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Predicting the future climate-related prevalence and distribution of crop pests and diseases affecting major food crops in Zambia

Wilson Nguru *☯, **Caroline Mwongera**☯

The Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT), Rome, Italy

☯ These authors contributed equally to this work.
* ngurumaish91@gmail.com

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Abstract

Environmental factors determine the suitability of natural habitats for crop pests and often facilitate their proliferation and that of the crop diseases they carry. Crop pests and diseases damage food crops, significantly reducing yields for these commodities and threatening food security in developing, predominantly agricultural economies. Given its impact on environmental factors, climate change is an important determinant of crop pest and disease distribution. This study uses Targeting Tools, a climate suitability analysis and mapping toolkit, to explore the potential impact of climate change on select environmental factors linked to crop pest and associated diseases' proliferation. Based on the existing literature, prediction modeling was performed on 21 key pests and diseases that impact the major food crops for Zambian consumption. Future changes in habitat suitability for these crop pests and diseases were mapped based on their optimal temperature and relative humidity conditions for proliferation. Results project that there will be an overall increased geographical spread of suitable habitats for crop pests (and as follows, crop diseases) that thrive in warmer environments. By the 2030s, crop pests and diseases will increasingly spread across Zambia, with a higher likelihood of occurrence projected under RCPs 2.6, 4.5, and 8.5. Crop pests and diseases that thrive in cooler environments will experience decreasing habitat suitability in the 2030s, but will transition to a slower decrease in the 2050s under RCPs 2.6 and 4.5. Overall crop pest and disease habitat suitability will continue to rise slowly in the 2050s; RCP 8.5 shows an increased habitat suitability for crop pests and diseases that thrive in warm environments, with a decreased likelihood of occurrence for crop pests and diseases that thrive in cooler environments. The results highlight the need for future-facing, long-term climate adaptation and mitigation measures that create less suitable microclimates for crop pests and diseases.

Introduction

Crop pests and crop diseases damage food crops and are a major cause of yield losses in agriculture (up to 40% crop loss globally) [1–3]. Climate change has been found to be an important

ccafs-climate.org/data_spatial_downscaling/). CCAFS climate portal citation: Navarro-Racines, C., Tarapues, J., Thornton, P., Jarvis, A., and Ramirez-Villegas, J. 2020. High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. Sci Data 7, 7, doi:10.1038/s41597-019-0343-8 Base layer for Fig 1–Fig 10 was obtained from this Geopackage (https://gadm.org/download_country.html); The license information can be found here (https://gadm.org/license.html)– it states that using the data to create maps for publishing in PLoS (and other journals) of academic research articles is allowed. Additional data used for the generation of mapping results in this article (including Fig 2) is provided in the manuscript and in Supporting Information files (includes explicit written permission and signed permission form by copyright owners, and reflected permission on the corresponding figure caption).

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determinant of the abundance, distribution and level of activity of these crop pests and the pest-related diseases they carry [4,5]. According to the Intergovernmental Panel on Climate Change (IPCC), global temperatures have increased by 0.6 ± 0.2˚C compared to pre-industrial levels, and are expected to reach a global climate warming of over 1.5–2˚C and up to 5.4˚C by 2100 [6]. The IPCC also predicts that if temperatures rise by 2˚C over the next 100 years, there will be negative effects on living organisms, including crops and livestock [7]. Climatic variability with increased temperature, increased carbon dioxide concentration, changes in precipitation patterns, and extended periods of drought already negatively affect agricultural sectors and exacerbate poverty and food insecurity in developing economies [8,9]. This is especially observed in Sub-Saharan Africa, where agriculture employs more than half of the working population, and drives economic growth [10,11].

Climate change can drastically affect the dynamics of insect pest populations and the diseases they carry [12,13]. These effects are either direct, through the influence of weather conditions on pest physiology and behavior, or indirect, mediated by habitat conditions, host plants, competitors species, and pests' natural enemies [14]. Indirect effects of climate change on crop pests and diseases also include changes in phenology, distribution, and community composition of ecosystems. In the face of rapid climate-change-related environmental changes, for many species, survival depends on adapting to shifting climates, as these changes can lead to the extinction or the increased proliferation of pest species [15,16].

Insect crop pests are poikilothermic, i.e., cold-blooded organisms, and are highly sensitive to environmental changes [14,17]. For example, many orthopterans—insects often native to warmer regions—have a very limited distribution in higher altitudes and cooler climates. Such crop pests are found in tropical and subtropical regions. The size of the geographical range occupied by a species at any one time is determined by ecological factors including habitat availability, as well as climatic and other environmental parameters [18]. For crop pests to survive, they often adapt to new emerging climate conditions, or create shifts in their geographical distribution to populate more suitable areas [19]. This often leads to an increase in the diversity and abundance of these crop pests and pest-related diseases. Thus, crop pest species that thrive in cooler climates or cooler seasons could be more negatively impacted by global warming as temperatures rise, while species that are adapted to warmer climates like orthopterans could benefit from global warming, with higher altitude areas becoming warmer and more conducive to their survival [20]. Additionally, by altering land use patterns, recent studies have shown that climate change also allows for viral sharing across species that were historically geographically isolated from one another. Thus, the impacts of climate change can lead to zoonotic spillover: cross-species pathogen transmission phenomenon between animals and humans, linking environmental changes and zoonotic disease emergence [16]. Using climatic factors have also been effective predictors for human disease incidence [21–23].

Climate variability has been shown to increase directly transmitted diseases of wildlife [22]. Although zoonotic spillover is primarily a concern for animal and human health, it remains important to consider the potential long-term impacts of climate change on disease emergence stemming from crop pest' and related diseases' distribution. In fact, zoonoses can be facilitated by multiple host taxa; historically, at least 5 zoonoses have been attributed to the order of Dipterans [24], which includes common crop pest species like the rice gall midge. This further highlights a need to better predict potential crop pest distribution.

The observed climate change-related rise of global temperatures alters two important, agriculturally relevant characteristics of insect pests: their metabolic rates, and the length of their life cycles. On one hand, individual insects' metabolic rates increase with temperature, and in turn, so do their growth and food consumption rates, leading to increased rates of crop destruction by said pests [25,26]. On the other hand, insect crop pest populations change as their growth rates vary with temperature. For instance, increases in mean annual temperatures result in some crop pest species growing faster, and completing their life cycles two to three weeks early [27]. The resulting shortened life cycles often lead to rapid population growth with an increased abundance of crop pests and pest-related diseases, and more destructive effects on crops [13,28]. This can be observed particularly in temperate regions and high-altitude areas. The global increase in temperatures will likely cause 10–25% yield losses from crop pests [12].

Climate change also impacts crop pests through changing precipitation patterns. For instance, climate change-related decreases in precipitations can lead to the extinction of some species of crop insect pests for lack of adequate water resources, and to the growth of other species that are more adapted to low humidity such as aphids [29]. Alternatively, increasing average precipitation and rainfall intensity can also facilitate or impede proliferation of certain species of crop pests and pathogens [30–32]. Such extreme events can in some cases disrupt both natural and implemented biocontrol methods, namely by impacting the growth and proliferation of biological control agents and their host targets [33]. In other instances, warmer environmental conditions stemming from climate change may increase the effectiveness of many natural enemy species of said crop pests, making them more vulnerable to control measures [34]. The extinction of crop pest natural enemy species can also occur as a result of changing precipitation patterns, leading to increased crop pest proliferation.

The occurrence, prevalence, and severity of crop diseases are impacted by climate change [35], which have numerous implications for how diseases and crops interact. The time, preference, and effectiveness of using chemical, physical, and biological control techniques, and their application within integrated pest management (IPM) strategies can also be impacted by climate change factors, which have an impact on both the host and the pathogen [36]. For instance, some temperature patterns can encourage pathogen growth or increase host resistance to pathogenic diseases. This is seen in wheat and oats, which become more susceptible to rust diseases with increased temperature, while other forage species become less susceptible to these diseases under the same conditions [37]. Furthermore, temperature changes may lead to certain pests going through between 1 and 5 additional lifecycles per season, increasing their associated pathogens' capacity to overcome plant resistance [38].

Warmer, wetter weather, and higher CO_2 levels are favorable conditions for the growth of many weeds, crop pests, and fungi [39,40]. High CO_2 concentrations may result in slower plant decomposition rates, which can raise fungal inoculum levels and aid the development of more fungal spores [39]; alternatively, elevated CO_2 levels can alter the physiological makeup of crops and increase their resistance to some crop diseases. Thus, crop fungal diseases threaten crops in areas where climate-related environmental changes can be observed [29], potentially exacerbating issues related to pest-transmitted crop diseases.

These climate change impacts on crop pests and crop diseases bring about major implications for crop production and food security, particularly in developing countries like Zambia where the need to increase and sustain food production is urgent. While many studies have investigated the isolated impacts of climate change factors on crop pests and diseases [33,41–44]; a notable gap in the available literature is the absence of an approach that assesses interacting environmental factors that are conducive to crop pests proliferation in specific contexts (e.g. agroecology), and analyzes these environmental factors' impacts on crop pests' habitats.

To help predict climate change impacts and plan for mitigation efforts, the IPCC 5th assessment report adopted four potential pathways to describe a range of probable climate futures that can be expected in the coming decades [45]. These pathways, known as the Representative Concentration Pathways (RCPs), capture assumptions regarding future temperature increases due to carbon concentration and radiative forcing. This collection of predictive greenhouse gas (GHG) concentration and emissions pathways (or scenarios) were created to support research on the impacts of climate change and associated policy responses [46]. They include RCPs 2.6, 4.5, 6.0, and 8.5, which cover a spectrum of more to less optimistic climate change outcomes. The different climate futures projected in the RCPs are all considered likely, based on the volume of greenhouse gases expected to be emitted in the near future, and can be used to define predictive modeling parameters [47].

The negative global impacts stemming from the spread of the Coronavirus during the COVID-19 pandemic highlighted the importance of assessing the role of environmental drivers in explaining pathogen proliferation to forecast future outbreak risks. Agriculture is one of the sectors most exposed to climate change and to the impacts of crop pests and crop diseases; it is hence increasingly important to accurately predict the future distribution of these harmful agents to enhance preparedness measures and mitigate crop losses due to climate change-related pest infestations. In this study, we combine global studies and a habitat suitability analysis and mapping tool (Targeting Tools) to develop an approach linking habitat suitability for crop pests and crop diseases to their proliferation patterns. We also infer some impacts of crop pests and crop disease proliferation on local food security under a spectrum of climate change scenarios. This approach will contribute to the development of recommendations that support forward-facing climate adaptation in vulnerable areas, with a strong focus on measures to mitigate the potential future climate change effects on crop pest and crop disease distribution in Zambia.

Materials and methods

Zambia: A case study for modeling pest infestations under climate change

The modeling of the potential distribution of agricultural pests and their related diseases in relation to climate change for this study focuses on Zambia. Zambia is a landlocked country in Southern Africa that according to the World Bank, has an approximate population of 18.38 million people, of which about 60% live in rural areas [48]. About two-thirds of Zambia's territory consists of high plateau with some hills. The northern plateaus' populations depend on rainfed agriculture for their livelihoods, a production system that is becoming increasingly vulnerable to climate change. The impacts of climate change on agriculture include excessive precipitation leading to flash flooding and erosion, increased frequency of droughts, and shortening of growing seasons. Zambia's climate is tropical but is also modified by elevation, with altitude giving the country subtropical weather from May to August. The country is part of the Central Zambezian Miombo woodlands ecoregion. Northern Zambia is flat and has broad plains. Temperatures in Zambia range between 21–26°C in winter and 25–35°C in summer, with temperatures lower at higher elevations and higher at lower elevations.

Fig 1 shows an administrative map displaying Zambian provinces. Administrative boundaries were obtained from global administrative boundaries (gadm.org).

Selection of the main agricultural cash and food security crops

For modeling purposes, several crops were selected based on their importance for food security and livelihoods in Zambia. The selection was based on a comprehensive literature review, and the selected crops included groundnuts, beans, soybean, rice, and cowpea.

Although not included in the analysis, maize is briefly discussed due to its similar importance to food security and livelihoods in Zambia.

Crop pests and diseases selection

For modeling purposes, some key crop pests and crop diseases were selected based on their occurrence in Zambia, and their impact on crop yields and on the country's economy. The

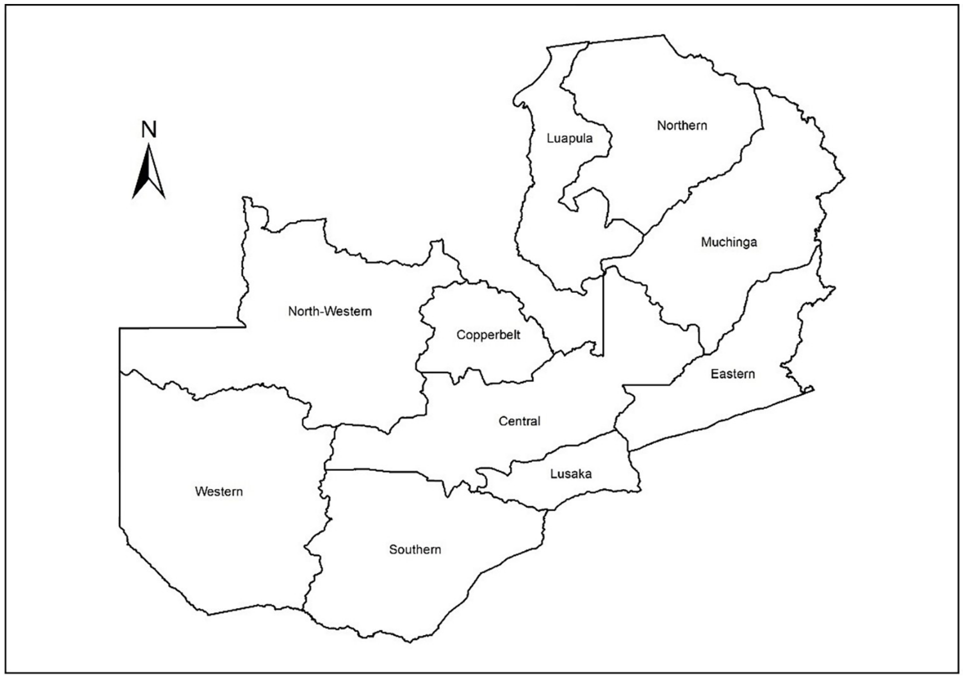

Fig 1. The administrative map of Zambia showing its provinces. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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pests and diseases selection was done by carrying out a desk review of existing literature on their distribution, optimal habitats and impacts on staple crops. Stakeholder input was also considered to assess the crops' contribution to food security and livelihoods in Zambia. Table 1 was developed based on that review.

The desk review was conducted using Google search engine and Google Scholar to obtain data on the occurrence of various crop pests and crop diseases in Zambia. The following key search terms were included to gather data: '[selected crop] pests and diseases in Zambia', '[selected crop] pests in Zambia', and '[selected crop] diseases in Zambia' (e.g., 'rice pests and diseases in Zambia'). Beyond journal articles, reports, and websites, the review also included online newspapers, which provided key information on the spatial distribution and new rise of crop pests in Zambia. Forty-one journal papers, six reports, twelve websites, and two online newspapers were reviewed to obtain the data on crop pests and diseases' occurrence.

Data on crop pests and diseases impacts on agriculture were obtained for each pest and disease identified, using the search terms 'impact of [selected pest or disease] in Zambia' (e.g. 'impact of rice gall midge in Zambia'); 'yield losses associated with [selected pest or disease] in Zambia' (e.g., 'yield losses associated with rice gall midge in Zambia'); and 'the economic impact associated with [selected pest or disease] in Zambia' (e.g., 'the economic impact associated with rice gall midge in Zambia'). 21 journal articles, three reports, four websites, and two online newspapers were reviewed, and the data obtained was summarized in S1 Table (see Supporting information). The crop pests and diseases selected for modeling and analysis in this study were then prioritized based on their pronounced impacts on agricultural yields and the country's economy where impact data was available.

A literature review was performed to obtain data on ranges and combinations of environmental factors that would create suitable habitats for the growth and proliferation of the selected crop pests and diseases. A search for peer-reviewed, published journals was carried out using the Google Scholar search engine, and a search for reports, working papers, websites,

Table 1. Pests associated with selected crops and the environments conducive to their growth and development.

Pest/disease	Scientific name	Temperature	Relative humidity
Groundnuts			
Groundnut aphids	*Aphis craccivora*	24–28.5˚C	65–86.5%
Early leaf spot	*Cercospora arachidicola*	25–30˚C	>75%
Groundnut rosette	*Groundnut rosette*	24–28.5˚C	65–86.5%
Pod borer, bollworm	*Helicoverpa armigera*	***See soybean***	
Groundnut bruchid	*Caryedon gonagra*	23–35˚C	70–90%
Bean			
Bean Anthracnose	*Colletotrichum lindemuthianum*	13–26˚C	65–96%
Bean rust	*Uromyces appendiculatus*	18–25˚C	>85%
Bean bruchids	*Acanthoscelides obtectus*	20–28˚C [49]	60–70%
Maruca pod borers	*Maruca vitrata*	***See cowpea***	
Aphids	*Aphis fabae* *Aphis craccivora*	***See groundnut***	
Rice			
Rice blast	*Pyricularia oryzae* *Magnaporthe grisea*	25–28˚C	80–100%
African rice gall midge	*Orseolia oryzivora*	25–35˚C	>60%
Armyworms	*Spodoptera frugiperda*	26–30˚C	50–100%
Soybeans			
Frogeye leaf spot	*Cercospora sojina*	25–30˚C	>90%
Red leaf blotch	*Coniothyrium glycines*	20–25˚C [50]	95–100%
Pod borer, bollworm	*Helicoverpa armigera*	25–30˚C	>45%
Cowpea			
Leaf spots of cowpea	*Mycosphaerella cruenta*	25–30˚C	70–92%
Cowpea aphid borne mosaic virus (CAMV)	*Potyvirus*	20–25˚C	>45%
Cowpea (weevil) seed beetles	*Callosobruchus maculatus*	17–37˚C	44–90%
Aphids	*Aphis craccivora*	***See groundnut***	
Maruca pod borer	*Maruca vitrata*	19.5–29.3˚C	40–93%

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and online newspapers was carried out using the Google Search engine. The search terms used in this literature review were 'optimal conditions for [selected pest or disease]'; 'conducive environment for [selected pest or disease]'; 'environmental conditions favoring [selected pest or disease]', or 'optimum environmental conditions for [selected pest or disease] development'. For the literature review of environmental factors', 40 journal articles and five websites were reviewed. Findings are recorded in S2 Table (see Supporting information), which shows the identified optimal ranges of environmental factors for each crop pest and disease. The environmental factors included in S2 Table are temperature, relative humidity, and rainfall; we note that limited information was available on other, potentially relevant factors.

Environmental variables selection for modeling

Environmental conditions favoring the development, survival, and proliferation of crop pests and diseases were selected based on their importance to the life cycle of said pests and diseases. Environmental factors that affect crop pests and diseases development include temperature, light and water availability, wind speed, soil fertility, and atmospheric carbon dioxide, methane, and ozone [51].

Carbon dioxide (CO_2), temperature, and water availability are factors that are most likely to have lasting impacts on the environment, and hence on habitat suitability for crop pest species. For instance, increased carbon dioxide has been linked to the global increase of temperatures, which affects crop pests' habitats [52]. Additionally, rising temperatures have been shown to result in increasingly severe and longer-lasting extreme weather events such as heat waves, droughts, floods, and heavy rains, which have also been linked to the rise of non-native agricultural pests.

Temperature is important for the growth of crop pests and in the development of crop diseases; it influences insect pests' development, physiological processes, and natural behavior. In fact, insects are poikilothermic (i.e., cold-blooded), and their body temperature varies with that of the environment. As such, most insect crop pests are known to develop quickly when temperatures are high and more slowly under cool conditions. Temperature also influences the spread of bacterial or viral crop diseases like leaf rust, with each crop disease having its own optimal temperature range for maximum development. Research has also documented that the diversity of insect species and their feeding intensity increases with rising temperatures [53,54].

Water-availability conditions in terms of rain, high relative humidity, and high soil moisture tend to favor the development of most crop diseases. Relative humidity is an important factor in the development of crop fungal diseases and crop pests, and is related to temperature: due to evapotranspiration, areas that receive high rainfall and have a warmer environment have more relative humidity, with incidences of insect crop pests and crop fungal diseases increasing with rising humidity [29]. Additionally, the air can hold more vaporized water at higher temperatures, increasing the relative humidity and, consequently, the potential for crop pathogen infections [51]. Rainfall facilitates the geographical spread of crop pests, plant pathogens, and crop diseases as wet conditions promote the germination of these harmful agents' spores and the proliferation of fungi and bacteria while providing water for their growth and that of their plant hosts [29]. Furthermore, both rainfall and high relative humidity exacerbate the severity of aerial tissue infection by plant pathogens [51] and are the two most significant factors in the development of crop pests.

The effects of carbon dioxide on the proliferation of crop pests and crop diseases are complex and mainly mediated by temperature changes, which directly affect the suitability of their habitats. Rainfall levels and plant evapotranspiration traits both determine relative humidity, which is also a direct determinant of crop pest and crop disease habitat suitability [55].

Hence, this study chose to focus on variables that pertain to temperature, rainfall and relative humidity as direct effectors of crop pest and disease habitat suitability and distribution.

Spatial data collection

For this study, gridded spatial data were used. Data for the current climate trends was obtained from Worldclim historical monthly weather data, for the years 1990–2018 [56]; historical temperature and precipitation Worldclim bioclimatic variables 1 (annual mean temperature) and 12 (annual precipitation) were used, and the monthly minimum and maximum temperature variables were obtained. The monthly maximum and minimum temperatures for November and December (which often receive rainfall), as well as January to April (considered the wet season in Zambia), were calculated and averaged for the period 1990–2018, and mean temperatures for the same months and period were calculated.

Future climatic data was obtained from the CGIAR's research program on Climate Change, Agriculture and Food Security (CCAFS) downscaled GCM data portal [57]. Relative Humidity (RH) was calculated monthly for the 6 months using the method first developed by the

Numerical Terradynamic Simulation Group at the University of Montana in their MTCLIM model [58], as proposed by Wesolowski et al. and Eccel [59,60]. Below are the equations.

We started by calculating the dew point temperature, T_d

$$T_d = T_{min} - \mathrm{k}\,(T_{day} - T_{min}), \tag{1}$$

Where k is a calibration coefficient (here k = 1), T_{min} is the daily minimum temperature and T_{day} is the estimated diurnal temperature.

$$T_{day} = 45 \times (T_{max} - T_{mean}) + T_{mean} \tag{2}$$

T_{max} is the daily maximum temperature, and T_{mean} is the daily mean temperature. Dew point (T_d) and temperature (T) are converted to relative humidity, using the following formula:

$$RH = 100 \times \frac{e^{\frac{(17.625\times T_d)}{(243.04+T_d)}}}{e^{\frac{(17.625\times T)}{(243.04+T)}}} \tag{3}$$

Relative humidity for the current climate was calculated by running the above method in R statistical software.

Data for the future climate trends was obtained from the CCAFS climate portal [57] for two time periods, namely the 2030s (2021–2040), and the 2050s (2041–2060). Five representative Global Climate Models were used as data sources: CSIRO, Australia, and CESM1-CAM5 by the University Corporation for Atmospheric Research, United States of America. Simple averages were calculated for the minimum, maximum, and average monthly temperatures from November to April (the main crop growing season) which were later used to calculate the monthly relative humidity of all three scenarios at a 5-kilometer resolution. The future relative humidity projection for the six months was calculated for the 2030s and 2050s. The future climate trends data for these periods were modeled based on three climate scenarios, namely RCP 2.6, RCP 4.5, and RCP 8.5 [57].

The three RCPs used for this analysis were selected to ensure that plausible impacts on the IPCC's low-, mid-, and high-warming scenarios (RCP 2.6, 4.5 and 8.5 respectively) were modeled. RCP 2.6 is the most optimistic carbon-concentration scenario and assumes that global warming will be kept well below a 2˚C increase above pre-industrial global temperature levels. RCP 8.5 assumes the most pessimistic carbon-concentration scenario available; it projects a future in which fossil fuels are abundant and no climate-mitigation policies are implemented, resulting in nearly a 5˚C global average temperature increase compared to pre-industrial levels by the end of the century [47]. RCP 4.5 is a stabilization scenario and falls between these two extreme scenarios of improbable, high- and low-risk futures, although leaning towards more optimistic outcomes for the development of more effective recommendations; it projects a global temperature rise between 2˚C and 3˚C, by 2100. Due to the similarities between RCPs 4.5 and the fourth RCP (6.0), only one mid-warming pathway was retained for modeling (RCP4.5). We note that RCPs account for long-term changes in temperature and precipitation, but not for changes in climate variability or incidences of extreme weather events. Modeling crop pest and crop disease habitat suitability based on all three scenarios ensures that habitat suitability projections capture a comprehensive range of possible proliferation patterns and supports the development of recommendations that are conducive to more positive outcomes in the future.

Crop pest and crop disease group characterization based on agroecological zone

Agroecological zones (AEZ) boundaries (Fig 2) were obtained from the World Agroforestry Centre (ICRAF) Geoscience lab. Zambia's territory displays three distinct AEZs based on rainfall amount, soil and other climatic characteristics [61]. The semi-arid Region I, of the first AEZ, includes areas of Southern, Eastern, and Western Zambia with a mean annual rainfall range of between 600–800 mm. It predominantly features small-scale farmers who mainly produce starchy crops such as maize and sorghum, as well as cowpeas and groundnuts. The second AEZ, Region II, encompasses much of Central Zambia, including most of Central, Southern, Eastern, and Lusaka Provinces; this region has annual rainfall averages of between 800–1000 mm. It is the most agriculturally productive area, with higher rainfall and large commercial farming of cash crops like tobacco, coffee, and cotton, as well as medium-scale farming of rice, beans, soybeans, and groundnuts. Both Sub-Regions IIa and IIb in this AEZ consist of plateaus with medium rainfall of 800–1000 mm. Region II has an average mean daily temperature of 23–26˚C in the hottest month of October, to 16–20˚C in the coldest months of June and July [62]. It overlaps with tropic cool semi-arid lands and the surrounding tropic warm semi-arid areas. The hottest average temperature in this region, which is approximately at the

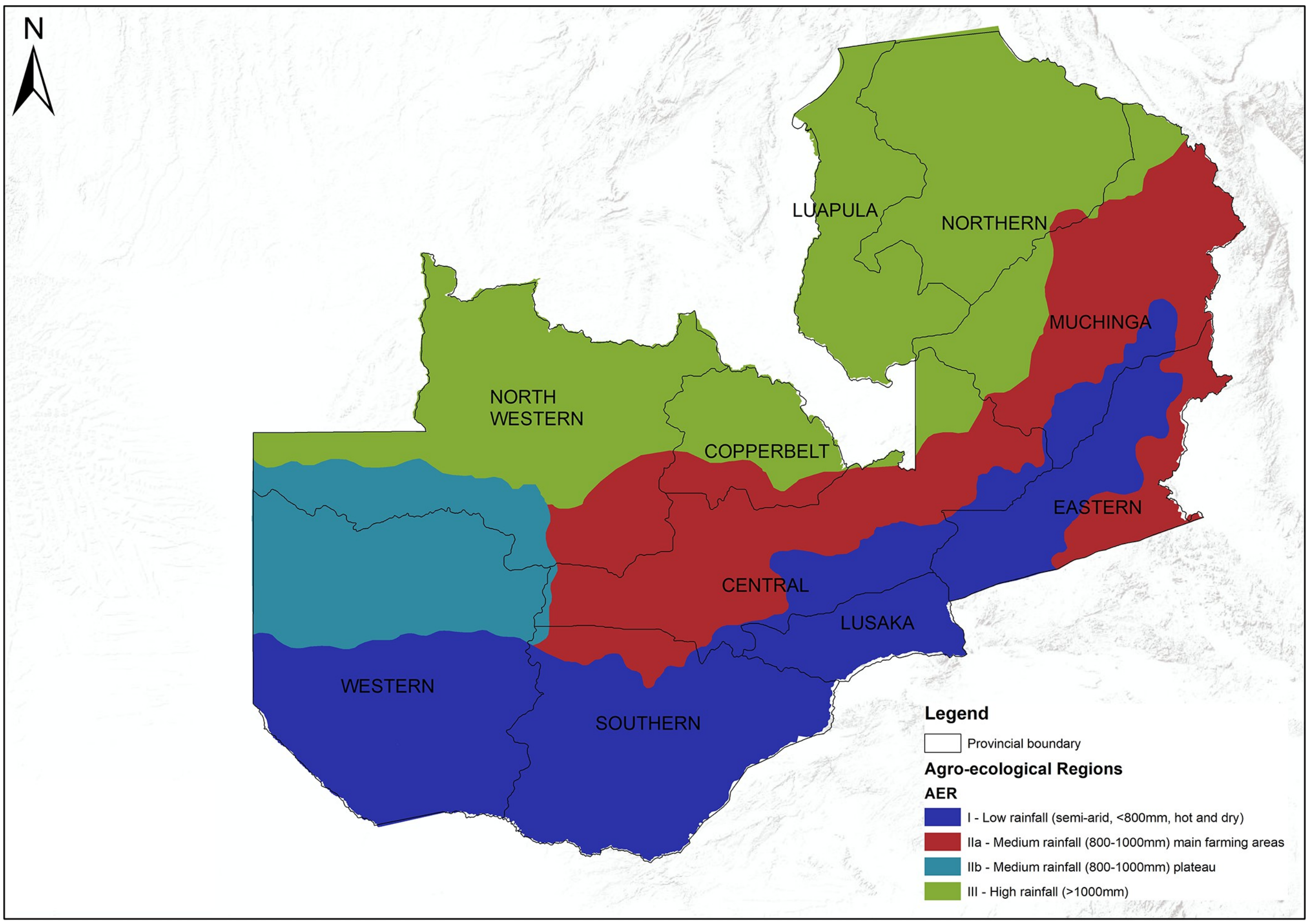

Fig 2. The agroecological zones of Zambia. Republished from World Agroforestry Centre (ICRAF) Geoscience Laboratory Landscape Portal under a CC BY license, with permission from ICRAF, original copyright 2015. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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Table 2. Crop pests and diseases grouped by AEZ type in which they are likely to occur. Group A indicates a cool AEZ. Group B indicates a warm AEZ.

Crop pest/disease	Scientific name	Temperature	Relative humidity	Group
Groundnuts				
Groundnut aphids	*Aphis craccivora*	24–28.5˚C	65–86.5%	B
Early leaf spot	*Cercospora arachidicola*	25–30˚C	>75%	B
Groundnut rosette	*Groundnut rosette*	24–28.5˚C	65–86.5%	B
Pod borer, bollworm	*Helicoverpa armigera*	***See Soybean***		
Groundnut bruchid	*Caryedon gonagra*	23–35˚C	70–90%	B
Bean				
Bean Anthracnose	*Colletotrichum lindemuthianum*	13–26˚C	65–96%	A
Bean rust	*Uromyces appendiculatus*	18–25˚C	>85%	A
Bean bruchids	*Acanthoscelides obtectus*	20–28˚C	60–70%	B
Maruca pod borers	*Maruca vitrata*	***See cowpea***		
Aphids	*Aphis fabae* *Aphis craccivora*	***See groundnut***		
Rice				
Rice blast	*Pyricularia oryzae* *Magnaporthe grisea*	25–28˚C	80–100%	B
African rice gall midge	*Orseolia oryzivora*	25–35˚C	>60%	B
Armyworms	*Spodoptera frugiperda*	26–30˚C	50–100%	B
Soybeans				
Frogeye leaf spot	*Cercospora sojina*	25–30˚C	>90%	B
Red leaf blotch	*Coniothyrium glycines*	20–25˚C	95–100%	A
Pod borer, bollworm	*Helicoverpa armigera*	25–30˚C	>45%	B
Cowpea				
Leaf spots of cowpea	*Mycosphaerella cruenta*	25–30˚C	70–92%	B
Cowpea aphid-borne mosaic virus (CAMV)	*Potyvirus*	20–25˚C	>45%	A
Cowpea (weevil) seed beetles	*Callosobruchus maculatus*	17–37˚C	44–90%	B
Aphids	*Aphis craccivora*	***See groundnut***		
Maruca pod borer	*Maruca vitrata*	19.5–29.3˚C	40–93%	B

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center of Zambia, is about 25˚C. Finally, Region III, the high-rainfall and third AEZ, lies in a band across Northern Zambia, including the Northern Luapula Copper Belt, the North-Western Province, and some parts of the Central province. This AEZ receives over 1000 mm of precipitation annually and predominantly features small-scale farming of roots and tubers such as cassava and potatoes, as well as beans. The south of Zambia is the hottest part of the country while the north is the coolest.

For this analysis, a temperature threshold of 25˚C was used to characterize warm and cool AEZ. This threshold represents the average temperature observed in areas of overlap between tropical cool semi-arid lands and tropical warm semi-arid lands in the second AEZ (Region II). The 25˚C threshold also emerged as a maximum and minimum from the ranges of conducive temperature for cool weather and warm weather crop pests development respectively, further justifying its use as the cut point separating two distinct groups. The selected crop pests and diseases were grouped as (A) those that grow and develop in temperatures below 25˚C, and (B) those that thrive in temperatures above that threshold.

Table 2 was populated by inserting the most probable group for each crop pest and disease. Significant overlap in terms of Relative Humidity was observed across crop pest and disease groups. Based on Table 2, crop pests and diseases that thrive in cool temperatures (group A,

Table 3. Grouping of pests and diseases based on optimal temperature.

Group	Temperature	Environment
A	13–25˚C	Cool
B	25–30˚C	Warm

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below 25˚C) and those that thrive in warm temperatures (group B, greater than 25˚C) were grouped in Table 3 based on their optimal temperature ranges for habitat suitability.

Crop pests and diseases suitability modeling

Crop pest and disease habitat suitability modeling was conducted using Targeting Tools [63]. Targeting tools is a set of tools developed by the Alliance of Bioversity International and the International Center for Tropical Agriculture, and is available in Desktop, Web, and Server versions. The toolbox has three tools, namely Land Similarity, Land Suitability and Land Statistics. The tools were developed with the aim of identifying suitable areas for the growth of a selected crop, based on some user-defined parameters of land composition and environmental factors; they were developed in Python and run in both Python and R; they are thus compatible with such analysis software.

The Land Suitability tool was designed to identify suitable areas for planting crops, for example, areas that are suitable for planting a certain crop type based on pre-set user criteria. Given a set of raster data and user-defined optimal values for several environmental variables, this tool determines the most suitable place to carry out an activity. In agriculture, it is often used to identify places with the best biophysical and socioeconomic conditions for a certain crop to flourish but can be used to generate suitability results based on different, arbitrary criteria. The Land Similarity tool was used to find new suitable sites similar in composition to already existing croplands, as identified by the Land Suitability tool. The Land Statistics tool was used to generate spatial statistics on the Land Suitability output.

In this study, we used the Land Suitability tool to identify areas with suitable environmental conditions (habitat suitability) favoring the growth and proliferation of crop pests and diseases across Zambia, and resulting from the interaction between defined rainfall, temperature, and relative humidity levels. Current and future climatic trends were modeled for the 2030s and the 2050s, and modeling was performed for RCPs 2.6, 4.5, and 8.5 in each studied time interval. For modeling purposes, Table 4 was developed from Table 2, grouping crop pests and diseases based on two sets of conducive environmental conditions. Suitability levels were extracted from each modeled layer to obtain mean suitability levels for current and future scenarios across all three AEZs, and for each group of crop pests and diseases.

Results and discussion

The crop pests and diseases habitat suitability trends shown in Fig 3 show that average suitability for crop pests and diseases is projected to decrease in Group A, while an overall increase is projected for crop pests and diseases in Group B. Note that the country shows a higher base

Table 4. Summary of Common conducive environments per group of crop pests and diseases in the studied AEZs.

Group	Relative humidity	Temperature
A	45–96%	13–25˚C
B	40–100%	25–30˚C

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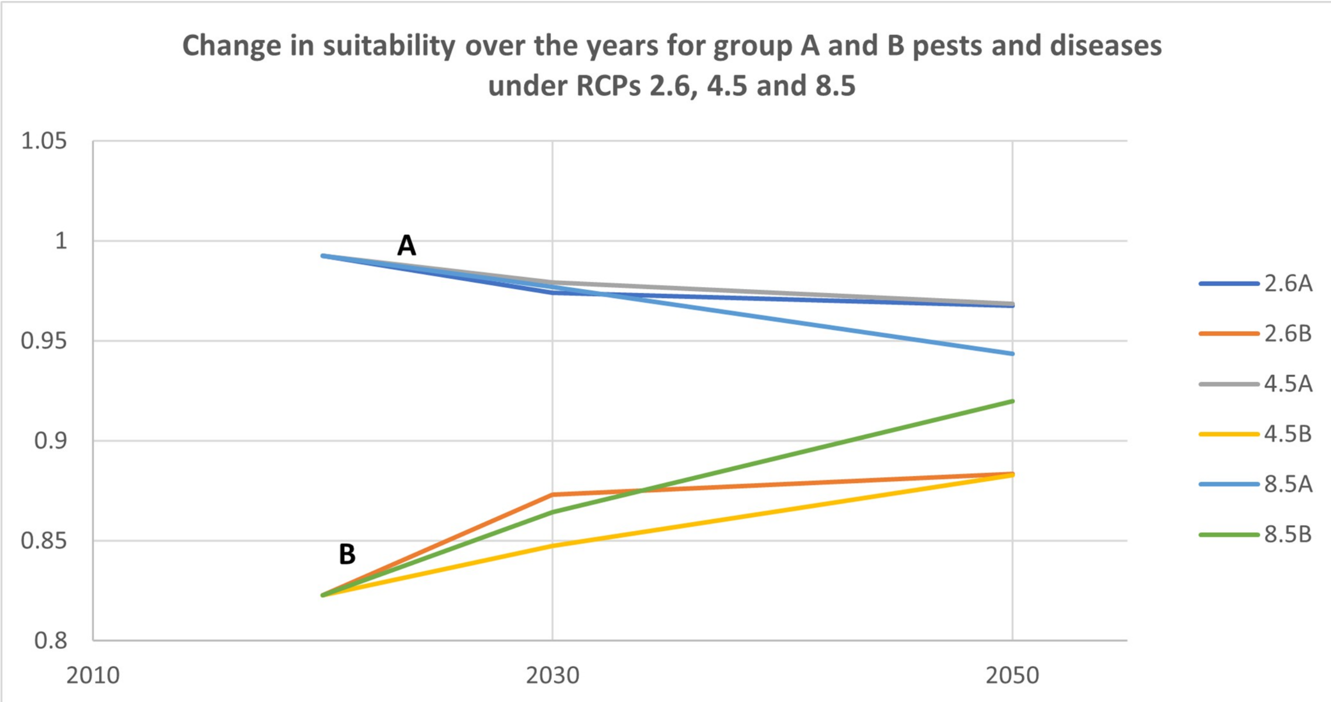

Fig 3. Trendlines of the projected changes in habitat suitability over the years for Group A and Group B crop pests and diseases under RCPs 2.6, 4.5, and 8.5. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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suitability of crop pests and diseases in Group A for the current period, and significantly lower overall suitability for Group B.

A moderate decrease in suitability of Group A crop pests and diseases is projected for all RCP scenarios in the 2030s; temperature increases due to climate change will negatively impact these crop pests and diseases, which thrive in cooler environments, potentially leading to the projected reduced habitat suitability for that group. In the 2050s, Group A crop pest and disease habitat suitability is projected to decrease further, particularly under RCP8.5, which assumes the highest rise in global temperatures. Under both RCP 2.6 and 4.5, a less pronounced decrease in suitability for Group A crop pests and diseases can be attributed to the effective climate-change mitigation measures assumed under these two scenarios; such measures would diminish the effects of rising temperatures on the Group's habitat suitability.

For Group B crop pests and diseases, a continued increase in suitability is projected under all RCPs in the 2030s, threatening productivity for the key crops that these pests and diseases affect (i.e. rice and groundnuts.) The 2050s, however, show differences in suitability as increases in habitat suitability under both RCP 2.6 and 4.5 become less pronounced, and habitat suitability under RCP 8.5 continues to rise across the country. Lower rates of increase in habitat suitability under RCP 2.6 and 4.5 can be attributed to the climate change mitigation measures and interventions assumed under these scenarios. Meanwhile, under RCP 8.5, the assumed lack of mitigation measures would allow Group B crop pest and disease habitat suitability to steadily increase as temperatures rise, potentially favoring the proliferation of the species in that group.

1. Current crop pests and diseases distribution in Zambia

Fig 4 shows the current suitability of pests and diseases in Zambia. Group A crop pests and diseases are generally favored by the climatic conditions in most of the areas of Zambia except the

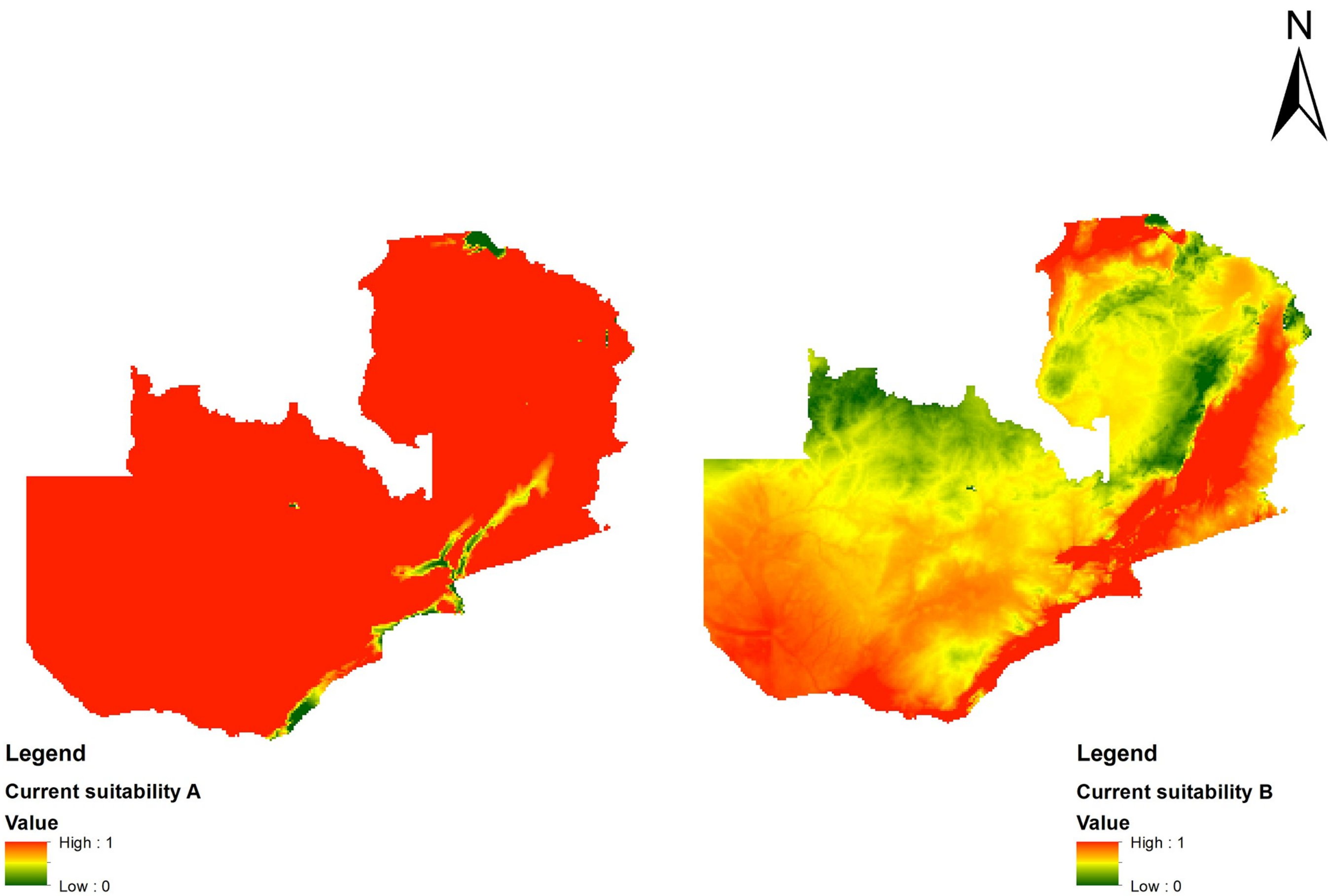

Fig 4. Current crop pest and disease habitat suitability distribution in Zambia for Group A and B. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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southmost end part of Southern Province, eastern parts of Lusaka, and western parts of the eastern provinces in AEZ 1 (Region I). In contrast, Group B crop pests and diseases are favored by climatic conditions of the Western, Eastern, Northern, and Luapula Provinces, falling across all AEZs with higher suitability in AEZs 1 and 2 (Region I and II) in the south of Zambia.

Climate vulnerability in Zambia. Current climate vulnerability in Zambia stems from hydro-meteorological hazards and their cascading effects, including crop disease epidemics and periodic incidences of macroeconomic instability. Key climate change-related food insecurity drivers are flooding, outbreaks of crop pests such as the African Migratory Locusts and Fall Armyworm, and high maize prices resulting from pest-related yield losses [64]. Improved crop pests and disease control solutions are even more relevant in this context, since maize is the staple food of Zambia and is produced in all AEZs. Thus, maize production, which plays a crucial role in Zambia's agricultural economy, is increasingly threatened by changing crop pest and disease habitat suitability profiles in each AEZ [65]. Thanks to large subsidies flowing into crop industries, most smallholder farmers are still able to cultivate maize, and the country is self-sufficient in terms of output [66]. However, overall productivity remains unsustainably low, and poverty is endemic in rural areas.

The Fall Armyworm's emergence in 2016 exacerbated the current maize production issues in Zambia, threatening food security [67]. The crop pest outbreak has been declared a national

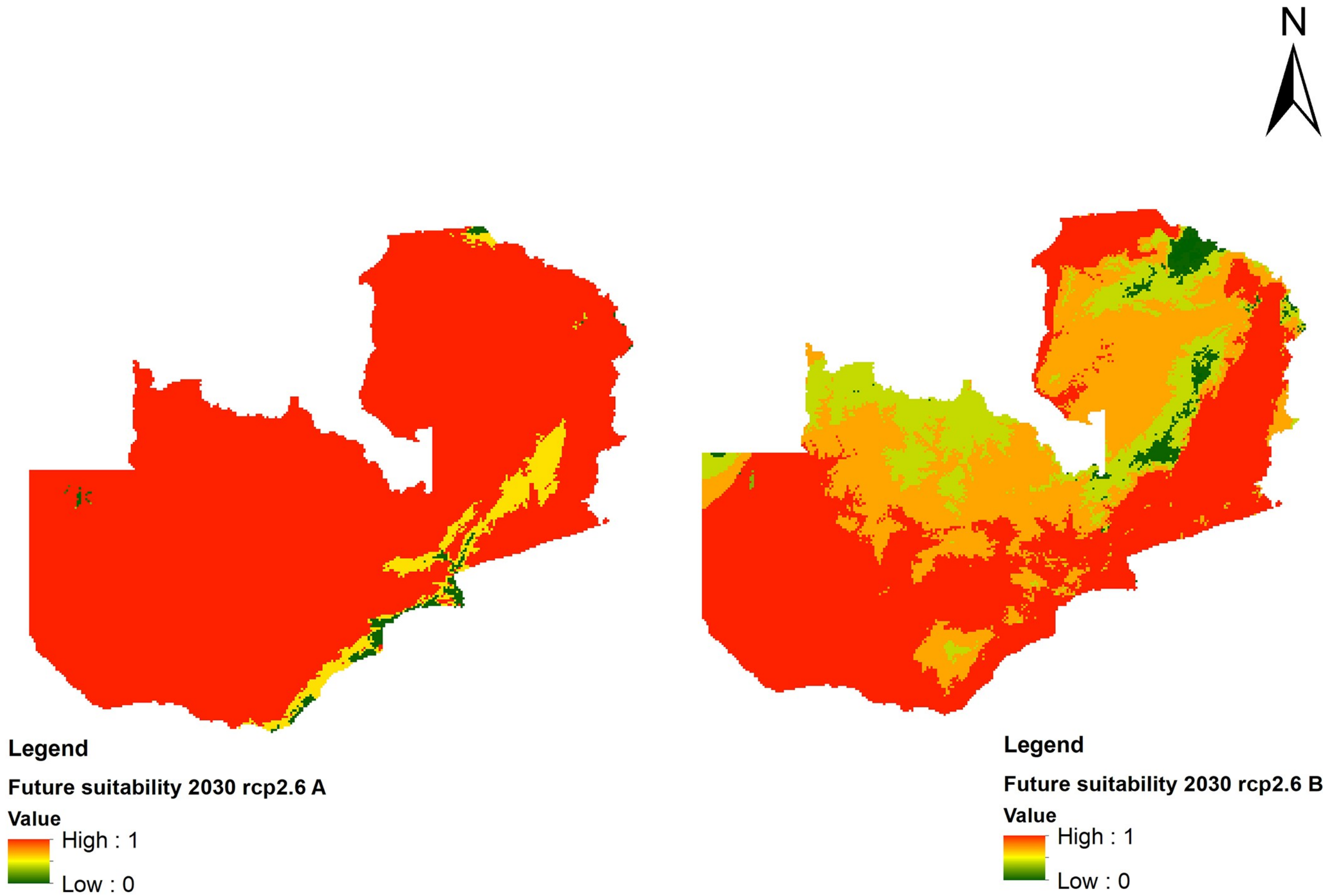

Fig 5. Future crop pest and disease habitat suitability distribution by 2030 under RCP 2.6. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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calamity, with the Zambian government allocating more than 3 million USD for crop pest management. Experts are concerned, however, that the armyworm's ability to burrow into the core of maize plants may make even chemical management difficult [68]. Thus, better understanding habitat suitability patterns for crop pests and disease may support the development of new and more effective management solutions.

2. Future crop pests and diseases distribution in Zambia for the 2030s

The RCP 2.6 climate scenario projections for the 2030s show decreasing habitat suitability for Group A pests and diseases in the eastern part of AEZ 1 (Fig 5). In contrast, habitat suitability for Group B crop pests and diseases is projected to increase across Zambia, with areas of AEZs 1, 2 and 3, which currently show lower suitability for Group B pests and diseases, becoming more suitable under this scenario. This increase is in line with the finding of Petzoldt and Seaman, who established that warm temperatures support pathogen growth and reproduction, and can either increase or decrease insect pest populations depending on their optimal growth characteristics [69]. This occurs as higher temperatures increase the metabolism of some insect pests, while others become less responsive and more vulnerable to predators due to temperature effects on their physiology [70].

The climate change intervention activities assumed under RCP 2.6 (including activities aimed at reducing carbon emissions and reverse the effects of climate change) may not be

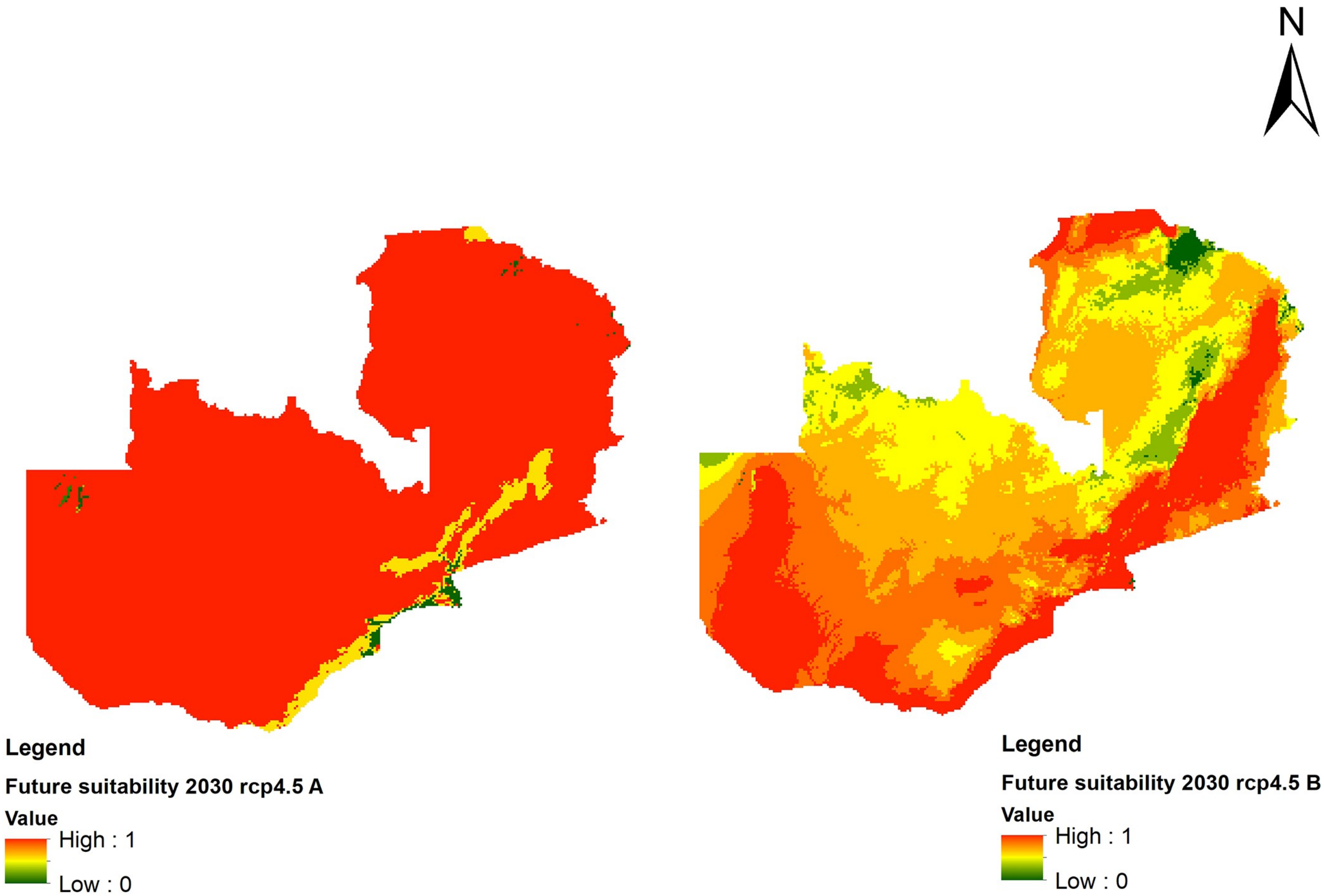

Fig 6. Future crop pest and disease habitat suitability distribution by 2030 under RCP 4.5. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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enacted or have measurable effects in the 2030s; this suggests that in the meantime, climate change effects like temperature rise will continue to worsen, explaining the projection of more unsuitable habitats for Group A crop pests and diseases. Conversely, the warming environment is likely to become more conducive for Group B pests, which thrive in higher temperatures.

RCP4.5 projections for the 2030s (Fig 6) show a decrease in suitability for Group A crop pests and diseases in the eastern part of AEZ 1, but at a lower rate than the decreases observed in RCP 2.6. In contrast, habitat suitability for Group B crop pests and diseases is projected to increase across Zambia under this scenario, but also at a lower rate than the increases projected under the RCP 2.6. This may be related to the somewhat stabilized effects of climate change on Group A and B crop pests' under RCP4.5, including slower temperature rise rates. This contrast highlights the importance of implementing emissions reduction measures using emerging technologies to actively combat, or at least, stabilize temperature changes in the coming decade, and effectively lower the levels of habitat suitability for crop pest and disease proliferation.

RCP 8.5 projections in the 2030s (Fig 7) also show a decrease in habitat suitability for Group A crop pests and diseases in AEZ 1, at even lower rates than those projected in RCPs 2.6 and 4.5. Habitat suitability for Group B crop pests and diseases are projected to increase across Zambia under RCP8.5, but also at a lower rate than projections under RCP 4.5 and RCP

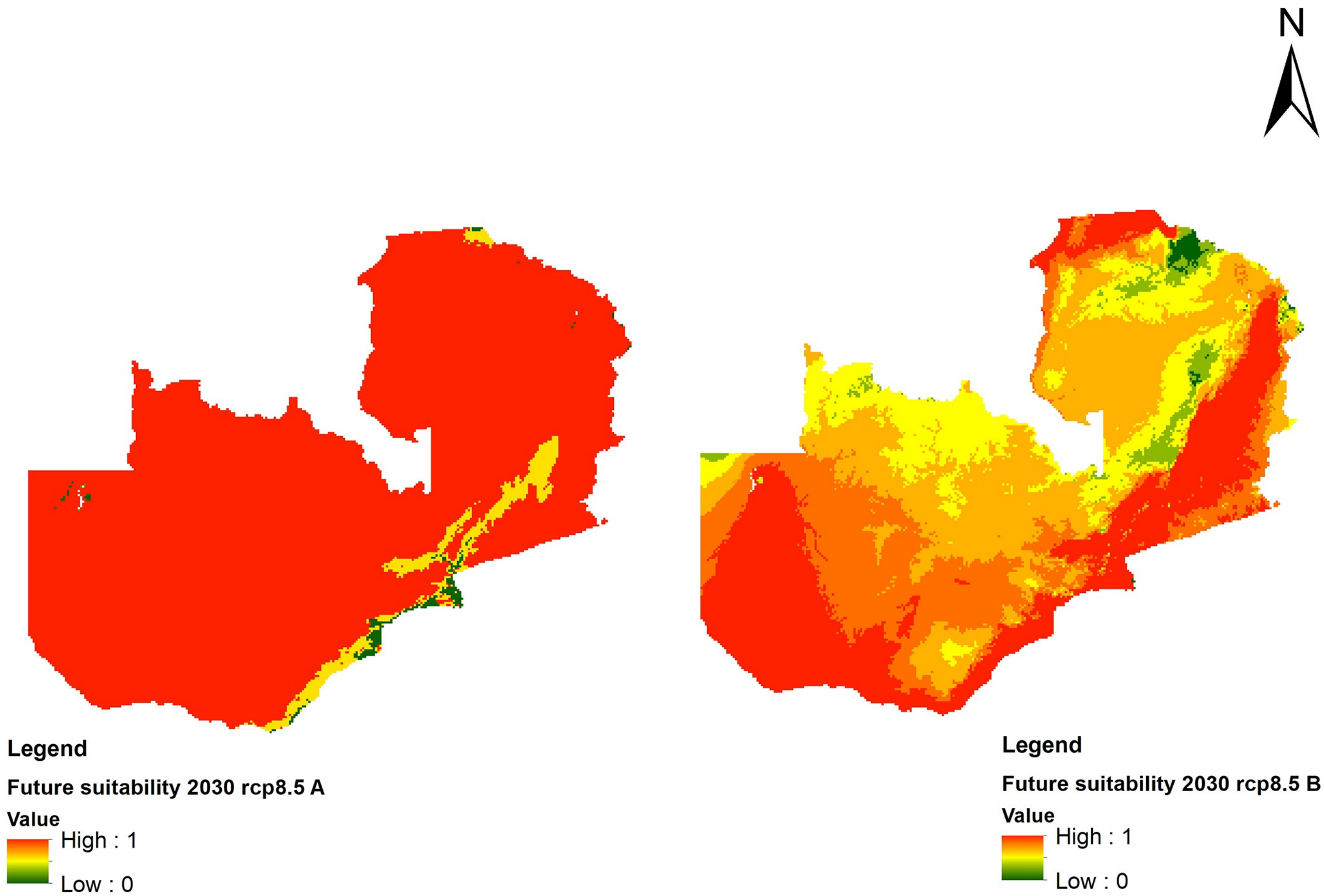

Fig 7. Future crop pest and disease habitat suitability distribution by 2030 under RCP 8.5. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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2.6. This further emphasizes that more or less optimistic climate-change scenarios (RCPs 2.5 and 4.5 vs RCP 8.5 respectively) that account for the enactment of mitigation measures—or lack thereof—can impact the potential for crop pests and diseases to find increasingly suitable habitats in Zambia by the end of the decade.

For the 2030s, it is important to note the decrease in habitat suitability projected for Group A crop pests and diseases across all RCPs and more notably in AEZ 1. This AEZ is a relatively Semi-arid region that predominantly houses small-scale agricultural exploitations of sorghum, finger millet, maize, groundnuts, cowpeas, pumpkins, and cassava [62]. These crops are staple food and significantly support the Zambian economy and livelihoods. Thus, a decrease in the prevalence of crop pests and diseases in this region would be advantageous for the development of new and existing production systems, and that of the agricultural sector in AEZ 1.

In AEZs 2 and 3, a relative increase in habitat suitability for Group B crop pests and diseases is projected under all RCPs. AEZ 2 is the most agriculturally productive area, with higher rainfall observed. It houses large commercial farming exploitations of maize, soybeans, wheat, cotton, tobacco, coffee, vegetables, and flowers that are vital for the country's economy; the zone also includes small- and medium-scale exploitations of maize, beans, groundnuts, rice, pumpkins, cassava, cotton, sorghum, soybeans, and sunflower. AEZ 3 is a high-rainfall area, and houses predominantly small-scale agricultural exploitations of cassava, landrace maize

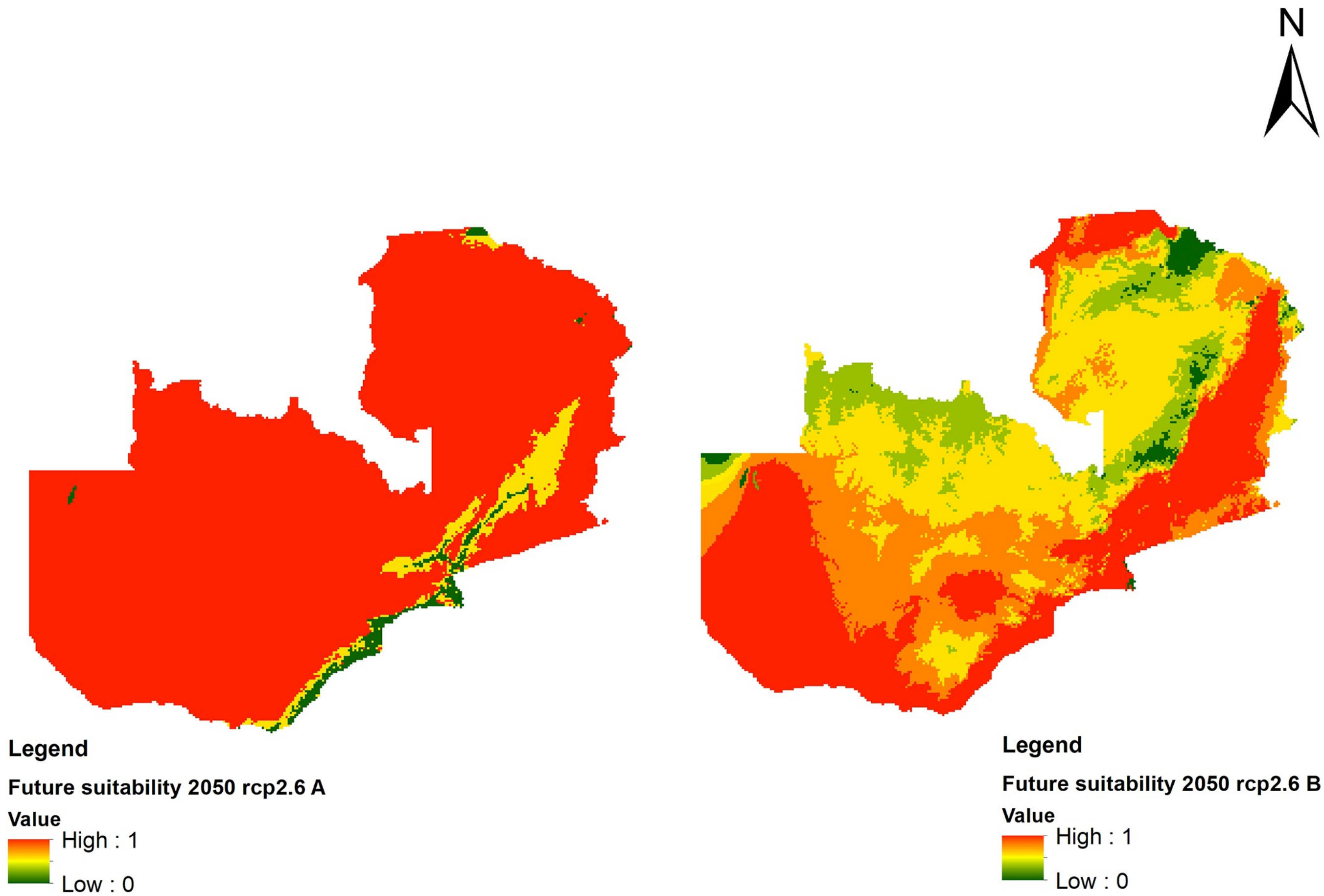

Fig 8. Future crop pest and disease habitat suitability distribution by 2050 under RCP 2.6. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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varieties, sweet potatoes, pumpkin, finger millet, and beans. Thus, given that AEZ 2 and 3 are pillars of the Zambian agricultural sector and economy, increases in Group B crop pests and diseases habitat suitability in these zones would negatively impact production as crops are destroyed and production costs rise due to the need for chemical pest control inputs.

3. Future pests' distribution of pests in Zambia for the 2050s

RCP 2.6 projections in the 2050s show a more pronounced decrease in habitat suitability for crop pests and diseases in both Groups A and B compared to the 2030s projections (Fig 8). The decrease in suitability will likely stem from the effective implementation of stringent emissions-reduction measures as proposed under this scenario, leading to reducing climate change impacts on the Zambian environment [71].

In the 2050s, RCP4.5 projections show a continued decrease in habitat suitability across Zambia for both groups of crop pests and diseases but at a lower rate than the decrease observed under RCP2.6 (Fig 9). This difference in rates can be attributed to stabilized yet unmitigated GHG emissions rates (as proposed under RCP4.5) impacting the environment less drastically than the measures reduction measures assumed under RCP 2.6.

In 2050, RCP8.5 projections show decreasing habitat suitability for Group A crop pests and diseases in Eastern Zambia in AEZ 1, as well as increasing habitat suitability for Group B crop

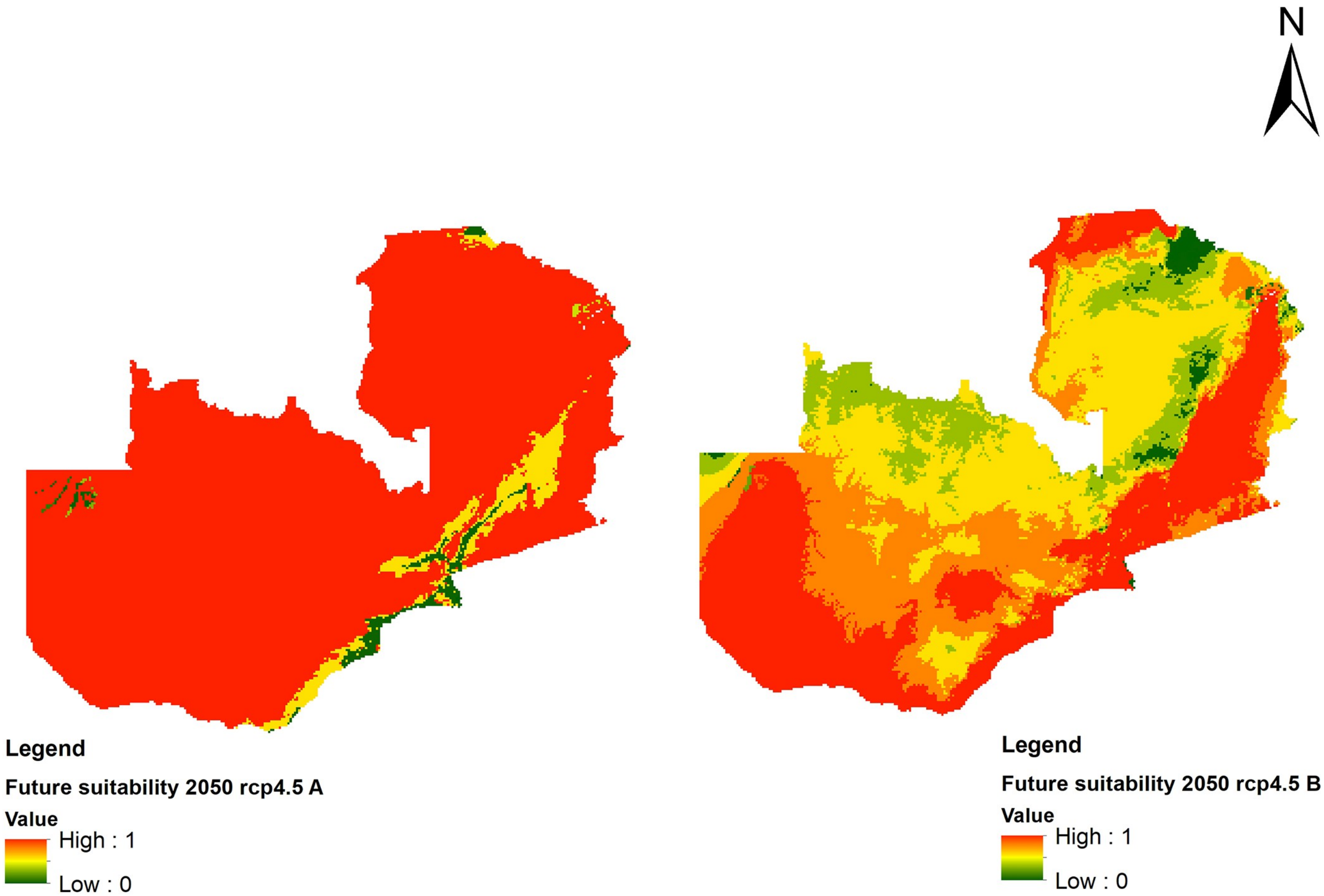

Fig 9. Future crop pest and disease suitability distribution by 2050 at RCP 4.5. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

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pests and diseases in AEZs 2 and 3 (Fig 10). The decrease in habitat suitability for crop pests and diseases in Group A could be attributed to adverse climate change effects as carbon emissions and temperatures are projected to rise in this scenario, making many areas less suitable for Group A pests and diseases proliferation. An increase in habitat suitability for Group B crop pests and diseases could result from the increased temperatures under this scenario that would have favored the development of these crop pests and diseases.

The projected increase in Group B crop pest and disease habitat suitability has significant implications for Zambia's agricultural economy. The increased suitability of Group B pests and diseases in AEZ 2 would negatively impact the production of the region's main food crops, namely rice, beans, soybeans, and groundnuts, all of which are affected by Group B species. This suggests that small- and medium-scale farmers in AEZ 2 would become more at risk from important yield losses. Such losses could also potentially affect commercial production systems, threatening Zambia's economy, and food security.

In the 2050s, a net decrease in climate change effects is expected, with an overall decrease in habitat suitability for our selected crop pests and diseases under RCPs 2.6 and 4.5 across the country. This suggests that under these scenarios, food production in Zambia will improve with the advancement of technologies targeting climate change remediation. However, projections under RCP8.5 show continued increases in habitat suitability for crop pests and diseases, similarly to and potentially worse than the 2030s projections.

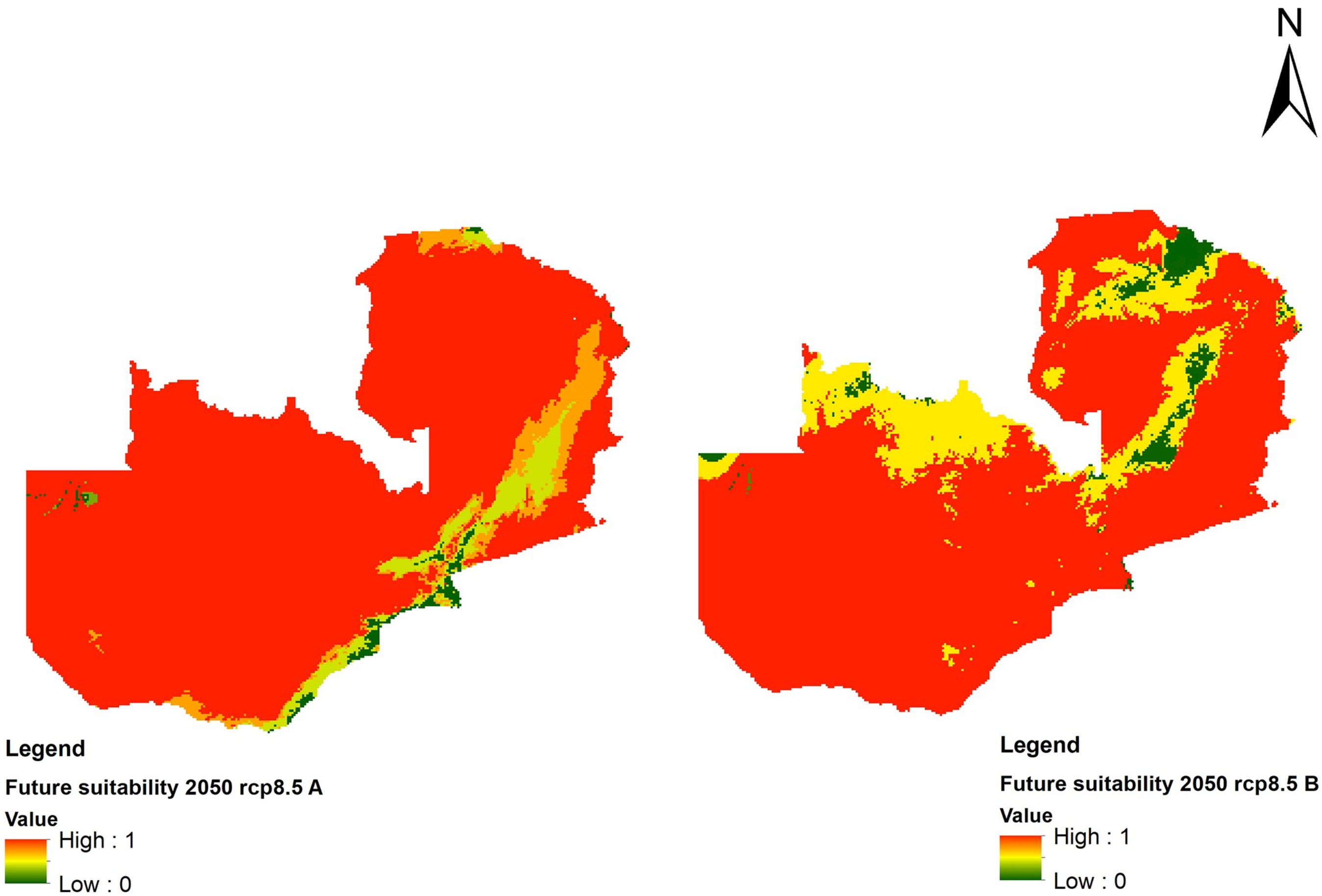

Fig 10. Future crop pest and disease habitat suitability distribution by 2050 under RCP 8.5. Base layer obtained from Global Administrative boundaries (http://gadm.org/).

https://doi.org/10.1371/journal.pclm.0000064.g010

General predictions on the impact of climate change on insect pests show that rising temperatures will lead to some species to shift their geographical ranges to higher elevations where the specific climate requirements essential for their growth, survival, and reproduction will remain available [72]. Thus, areas that are currently not suitable for our studied crop pests and diseases could become more suitable, leading to the introduction of non-native crop pests into new areas. This increased distribution and abundance of crop pests and diseases can lead to an increased incidence of crop destruction, crop disease outbreaks, pest resurgence, and crop pest resistance to non-chemical control measures; all of these will negatively impact agricultural production in Zambia. In turn, stifled agricultural production due to crop pest and disease damages will result in increased incidences of poverty and food insecurity. An effective integration of crop pests and disease control measure to climate action activities is hence essential to mitigate or avoid the negative effects of climate-enabled crop pest and disease proliferation on agricultural production.

4. Additional considerations for habitat suitability modeling results

An important consideration for this methodology was that other shifts could influence the modeled crop pest distribution patterns above in crop pest geographical distribution, namely species importation via human air or sea travel [73]. In fact, studies have shown that anthropogenic factors can influence disease vector occurrence and distribution [74]. However, within the scope of our study, local climate and environmental conditions were considered the primary determinants of habitat suitability for crop pests, including imported species, since suitable environmental conditions would still be required in new territories to permit imported pests' growth proliferation.

Another potential limitation considered in this methodology is that habitat suitability modeling is highly sensitive to sampling bias of the species occurrence, which is a common issue in disease distribution data [75]. This suggests that the crop pest habitat suitability findings that scientific literature is likely to pertain to the select pests and diseases that affect key crops and may not be generalizable to all known crop pests and their diseases. However, since the scope of our research spanned only the pests and diseases that affect select key crops for food security in Zambia, we believe this limitation will not affect the strong basis for this methodology.

This study focuses on predicting potential crop pest and disease prevalence and distribution based on long-term climate changes under three scenarios for the 2030s and 2050s. The effects of climate variability, and in particular, interest in predicting the prevalence of pests and diseases because of increases in unpredictable climate variation are not wihin the scope of this paper.

5. Policy environment for pest and disease control in Zambia

Crop pest and disease control has been established as a priority in Zambia's agricultural sector for decades, leading to a highly enabling environment for the adoption of innovative crop pest and disease control solutions. The Plant Pests and Diseases Act No. 13 of 1994 aims to achieve the following goals: (1) the eradication and prevention of the spread of plant pests and diseases in Zambia; and (2) the prevention of the introduction into Zambia of plant pests and diseases. The Act contained measures to prevent the spread of diseases affecting plants, including tubers, bulbs, corns, roots, cuttings, grafts, seeds, fruits, and non-processed plant products [76,77]. In 2011, Section 2.2.1 of the Zambia National Agricultural Policy 2012–2030 aimed to "promote sustainable increase in crop productivity". Although it did not explicitly promote Integrated Pest Management (IPM) as a crop pest and disease management option, the policy included aspects of IPM, such as conservation farming, by "promoting environmentally friendly farming systems" [78]. More recently, the Farmer Input Support Programme Electronic Voucher initiative launched by the Zambian Ministry of Agriculture in the 2015–2016 farming season provided Zambian farmers with access to a great variety of agro-inputs. Starting in 2016, in addition to fertilizer and seeds for maize production, farmers were able to exchange vouchers for herbicides, insecticides for their own crop choices, and application equipment such as sprayers. Such incentives have encouraged the use of synthetic pesticides by farmers [79]. Today, the promotion of good agricultural practices (GAPs) takes place under the current Zambia National Agricultural Investment Plan (NAIP 2014–2018), complemented by the second National Agricultural Policy of 2016. One aim of this plan relates to crop protection, specifically to promote GAPs, such as crop pest and disease control, fertilizer application, and weed management [78].

The Zambian Ministry of Agriculture prioritization of crop pest and disease control solutions in the sector highlights the importance of IPM for Zambian agriculture, and provides stakeholders with a framework that could utilize the findings of this study to enact location-targeted climate change mitigation activities. Additionally, the institutional dispositions stemming from the implementation of these policies represent an opportunity to promote new pest and disease control solutions in areas of high projected pest vulnerability such as AEZ 2.

Conclusion and recommendations

This study found that habitat suitability for the studied crop pests and diseases are likely to increase in the future, potentially destroying agricultural products and reducing yields. Group A crop pests and diseases, which include the cowpea aphid-borne mosaic virus (CAMV), red leaf blotch, bean rust, and anthracnose are distributed in all areas of Zambia and could cause worsened infestations by 2050. Future predictions show Group B pests and diseases—the Maruca pod borer, cowpea (weevil) seed beetle, leaf spots of cowpea, frogeye leaf spot, rice blast, African rice gall midge, armyworms, bean bruchids, groundnut aphids, early leaf spot, groundnut rosette, pod borers, and groundnut bruchids—could spread into the central and northwestern parts of the country, which are currently free from these pests. While climate change is not the only driving force responsible for the distribution of crop pests and diseases, it should be considered a key factor that influences the occurrence of suitable environments for the survival of these harmful species.

Results of this analysis highlight the potential role of environmental variables in driving the proliferation of crop pests and diseases. From 2020 to 2039, suitability modeling suggests that climate change will cause the increased distribution of pests and diseases that thrive in warm environments, as climate conditions become more conducive for their growth and development. Climate change will also result in reduced habitat suitability for crop pests and diseases that thrive in cool environments as temperatures increase. Between the 2030s and the 2050s, the RCP8.5 scenario in particular would see a continued increase in habitat suitability for crop pests.

Farmers, extension workers, and the Zambian Government can support efforts to reduce the spread of crop insect pests, as it would eventually overwhelm the current emergency response strategies for crop pests' control. Apart from the use of chemical control of crop pests and diseases, stakeholders have an opportunity to invest in other organic crop pest control methods, including biocontrol and the use of natural enemies of crop pests. Another opportunity for improved crop pest and disease control can be found in tree planting; planting trees to enhance microclimates is a viable method of mitigating the adverse effects of climate change. Certain tree species such as Mahogany and Neem may support the agricultural sector by: feeding into new agroforestry value chains; mitigating tree depletion due to illegal timber extraction; and providing biopesticides for sustainable control of crop pests and diseases. Additionally, combatting new crop pest and disease infestations through sustainable land-management practices is also an opportunity to support climate change mitigation activities. For instance, promoting practices such as intercropping and crop rotation (among other best agricultural practices and climate-smart agriculture activities,) would support farmers in their efforts to shield their assets from the adverse effects of new crop pest and disease infestations.

Opportunities for better pest and disease control in Zambia also include investing in methods that are already being used for crop pest and disease control in the country. These methods include planting pest and disease tolerant crop varieties; rotating legumes with cereals such as maize to break crop disease life cycles; planting crops early to enable growth before the build-up of disease in the environment and to help plants get passed the growth stage most susceptible to disease (four- to six-leaf stage) [80]; avoiding cross-contamination via infected equipment and clothing from one field to another; applying pesticides and fungicides; using natural enemies or beneficial organisms such as wasps, ants, spiders, wild birds, and chickens, who prey on crop pests' larvae; and intercropping legumes with plants that are attractive to these natural enemies. Advocacy for the promotion and development of these methods would support increased adoption by farmers, and would mitigate the projected negative effects of climate change on crop pest and disease distribution in Zambia.

Thus, this study points to the need for Zambia to expand its current efforts to address crop pest and disease control in agriculture, expanding from short-term response actions to adaptation and mitigation measures with a potential to reduce or prevent long-term effects of climate change.

Supporting information

S1 Table. Pests and diseases of Zambia occurrence and impact.
(XLSX)

S2 Table. Conducive environments for growth of selected pests and diseases in Zambia.
(XLSX)

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Author Contributions

Conceptualization: Caroline Mwongera.

Data curation: Wilson Nguru.

Formal analysis: Wilson Nguru.

Validation: Caroline Mwongera.

Visualization: Wilson Nguru.

Writing – original draft: Wilson Nguru, Caroline Mwongera.

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