51,280 km$^2$ to 11,256 km$^2$) (Table 1; Figs 2–6; Supplementary Table 1). This also demonstrates that, in Ethiopia, considerably more land could be used to grow coffee than is currently the case.

## Discussion

**Modelling considerations.** The outcomes of our projections should take into account the assumptions and uncertainties associated with SDMs generally[41], within the regional context[25], and the projection of SDMs with climate change[41]. We have done our utmost to represent assumptions and uncertainties. Predicting future climate with any great certainty is not possible, but by using multiple climate models it is possible to make future projections assuming certain pathways of greenhouse gas emission. These are highly uncertain and cannot be validated, since we have no analogue for future climate. However, climate model projections provide useful estimates of potential future conditions[41], which we can use to explore the sensitivity of coffee production. By comparing different climate models and exploring reasons for the projected change in the coffee farming suitability niche, we can start to understand the vulnerabilities of coffee growing, at least in terms of exposure[35,36], and the level of confidence in the projected change of the niche.

**Projections 1960–1990 to 2010–2039.** Projections from the recent past (1960–1990) to present/near future (2010–2039) under the No Migration (D) scenario (Fig. 3) agree with our on-the-ground observations for climatic coffee farming suitability, the overall productivity of specific areas[42] and climate station data. Specifically, areas categorized by us as Unsuitable or Marginal generally have poor and inconsistent harvests, produce lower quality coffee and in extreme circumstances (for example, drought episodes) coffee trees experience severe stress or death. We present three examples to illustrate this. (1) In the Zege Peninsula, near Bahir Dar (on the shores of Lake Tana), coffee farming is problematic, with good harvests only every five years. The farmers report (personal communication) that there has been a long-term decline in productivity, from good harvests every year or two in the 1930s, to good harvests every five years (since the late 1990s). We assess the suitability of the Zege coffee locality as Marginal (1960–1990) to Fair (2010–2039), and then Unsuitable (2040–2099), with very strong SDM model agreement (Figs 2 and 3). The main climate constraint for Zege is not the amount of total annual rain, but rather the long dry season (Supplementary Fig. 4). (2) In the central and eastern parts of Wellega coffee area, where the SDM (1960–1990) categorizes suitability as Marginal, farmers and intervention workers report (personal communication) increasingly inconsistent harvests (a good harvest every three years or so), which they attribute to a shift in less rain from the late 1970s and mid-1980s. (3) For the Harar Zone, the niche is categorized as Unsuitable (Figs 1–3), which is a fair representation of conditions there at the present time: coffee farming is mostly suboptimal unless improved agronomy is practised (for example, irrigation, terracing), where the local or micro-climate is more suitable, or where the water table brings sufficient moisture to the soil. During the course of our field survey work we received numerous anecdotal reports (from farmers and coffee sector representatives) of a long-term decrease in rainfall over the Harar Zone and a steady, long-term decline in coffee farming. It seems clear, however, that the conversion to the narcotic khat (*Catha edulis*) has also had a considerable influence on declining coffee production in the Harar Zone. Since at least the 1960s, farmers have moved to growing this more lucrative crop at the expense of coffee farming and best-practice coffee agronomy. Given that there are also no gains in niche suitability in the Harar Zone across any of the modelling to 2099 (Figs 1–3 and 6) and that the modelling is in strong agreement (Figs 2 and 3), it seems that Harar coffee production will continue to decline unless considerable interventions are made. Overall, our modelling projects low-value categorizations (Unsuitable, Marginal, Fair) for the 1960–1990 to 2010–2039 time periods, for areas that are currently suboptimal for coffee farming. One unexpected exception is the Bale coffee area and the eastern part of the Sidamo coffee area (Figs 1–3 and 6), which is projected to be no longer suitable for coffee by 2039. Most of these two areas currently fall within the Excellent niche category. This result has strong to very strong model agreement (Figs 2 and 3). Our explanation for the loss of the Bale area and the climate mechanisms behind declines and increases in coffee suitability are discussed below.

**Projections 2010–2039 to 2070–2099.** As the century progresses (2010–2039 to 2040–2069 to 2070–2099) the projected outcomes are profound, depending on the migration scenario (Fig. 5). By the end of this century the current coffee-growing niche of Ethiopia could decrease by 39–59% (of the original area; 41–61% suitable area remaining), under our most restrictive migration and emission scenarios (the low-range (area in km$^2$) outcome, under migration scenario E and emission scenario A2) if no interventions are made (Table 1). The scenario of No Migration (D) (A1B = 45–64% remaining) most closely resembles a 'do nothing' scenario, although forest and tree canopy cover would have to remain stable (no deforestation or afforestation). At the other extreme, under the Full Migration (A) scenario (emission scenario A1B), there would be substantial gains with the potential for a more than fourfold increase in coffee farming area compared to the No Migration (D) scenario.

The main reason for the substantial increase in the area for coffee suitability in 2010–2039, under the Full Migration (A) scenario, is due to higher elevation areas coming into suitability. This is seen predominantly in the South West Zone (Fig. 1), where a huge area (in excess of 15,000 km$^2$) within the south-western highlands comes into suitability in 2010–2039. After 2010–2039, an elevation ceiling (literally) is reached, resulting in a decline from there onwards. There are of course interactions with rainfall (adding more nuanced changes), but the dominant climatic factor for the expansion is temperature, which is manifest as an upward elevational shift. An elevation profile across the South West Zone (Fig. 6b) illustrates this topographical expansion.

Particularly vulnerable coffee areas over these two time periods, under any migration scenario, include large parts of Wellega, the northern part of Illubabor and Bench-Maji (Figs 1–3 and 6), with variable but mostly strong SDM model agreement for these projections (Figs 2 and 3). All of the five circumscribed coffee zones (Fig. 1) could be negatively influenced to some extent (Figs 2 and 3), particularly at lower altitudes (Fig. 6). The main South West Zone has the most inherent resilience, mainly due to the potential for the coffee niche to improve in suitability at higher elevations (Figs 6 and 7). Across Ethiopia, the most climatically suitable part of the overall niche (the Excellent category; Box 2) is projected to drastically decline in the long-term (Figs 2–5).

**Identifying the drivers of change.** There has been considerable focus on the influence of increasing temperatures and supra-optimal temperatures on coffee production[8,43]. It is clear from our study, however, that rainfall is also a major contributing factor; as well as this, field observations, climate station data and our weather station recordings show that temperatures rarely reach the extreme limits for Arabica coffee[43] in Ethiopia. Analysis of the BIOCLIM[34] layers reveals that a combination of rainfall, temperature seasonality

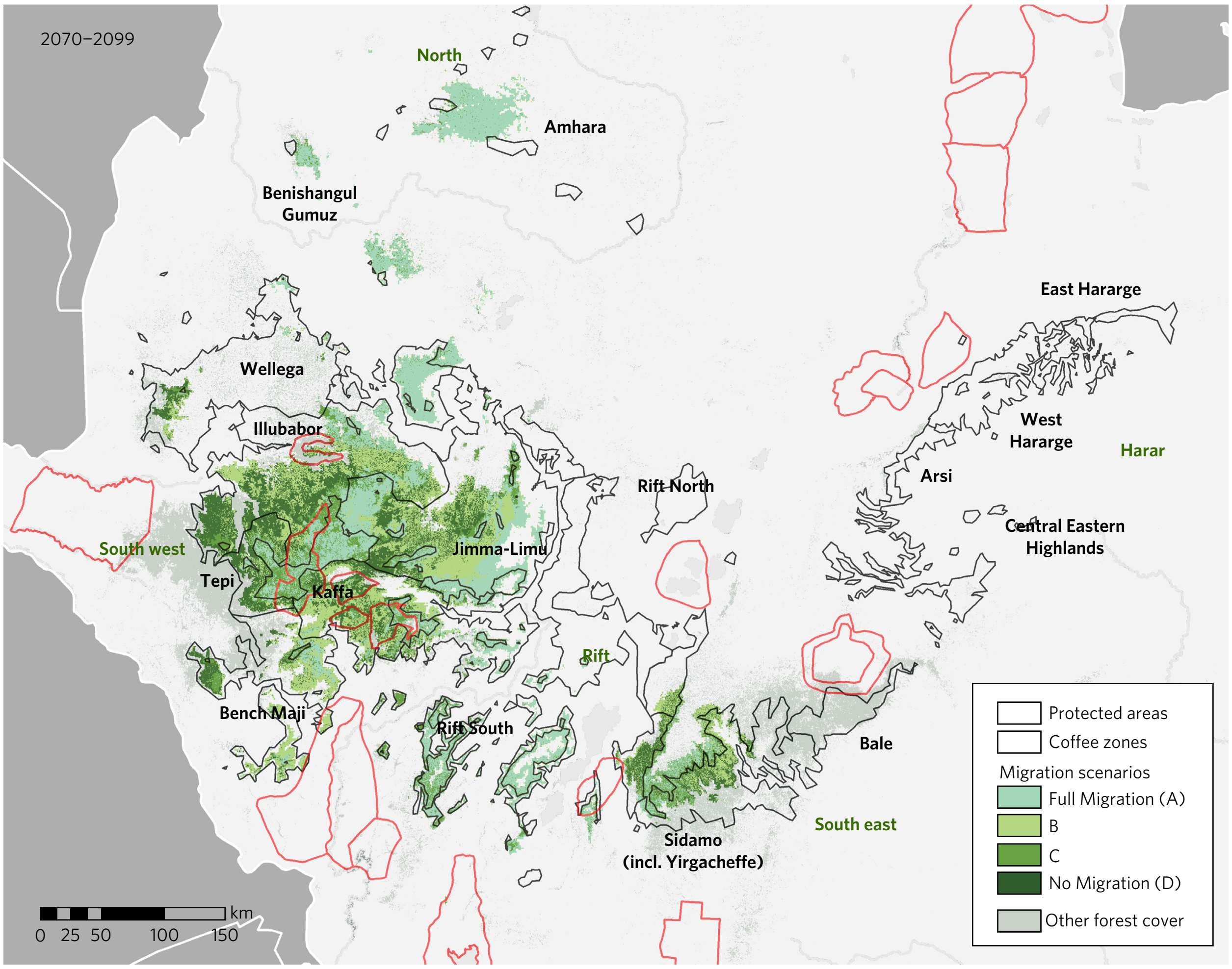

**Figure 7 | Projections for coffee suitability 2070–2099 (emission scenario A1B) for scenarios Full Migration (A) and No Migration (D), with main coffee areas (black lines; see Fig. 1) and protected area boundaries[53] (red lines).** Migration scenario A (Full Migration (A); green-blue) represents new coffee suitability niche for 2070–2099. Migration scenario B (light green) represents 1960–1990 niches that persist into 2070–2099. Migration scenario C (mid-green) represents new coffee suitability niche for 2070–2099 (as in migration scenario A), but with present-day forest cover. Migration scenario D (No Migration (D); dark green), 1960–1990 niches that still persist into 2070–2099 (as in migration scenario B), but with present-day forest cover. Grey represents other forest cover (with no end of the century coffee niche predicted). Figure 7 should be reviewed with model variability (Fig. 2.). Note, migration scenarios E and F are not represented on this map as they are too small to be visible at this scale.

and annual temperature (east and west of the Rift Valley; Supplementary Tables 2 and 3) were contributing most to the SDMs. By comparing these bioclimatic variables against each of our GCM projections (for emission scenario A1B), we were able to identify the main drivers in our models for change for each of the major coffee zones (Figs 1–3, for context; Supplementary Figs 9–12 show the trends for each zone). Across the entirety of the coffee landscape, the temperature BIOCLIM (BIO1) shows projected temperature increases of 2.7–3.2 °C (under emission scenario A1B) from 1960–1990 to 2070–99 (Supplementary Fig. 9), which is in good agreement with historical records (1960s onwards) and temperature projections from other sources (see Introduction). Temperature seasonality (BIO4) generally increases (Supplementary Fig. 10). Critically, the rainfall BIOCLIMs (BIO12 and BIO18) show little change across this century (Supplementary Figs 11 and 12). Thus, the total rainfall for each area experienced in the present day is key to understanding future suitability, as any increases and decreases in rainfall are mostly projected to be negligible to slight. Harar does show some decline in rainfall towards the end of the century, but the GCMs are in poor agreement (varying in decline of 250, 100 and 0 mm to the end of the century). Any decreases in rainfall for Harar would compound the already unsuitable coffee niche in this area, particularly if temperature increases continue to track future projections. To summarize, the key influencing factors can be viewed as a relatively simple interaction between rainfall and temperature: coffee areas that start with low rainfall cannot tolerate an increase in temperature, especially as rainfall is not projected to change by any considerable amount; temperatures are projected to increase steadily and substantially. If Ethiopian rainfall declines continue (see Introduction), in contrast to the negligible changes in precipitation observed in our projections (Supplementary Figs 11 and 12), they would further amplify the temperature-driven changes identified here. The Harar Zone and some locations within the South East Zone (the latter includes the coffee areas of Bale and Sidamo) have the lowest total rainfall at the present time (<1,300 mm), giving these areas little potential to deal with any temperature increases. In Harar and the South East zones, air temperatures tend to reach a seasonal maxima between January and May, that is, just before or during the onset of the spring rains (and coffee flowering time). These areas would be particularly sensitive to warming and evapotranspiration increases at the end of the dry season, for example, between November and March. This is consistent with projections indicating that increases in potential evapotranspiration may reduce the effective length of the African growing seasons[44].

The Rift and South West zones have greater rainfall (1,320–1,690 mm) and therefore greater scope to tolerate temperature increases. Areas that are presently too cold (the North Zone and parts of the South West Zone, at higher altitudes), but have enough rainfall, will start to come into suitability as temperatures increase.

A better understanding of the critical relationship between low rainfall (and a corresponding soil moisture deficit) and high temperatures is starting to emerge from our in-country observations of plant stress, in conjunction with the use of climate data logging equipment. At the beginning of the year (January to March), we observe low rainfall and steadily increasing temperatures, resulting in low soil moisture levels, which in some cases reach or exceed the permanent wilting point. For example, in the Bench Maji coffee area we recorded severe plant stress in March (2015), after two months' total rainfall of less than 10 mm per month, an average temperature (based on 1 reading per hour) of 24 °C (minimum 16.4 °C; maximum 34.5 °C) and a volumetric soil moisture content of c. 20%, and soil water potential values of −400 kPa to −1000 kPa (both recorded at 40 cm soil depth). Arabica coffee will perform well in areas with higher temperatures than Ethiopia, but only if there is sufficient rainfall, especially if there are few, short or no periods of the year with a soil water deficit, for example as found in Panama and Costa Rica[45,46]. However, it should be clear that none of our projections would lead to a comparable environment for Ethiopia, given that rainfall is not projected to increase by any considerable amount.

**CMIP5 versus CMIP3.** In their overview of CMIP5, Knutti & Sedláček[39] compare CMIP5 and CMIP3 and state: "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." Our SDM results show no considerable differences between A2 and A1B, so if we see scenarios that fall within our present A2 and A1B we would expect similar results. Following Knutti & Sedláček[39] and comparing RCP8.5 with A2, we are provided with an indication of likely differences. The only substantial difference seen is an increase in annual mean temperature (BIO1), with an average additional increase of 0.9 °C (Supplementary Fig. 9), and an increase in temperature range between GCMs. We see some difference in rainfall between A2 and RCP8.5, with projections for increased rainfall (North and Harar zones), but with large disagreement between GCMs. These increases are unlikely to be sufficient to compensate or override projected severe temperature increases, although in the North Zone it is possible that some areas could move to higher suitability under this pathway (Supplementary Figs 11–14 and 16–17). The larger increase in temperature observed for RCP8.5 would indicate that both the A2 and A1B scenarios could be more conservative, compared to RCP8.5. It is also possible that the North Zone, which comes in as a new area in our CMIP3 future predictions, could come into better conditions under RCP8.5, but the increase in rainfall is slight and highly variable (Supplementary Figs 11 and 12). It should be reiterated that RCP 8.5 is the most extreme emissions scenario of the new CMIP5 pathways. Reviewing all of the RCPs for CMIP5 (which for the first time includes a low-emission mitigation scenario), these pathways are likely to deliver a broader range of outcomes. Overall, and as demonstrated by Knutti & Sedláček[39], CMIP5 scenarios give higher warming compared to CMIP3. If temperature change trends track according to (CMIP5) RCP8.5, we would see an amplification of the negative changes identified here using CMIP3.

**Other influences.** Our modelling does not include the potential influence of elevated $CO_2$ concentrations in the atmosphere, even though it has been shown that this may have a beneficial physiological influence on coffee, due to improved (leaf) water-use efficiency, which may mitigate high temperatures, at least where there is unrestricted water supply and high relative humidity[43]. Free air $CO_2$ enrichment experiments show that trees are more responsive than herbaceous plants to elevated $CO_2$[47] and that elevated $CO_2$ benefits plant species under drought conditions[48,49], although research indicates that the influence of $CO_2$ enrichment for crop production may be over-emphasized[50]. If projected increases in $CO_2$ prove to have a substantial role in mitigating the impact of drier, warmer conditions on coffee production, then our projections of climate exposure could be over-estimated. However, in Ethiopia we observe that drought (water stress) is one of the major causes of crop failure for coffee, and severe drought (lethal water stress) the most significant climate-related cause of plant fatality. We argue, therefore, that while there could be benefits from elevated atmospheric $CO_2$, drought (in its duration, timing and severity) may far outweigh these gains in the longer term. One might also contend that the forest will change as the climate changes, including responses to elevated $CO_2$. In this study, we review changes in niche and not forest, although our scenario of Full Migration (A) would encompass a broad spectrum of vegetation change (species and forest composition) within the humid forest vegetation class (MAF and TRF[6]). As well as increasing drought stress, high deforestation rates[5] and particularly their influence on local and regional climate are likely to override the benefits of atmospheric $CO_2$ enrichment for forest performance and survival and the physiological behaviour of Arabica coffee. We also have little knowledge about the potential influences of pests and diseases, although these are likely to have a compounding negative influence under a warming climate[25,51].

**Migration scenarios and interventions.** Under the Full Migration (A) scenario, there would be substantial potential to increase coffee farming and thus production volumes. As outlined above, comparison between Full Migration (A) and No Migration (D) (no migration, no forest loss) scenarios shows that the potential to increase the coffee growing area, over the three future time periods (2010–2039, 2040–2069 and 2070–2099), is at least fourfold (>400%), although the niche peaks in 2010–2039 (Table 1; Figs 4–7; Supplementary Table 1). Most of this change comes from up-slope migration to higher elevations. Under Full Migration (A) (emission scenario A1B) there would be a projected altitude shift for overall coffee suitability of 32 m per decade, from 1960–1990 to 2070–2099 (Fig. 6), with a considerable change in the extreme upper limits to 2,800–3,300 m (from 2,200–2,600 m). The emergence of coffee suitability areas at higher altitudes (to those existing now) is projected over a large area of the south-western Ethiopia plateau, but also in areas of the North Zone (Amhara and Benishangul–Gumuz coffee areas), Rift Zone (Rift South area) and South East Zone (Sidamo coffee area), although with different levels of model agreement (Figs 2 and 3). For the Full Migration (A) scenario to be realized, significant intervention would be required, including the planting of shade cover or the restoration of humid forest cover for areas with little or no present-day forest cover (Fig. 7). A concerted effort would be needed to identify and establish new coffee areas at higher altitudes, with particular attention placed on competing land-use issues (for example, existing land-use ownership, nature conservation sites), soil and micro-climate suitability and access to roads and other infrastructure. Shifts could also occur without major intervention, as farmers realize the potential for growing coffee in their upland areas. Field observations made by us in 2015 show that locations in the North Zone are already being developed as new coffee areas (in correspondence with our projections; Fig. 2), at altitudes in excess of 2,500 m (not previously seen for coffee farming in Ethiopia), indicating that assisted migration is already underway.

Resilience built via the migration of coffee farms could be supplemented with (location- and time-specific) improvements in coffee productivity (kg per hectare; for example, by increasing soil fertility and pruning) and quality (kg per $; for example, better harvesting and post-harvest processing), in order to offset unit area reductions in environmental suitability. In addition, there is scope for investing in locally appropriate, cost effective agronomy adaptations (such as mulching, irrigation, improved shade management and terracing). Irrigation would provide the single most effective adaptation measure, especially where implementation costs are low, for example, the diversion of nearby streams and rivers. Our projections would serve to provide a framework for the likely success, timing, duration and location of interventions.

**Wild coffee forests.** Ethiopia's wild coffee forests have considerable fundamental value as the main storehouse of *C. arabica* (Arabica coffee) genetic resources[25], with specific benefits for the coffee sector, locally, regionally and globally[52]. Most directly, indigenous Arabica coffee plays a key role in Ethiopian coffee production as an important source of planting material for farms via seed and seedlings. Protection of these resources should thus be seen as a key part of a resilience strategy. Using all migration scenarios (to 2070–2099), but selecting scenario E to represent the most resilient areas (refugia), provides an indication of which protected areas might have value as reserves for coffee genetic resources (Fig. 7). This exercise identifies protected areas in Kaffa (Kaffa Biosphere Reserve) and northern Illubabor (Yayu, a UNESCO registered Coffee Forest Biosphere)[53], although Yayu would have limited long-term potential unless contiguous areas at higher altitudes are included in the delimitation of its core area. Another important consideration is the preservation of specific coffee origins (and their unique flavour profiles), some of which are identified in the modelling as highly susceptible to negative climate change influences, including the coffees of Harar and Bale.

**Summing up.** Timely, precise, science-based decision making is required now and over the coming decades, to ensure sustainability and resilience for the Ethiopian coffee sector. Our projections show an overall negative influence, due to climate change, across this century for the present coffee growing landscape. Despite this, there is the potential to increase the area where coffee can be grown (by at least fourfold) via relocation and expansion, even if climate change tracks to our projections, although this would have to be done in combination with forest conservation and re-establishment. We also identify key coffee areas that could be climatically resilient, even without major intervention, at least until the end of this century.

## Methods

**Mapping the extent of humid forest in Ethiopia.** A map of humid forest cover (TRF/MAF[6], and comparable agroforestry environments; Supplementary Fig. 6) was produced from Landsat 8 imagery (http://landsat.usgs.gov/landsat8.php)[26], downloaded for December of 2013 to February of 2014 (http://earthexplorer.usgs.gov (38 images covering 24 scenes)). The images were atmospherically corrected using the Fast Line-of-sight Atmospheric Analysis of Hypercubes algorithm (FLAASH) in ENVI 5.1 (ref. 54) to obtain surface reflectance values. To produce a cloud-free composite, the images were processed to identify clouds and cloud shadows using the Fmask 3.2 algorithm[55]. ERDAS Imagine 2013 was used to produce Normalised Difference Vegetation Indexes[56] from the surface reflectance cloudless composites. Finally, we produced a Normalised Difference Vegetation Index composite using two thresholds to identify the humid forest.

A set of 300 training data points were used to identify the most appropriate thresholds and the individual maps were combined in ArcGIS ver. 10.1 (Environmental Systems Research Institute (Esri)). Testing of the final map yielded an accuracy assessment of 97%. The humid forest map was uploaded to Google Earth for review, as well as large-format mobile phones (Samsung Note II, GT-N7100) using Locus Map Pro 3.1, Asamm Software, Praha, for validation during eight fieldwork trips (2014–2016), with an emphasis to identify and remove non-coffee production areas (for example, tea, mango, avocado plantations and commercial forestry).

**Point data and ground-truthing.** We collected 3070 data points (Supplementary Fig. 3), of which 1624 were coffee presence data points (1446 non-coffee points), comprising 824 historical (1941–2001) and 800 contemporary (2013–2015) points (with coffee production type, forest cover and condition, and global positioning system (GPS) data recorded). To reduce sampling bias and sampling errors, the ground data was filtered: historical data points collected before 2001 (early-generation GPS, herbarium specimens and literature records) with an accuracy lower than 1 km were rejected; multiple points falling within a 1 km$^2$ grid were reduced to a single point; any points covering locations with significant interventions (all irrigated and high water table areas) were removed. This left 381 points to build the final SDM. Many of the data points appear to lie close to roads, although a considerable amount of data was collected on foot (c. 40%). There were no indications of a road-like bias in our SDMs. In well-sampled studies, sampling along roads should not represent a bias issue[57], especially where roads cut across numerous environmental gradients, as in Ethiopia. Moreover, the niche and landscape were very well sampled (Supplementary Fig. 3). We double-checked to see if our sampling would show any significant sampling bias by comparing histograms of elevation versus percentage sampling. The range of elevations sampled by the 3,070 data points was 426–3,877 m, which is much greater than the range (991–2,263 m) for the 381 points used for the SDMs. Both histograms showed consistent sampling across 250 m elevation bands.

In addition to the 3070 original points, an additional 1028 points for coffee presence and absence were collected after the initial modelling (2015). These points were used to informally validate the modelling and remote sensing, although no mapping or analyses were undertaken with these data. The 800 contemporary data points (2013–2015) and the additional 1028 data points (2015–2016) were collected during ten field missions, covering c. 30,000 km by road and on foot (plots and transects), across almost the entire coffee landscape of Ethiopia. During our fieldwork, we also informally interviewed farmers for perceived changes in coffee farming, on a year-by-year and generation-by-generation basis.

**SDM—the niche.** There has been much discussion about the actual niche represented by an SDM and particularly the question over realised niche versus fundamental niche. Most SDM studies identify the realised niche[58]; the closer the realised niche gets to the fundamental niche, the better the projections are likely to be. When using bioclimatic variables, the results will tend towards the fundamental niche, especially when extrapolating to new areas (for example, introduced ranges) or future climates[58,59]. In this study, the niche-only scenarios (A, B and E), combined with exhaustive ground validation, show that our SDMs are very close to representing the fundamental niche, that is, where coffee grows and is farmed. Our niche and forest (migration) scenarios (C, D and F; Supplementary Fig. 5) preserve the relationship to the fundamental niche; applying the humid forest mask also means that we are closer to the realised niche than using an SDM alone.

**SDM—division into climatic groups.** After running preliminary models for the present day, investigating climate profiles, and considering the biology of Arabica coffee in Ethiopia, it became clear that we should treat east and west of the Rift Valley (Fig. 1) separately. The rainfall pattern east of the Rift Valley is bimodal, and in the west it is unimodal (see Supplementary Fig. 4). Molecular[60–62], morphological[63] and physiological data[64] support Arabica coffee differentiation either side of the Rift Valley. Thus, for our modelling, we treated east and west independently, running the models for each and combining only at the end of the procedure to provide final modelling outputs.

**SDM—selection of environmental variables.** We examined the full BIOCLIM dataset[34] of 19 variables, independently, east and west of the Rift Valley. Paired dataset correlations and boxed plots were reviewed and we examined which variables had significant influence on the Generalised Linear Models (GLM) and Generalized Additive Models (see below). For each BIOCLIM variable, we ran an analysis of variance (ANOVA) test by examining output model results for our validation points and comparing these to the pseudo-absence points. We also ran models using random pairs of variables to investigate the best variables for model fit (see below). Finally, we examined the resultant BIOCLIM variables and reduced the selection to those that were significant in the above tests, not highly correlated (as pairs) and which represented the ecological requirements of Arabica coffee. By comparing the results independently for east and west of the Rift Valley, we reduced the 19 BIOCLIM variables to nine (Supplementary Table 4), for use in our modelling. The same variables were used for the east and west split, to allow our models to be comparable.

**SDM—processing.** Using the selected environmental variables (see above), we ran the data (381 ground points) in the Biomod2 R package, version 3.1–64 (ref. 65), using six modelling methods (GLM, Generalized Boosted Regression Models, Generalized Additive Models, Multiple Adaptive Regression Splines (MARS), Random Forest and Maximum Entropy (Maxent) software version 3.3.3 (refs 65–68) to produce an ensemble model for either side of the Rift Valley. Each of the models used the nine selected environment variables to maximise its fit to the output prediction. We largely followed established methodologies[65,69–71] for model evaluation, runs, replications and combination. We used the default setting in Biomod2, except for increasing the number of iterations for GLM and Maxent, to reach convergence. Three sets of background or pseudo-absence data were generated. Ground control data, both presence and background for each of the three sets, was split randomly ten times with a ratio of 70:30 to build training and testing data, respectively[72]. Model outputs from Biomod2 were evaluated by viewing the actual results and using sensitivity, specificity, True Skills Statistics (TSS), Cohen's Kappa statistic (KAPPA) and relative operating characteristic curve for east and west of the Rift Valley models (see Supplementary Information). Following Araujo & New[70] and Thuiller *et al.*[69,71] we took the six individual models to produce an ensemble prediction for either side of the Rift Valley, using the suggested model evolution threshold of 0.7 (using TSS), to remove poorly performing models (although no models were removed during this process, as they all exceeded this threshold). We also implemented proportional weighted overlay, to give better fitting models a higher weight. During the statistical evaluation of the six models, expert review was used to make sure that they were in agreement with the biotic and abiotic requirements for Arabica coffee. The testing and training data were assessed and reviewed to give the relative importance of the variables used in each developed model, model sensitivity and specificity, as well as overall model performance[72]. All six niche model methods performed exceptionally well (over 90% for specificity and sensitivity for each model).

There are two assumptions associated with the models for 1960–1990: (1) because the 2014 TRF/MAF[6] forest cover (see Supplementary Fig. 6) was used with 1960–1990 data, the surface area will be underestimated, as there has been considerable deforestation since the 1960s[5]; and (2) we assume that the suitable coffee niche, if forested or having sufficient shade cover, is being used for coffee production of some description[25].

**SDM—evaluation.** Model outputs from Biomod2 (ref. 65) were evaluated by viewing the resultant maps and using the statistics; sensitivity, specificity, TSS, KAPPA and relative operating characteristic curve for east and west of the Rift Valley. For our purposes, sensitivity and specificity was the most useful and easiest to use metric, but we reviewed all statistics. All six niche model methods performed very well (over 90% for specificity and sensitivity), but east of the Rift Valley showed slightly lower specificity values, compared to west (this is not surprising as the sample for the east is much smaller). GLM and MARS showed the lowest scores (90–93% for GLM and MARS for specificity), which is still very good, but suggests they are not fitting the data as well as other models. Final models were produced from ten runs and three replicates. We checked the outputs visually to see if there was a noticeable difference between model runs (which may suggest problems, for example, overfitting or incorrect models).

**SDM and WorldClim—validation.** The ensemble SDM was loaded onto four large-format, GPS-enabled mobile phones (Samsung Note II, GT-N7100), using Locus Map Pro 3.1, Asamm Software, Praha, for validation during seven fieldwork trips (2015 to 2016). This activity revealed excellent correspondence between the ensemble SDM and coffee farming areas; the SDM predicted coffee farming activity to within a 1 km radius of each validation location.

As a means of checking the WorldClim[34] precipitation data, we compared precipitation data from 27 weather stations over a 30-year period (1984–2014) (National Meteorology Agency Ethiopia) against the WorldClim[34] data (1960–1990). We found acceptable to excellent agreement between the two data sets, when visualized as c. 30 year averages for numerous locations. Climate profiles (30-year period; 1984–2014) for total monthly rainfall and average monthly temperature (minimum, median and maximum) for an additional 20 weather stations (National Meteorology Agency) situated within, or adjacent to, coffee growing areas, were also found to be in good agreement with 1960–1990 WorldClim[34] data. Six examples are provided in Supplementary Fig. 4. At Yayu (Illubabor), Ashi (Wellega), Gesha (Bench-Maji), Yirgacheffe and Yirga Alem (Sidamo), Bale (Bale) and Gololocha (Arsi) (see Fig. 1) we installed (2013–2016) proprietary data-logging equipment (Tinytag Plus 2—TGP-4500, with Stevenson type screen (ACS-5050), both from Gemini Data Loggers), to measure air temperature and relative humidity (RH%). At Ashi, Gesha and Bale we also installed soil temperature probes (Tinytag Plus 2—TGP-4510, Gemini Data Loggers), soil moisture (10HS) and soil water potential sensors (MPS-6) connected to EM50 digital data loggers (all from Decagon Devices) at 20 and 40 cm soil depths and low resolution rain gauges (ECRN-50, Decagon Devices). The logging interval was every hour on the hour for Tinytag Plus 2 and twice daily for the Decagon equipment. The data was not analysed for this study, but simply used to ground-truth WorldClim[34] data and the coffee niche and to better understand the climatic variables causing physiological stress in coffee.

**SDM—assessment of climatic variables.** We examined the BIOCLIM[34] data to see which bioclimatic variables were contributing most to the SDMs, by summarizing the contribution of each variable for each of the six niche modelling methods (Supplementary Table 2 and 3), for east and west of the Rift Valley. For the east, the most important were temperature seasonality (BIO4) and precipitation of the warmest quarter (BIO18); and the west, annual mean temperature (BIO1) and annual precipitation (BIO12).

**Selection of GCMs.** The evaluation and selection of GCMs for a study area and set of circumstances is a challenging activity[24,73,74]. Ideally, we would have used all GCMs to assess the full range of outcomes, but selected three in order to keep processing time and storage to a manageable level and to reduce redundancy (for example, where GCMs were in agreement). To make our selection, we processed all 23 GCMs available for the study area, excluding models that did not fit our future time periods (2010–2039, 2040–2069 and 2070–2099). We then reviewed the projections for each of the contributing BIOCLIM layers, for eight coffee locations either side of the Rift Valley, as a representative sample of the of the coffee farming landscape: for the South West Zone (Yayu (Illubabor), Dembi Dollo and Ashi (Wellega)); South East Zone (Bale (two sub-locations), Yirgacheffe and Yirga Alem (Sidamo)); and Harar Zone (Gololocha (Arsi)); an example for one of these locations (Ashi) is shown in Supplementary Fig. 15. On reviewing these graphs, we rejected GCMs that were highly anomalous for temperatures and anomalously high or low values for precipitation; an emphasis was placed on the 2010–2039 period, where anomalies are more easily assessed. We selected a representative GCM for those showing similar results across the nine BIOCLIMs, two emission scenarios and four time intervals. This still left us with eleven GCMs from which we choose three (BCCR-BCM2.0, CSIRO-MK3.5 and GFDL-CM2.1) to represent climatic changes over time (for the subset of 11 GCMs; across the nine BIOCLIMs).

**GCM data downscaling.** The original ground resolution for the GCMs was approximately 200 km. To make this data more useful for SDM and to see variation at higher resolutions, we used downscaled GCMs[34,75,76]. We employed the downscaled (Delta method of the Intergovernmental Panel on Climate Change (IPCC) AR4 (ref. 76)) climate models from CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (http://ccafs-climate.org/data_spatial_downscaling/ and http://www.ccafs-climate.org/data/). The downscaled method used by CCAFS is based on thin plate spline interpolations of deltas (anomalies) of the original low-resolution GCM outputs. These deltas are applied to the WorldClim[34] data (the same data we used for our 1960–1990 SDM) at a resolution of 30 arc seconds (approximately 1 $km^2$ cells size for Ethiopia) by interpolating between GCM cell centroids[76]. The 19 bioclimatic indices (BIOCLIM)[77] were calculated by CCAFS from the resultant rasters.

**GCMs—modelling future projections.** Our three selected GCMs were: (1) BCCR-BCM2.0—BCCR, Univ. of Bergen, Norway (BCM Version 2); (2) CSIRO-MK3.5—Centre for Australian Weather and Climate Research (Mark 3.5); and (3) GFDL-CM2.1—GFDL USA (Coupled Climate Model 2.1). The future SDM variability of the selected GCMs is illustrated in Figs 2 and 3. We used two $CO_2$ emission scenarios, A1B and A2: A1B reaching 13.5 giga tonnes of carbon (GtC) by 2099; and A2 reaching 29.1 GtC; this is against a baseline of 9.8 GtC (in 2014/15). The projections (areas of coffee-growing suitability given as percentages and $km^2$) produced from the three GCMs were categorised into three classes: low, middle and high (Table 1). For the Results and Discussion, we provide percentages and area measurements ($km^2$) for the middle-range outcome, based on the three GCMs (Table 1; Supplementary Table 1). The GCM CSIRO-MK3.5 predominately produced the middle-range outcomes; BCCR-BCM2.0 tended to produce low-range outcomes and GFDL-CM2.1 the higher ones, although these switched between low, middle and high, depending on the suitability category and time intervals across this century.

The future projections were modelled in the Biomod2 package Ensemble Forecasting[65], which projects the ensemble recent past and current model in space and time. The projection was performed on the nine BIOCLIM variables as identified above. Future models were run for each GCM, for east and west of the Rift Valley and over three time periods (2010–2039, 2040–2069 and 2070–2099; Supplementary Fig. 1), giving 18 future projections (two regions, over three dates and three GCMs) as a final output.

**Combining SDMs and GCMs—analysis and mapping.** The outputs from the four time periods (1960–1990, 2010–2039, 2040–2069 and 2070–2099) were imported into ArcGIS ver. 10.1 (Esri), with the spatial analysis extension, for further analysis and visualization. The Rift Valley separation, from each modelling stage, was combined using the raster calculator tool to give the maximum suitability value for each pixel, giving 19 models for the final analysis (one time period (1960–1990) plus three GCMs × two emission scenarios, across three further time periods). To visualise the SDM variability, the projections were processed to show the range of SDM values and these ranges were categorised into three classes: (1) Very Strong, model variability 0 to 200; (2) Strong, 200 to 400; and (3) Weaker, 600 or higher. Very strong (solid colours, with no overlay) shows where the model class (Excellent, Good, Fair, Marginal and Unsuitable) is unlikely to change, except at the edge of the ranges. Strong (overlaid with dots) shows where a class could change up or down by one class (for example, Good could range from Excellent to Fair). The Weaker class (diagonal lines) is where classes could change by more than one class; the largest range is 610, indicating a movement of up to one and a half classes. We adopted the same symbology as used in a widely read IPCC report[22], although it should be noted that we used it for SDM variation not GCM variation (as in the IPCC report). We also calculated the median for each model, which was used only for visualization of the results (Figs 2 and 3).

**Categorisation of projection maps.** To provide area measurements (in km$^2$) for each category (Unsuitable, Marginal, Fair, Good, Excellent), we needed to threshold the continuous SDM values (those between 0 and 1,000). To achieve this, we examined the SDM values for our ground point data (ground control, absence and pseudo absences data), by comparing TSS and the cumulative percentage of points to give us our initial threshold. This was further subdivided to give a total of five categories (Supplementary Fig. 2; Supplementary Information).

**Migration scenarios for climate change projections.** The six migration scenarios (Box 1; Supplementary Fig. 5) were processed in ArcGIS, using simple map algebra, summarized, with the following processing: (A) no processing; (B) all models cookie-cut with 1960–1990 suitable niche (all areas outside of the 1960–1990 niche were clipped for all dates); (C) as A but cookie-cut with forest cover; (D) as B but cookie-cut with forest cover; (E) as B but 2040–2069 cookie-cut with 2010–2039 suitable niche and 2070–2099 cookie-cut with 2010–2039 and 2040–2069 suitable niche; (F) as E but additionally cookie-cut with forest cover. The forest cover niche models were resampled at 30 m resolution using a simple nearest-neighbour resampling (to preserve the original model resolution of 1 km$^2$).

**Analysis of regional trends and drivers.** To understand the trends and the main drivers for climate change outcomes we produced graphs of change for the most influential BIOCLIMs. Supplementary Figs 9–12 show the trends for each of the five coffee zones (Fig. 1), from 1960–1990 to 2070–2099. The most influential BIOCLIMs were: temperature seasonality (BIO4), precipitation of the warmest quarter (BIO18), annual mean temperature (BIO1) and annual precipitation (BIO12). We calculated the mean, max, min and range for each zone, for CMIP3 scenarios A1B and A2, the three GCMs and all four date periods.

**CMIP3 versus CMIP5.** Our projections are based on the WCRP's CMIP3 multi-model dataset[37]. The newer and more developed WCRP CMIP5 multi-model ensemble[38] was released as a downscaled dataset after the project research period. A direct comparison between CMIP3 and CMIP5 is not straightforward, as CMIP3 uses emission scenarios, whereas CMIP5 uses RCPs[39]. Following the methods of Knutti & Sedláček[39], we compared CMIP5 RCP8.5 against CMIP3 SRES scenario A2, which represents the two scenarios with the highest temperature changes. Supplementary Figs 15 and 16 show a comparison of the GCM robustness across Africa for CMIP5 (RCP8.5) vs CMIP3 (SRES A2) based on Knutti & Sedláček[39]. For further comparison, we included CMIP5 RCP8.5 in the same analysis that we used to represent the five coffee zones (Fig. 1) for CMIP3 A1B and A2 (Supplementary Figs 9–12). Both the GCM and the downscaling methods (Delta method[76] IPCC AR4[78] to Delta method IPCC AR5 (ref. 79)) were updated when moving from CMIP3 to CMIP5. Where possible, we used the most up to date version of each GCM: GFDC-CM2.1 and CSIRO-MK3.5 for CMIP3 scenarios A2 and A1B were updated to GFDL-CM3 and CSIRO-MK3.5 for the CMIP5 scenarios, respectively. There was no updated GCM for BCCR-BCM2.0, so we used BCCR-CSM1.1m to give us an output level for comparative purposes. The period 2010–2039 was not available for CMIP5, so we substituted the period 2020–2049.

**Data availability.** The data that supports the findings of this study are available from the corresponding author upon request. The supply of ground point data is restricted, as ownership is shared across the authorship and externally.

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## Author contributions

J.M. and A.P.D. conceived and led the study; A.P.D. and J.M. led the project; all authors collected data; J.M., A.P.D., J.W., S.B. and T.W. analysed and processed the data. J.M. and A.P.D. wrote the paper with contributions from all authors.

## Additional information

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## Competing interests

The authors declare no competing financial interests.