

Potential impact of climate change on potato (*Solanum tuberosum*) crops and their main pathogens and pests in the Neotropical region of northern Andes

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Abstract

In regions vulnerable to climate change, ecosystems and agriculture face growing threats from droughts, temperature fluctuations, and floods, which harm crop yields. Climate change may also exacerbate the spread of crop diseases and epidemics, endangering food security, natural landscapes, and human health. Potato cultivation, crucial for global food security, requires a deeper understanding of climate change impacts to develop effective adaptation strategies. This study presents a novel analysis of climate change effects on potato cultivation and its interaction with key pathogens and pests in northern South America's Neotropical region, including *Phytophthora infestans*, *Ancognatha scarabaeoides*, *Liriomyza huidobrensis*, and *Tecia solanivora*. Using an interaction matrix and habitat suitability models, the prevalence of the crop and its aggressors was evaluated under short, medium, and long-term climate scenarios. Findings reveal that medium-term conditions for potato cultivation will decline but remain viable. However, the fungus *Phytophthora infestans* is likely to highly benefit from climate change, posing a significant threat to potato crops. In the long term, the climatic niche for late blight becomes less favorable, and potato cultivation conditions will also deteriorate, potentially rendering it economically unviable. This study highlights the urgent need for adaptive strategies to mitigate the dual challenges of climate change and pathogen pressure on potato farming.

Introduction

Many regions of Earth show accelerated changes related to climate. In regions that are more vulnerable to climate change, physical conditions, ecological and socioeconomic systems are losing resilience regarding these changes which unleash a series of problems, such as an increase in carbon dioxide (CO₂), frequent droughts and temperature changes, which pose a substantial obstacle for the yield of crops and food security. Consequently, many people and their means of subsistence are affected due to the tight interconnection between humans and natural vulnerabilities (Martin et al., 2022), (Subedi et al., 2023).

Likewise, the change in climatic averages and extremes has collateral effects on the societies and ecosystems on the planet. It is projected that climate change will be a multiplier of poverty, which means that it is expected that its impacts will make the poor poorer and that the number of people living in poverty will be more significant. On the other hand, the 0.5 °C increase in global temperatures that we have experienced within the last 50 years has contributed to changes in the distribution of plant and animal species, decreases in crop yields, and more frequent forest fires (Hoegh-Guldberg et al., 2022).

Climate change is expected to be one of the greatest threats to the integrity and stability of eco-systemic services, with possible direct and indirect impacts on society and human wellbeing given that, according to Manés & Vale (2022), climate change will potentially deplete many of these eco-systemic services, with provisioning among them (Provisioning—e.g., raw materials, food, and water) (Manes et al., 2022), due to this, there is global concern about how plants and ecosystems will respond and adapt to new environmental conditions provoked by global warming (Warren et al., 2018). In this sense, due to the strong dependence of agriculture on climatic variables such as temperature and the availability of water, mainly, (Bonifácio-Anacleto et al., 2024) any change or alteration in these variables may have an enormous influence on crop yields and productivity (Subedi et al., 2023). Climate change could be very unfavorable for agriculture, particularly in areas where crops grow under limiting temperature and/or hydric availability conditions. Thus, considering crops depend on water, among other aspects, any change in the precipitation regime and the occurrence of drought periods, in particular, would seriously affect productive systems, especially those in the Andean region, which are some of the most vulnerable. On the other hand, since the epidemiological development of infectious diseases attacks crops results from the interaction of three main factors: a conducive environment, a susceptible host, and a virulent pathogen (Mundt, 2009), The affectation will be greater if these attacking agents are favored by changes in climate conditions or if they move to habitats more adequate for their development. In this context, it is expected that climate change will have a substantial impact on epidemics and the ecology of diseases in plants (Zhan et al., 2018), which threatens, to a great degree, the food security, current natural landscapes, and human health (Myers et al., 2017).

Different authors have addressed these problems through the creation of models that look to identify the effects of climate change on important crops for community food security (Leng & Huang, 2017), (Xiao & Shi, 2023) [1]. Other models are focused on predicting the distribution of species such as plagues, weeds, pathogenic species and biological control agents concerning climate change (Subedi et al., 2023), (XIAN et al., 2023), (M. Victoria Lantschner & Corley, 2019); however, research that simultaneously approaches the effect of climate change on important crops for food safety and its aggressor organisms is necessary [2].

Concerning these problems, this study presents the first approach to understanding how climate change would simultaneously affect crops and organisms of agricultural and commercial importance. For this, models of habitat suitability were generated both for potatoes, as well as their scenario SSP370 (SSP stands for Shared Socioeconomic Pathway), which contemplates a forcing of 7 W/m² until 2100 and shared socioeconomic conditions of regional rivalry, inequality, and drastic environmental damage in some regions (Deutsches Klimarechenzentrum, 2022). Afterward, a spatial suitability analysis of crop habitats and their aggressor organisms was carried out through the categorization and intersection of habitat suitability models with the use of SIG tools (QGIS software,

Case study Nariño

Regarding food security, the potato crop (*Solanum tuberosum*) in Nariño is fundamental, as is the case for a large part of Colombia, since this department is the second producer of potatoes in the country, with around 30.482 planted hectares and an approximate production of 511.497 annual tons (ICA, 2021) and 21% of the national production in 2022 (Pulido et al., 2022). Therefore, knowledge about the possible affectation of climate change on the potato crop is fundamental for supporting the adoption of management, mitigation, and adaptation measures to the negative impacts of climate change on the agricultural production of the region.

Our research contributes to the knowledge of the impact of climate change on the *Solanum tuberosum* crop, exploring an unprecedented/unpublished method for simultaneously establishing the effect of interactions with organisms that affect the growth and production of this crop greatly, which is a pillar of the food security of the Andean-Amazonian region of the Colombian south, with regards to climate change.

Theoretical background and conceptual framework

3.1 Climate change models and scenarios

The Coupled Model Intercomparison Project (CMIP) is the comparison model design for improving knowledge about climate change. It was organized in 1995 by the Working Group on Coupled Models (WGCM) of the World Climate Research Program (WCRP) and makes available the information on the Coupled Model Intercomparison platform version 6 (CMIP6).

The CMIP6 platform or Project provides daily and monthly global climate projections from a great number of experiments, models, and periods calculated in the framework of the Project's sixth phase. These data support the Evaluation Reports of the Intergovernmental Panel on Climate Change (Copernicus Climate Change Service (C3S), 2022) and they provide estimates about future climate change (and its related uncertainties), as well as other aspects referring to the predictability of weather.

The CMIP6 contemplates experiments with historical data covering the period in which modern climatic observations exist (mainly between 1850 and 2005). These experiments show how Global Circulation Models (GCM) behave for past climate, and reference periods can be used to compare with future scenario projections.

Likewise, CMIP6 includes climate projection experiments that combine diverse Shared Socioeconomic Pathways scenarios (SSP) and Representative Concentration Pathway conditions.

The analysis by different scenarios is based on relevant scientific and political issues, as well as specific forcings such as the use of land and aerosols, the effect of a peak and a decrease in the forcing (in the radiation), the consequences of scenarios that limit warming below 2°C, the relative contributions to the uncertainty of scenarios, the climate models and internal variability, as well as the results from the long-term climate system of the XXI century (O'Neill et al., 2014), (O'Neill et al., 2016).

To work with a realistic scenario that reflects a future projection of the climate in the short, medium, and long term in the Andean region with Good probabilities, it was taken into account, among other things, that despite the goals of the Paris Accord (2016) aim: "to reduce greenhouse gas emissions substantially to limit the increase of global temperature in this century to 2°C and make an effort to limit this increase to only 1.5°C", there are no evident signals of political will both at a global and local level, of accomplishing these goals. It was also considered that, in Colombia, for example, and in most of the signatory countries to the agreement, only the measures that try to achieve carbon neutrality by 2050 are being considered; that is, emissions will continue their course despite that science is warning that carbon emissions to the atmosphere should be reduced drastically and immediately. Additionally, current events (2023-2024) such as conflicts and wars in the planet tend to intensify.

As a result, for this research scenario SSP370 was. It best represents the current socio-political reality since it foresees the shared socioeconomic conditions of regional rivalry that put global problems in the background (O'Neill et al., 2016).

In this scenario, policies are evermore centered on national and regional security matters. Education and technological development investments decrease, inequality increases, and some regions suffer drastic environmental damage. The SSP370 scenario considers a forcing of the radiation of 7 W/m² for the year 2100 and is found in the medium-high part of the complete range of scenarios (O'Neill et al., 2016). This was recently introduced to adjust the scenarios considered in the previous phase of the CMIP project. It is a scenario with a substantial change in the use of the land (particularly, a decrease in the global forest coverage) and high emissions of near-term climate forcers (NTCF) (particularly SO₂) and also, SSP3 (combined with this forcing route) is especially relevant for integrated evaluation models and for the impacts, adaptation, and vulnerability, because it combines a relatively high social vulnerability (SSP3) with a relatively high forcing (O'Neill et al., 2016).

Under this scenario, bio-climatic data were obtained from the updated climate model GISS-E2.11 of the Goddard Institute for Space Studies (GISS) of the National Aeronautics Space Administration (NASA) (NASA Goddard Institute for Space Studies (NASA/GISS), 2019), with which we worked to model the suitability of the habitat in the different species that are the subject of study of this research.

3.2 Ecological niche modeling

One of the greatest difficulties in determining the current distribution of a species is obtaining the data of areas with an absence of the species; this problem is severe in tropical regions where adequate sampling has not been done (R. Anderson et al., 2002). In order to solve said difficulty, the current classification of soil coverage derived from remote sensor data can be used to exclude very altered habitats (R. P. Anderson & Martínez-Meyer, 2004), (Phillips et al., 2006a). This premise is applied by the methodology of maximum entropy employed by the Maxent model.

3.2.1 Maxent

Maxent is a general-purpose method for making predictions or inferences from incomplete information. Its origins are found in statistical mechanics (Phillips et al., 2006a). The MaxEnt software package, developed by Phillips et al. (2006) was created for the application of this method, which is particularly popular in the modeling of environmental niches/species distribution, with more than 1000 applications published since 2006 (Merow et al., 2013), (Burrows et al., 2022).

The purpose of Maxent is to estimate a target probability distribution, finding the probability distribution of maximum entropy, subject to a set of restrictions that represent incomplete information over the target distribution (Phillips et al., 2006a).

The available information on the target distribution is often represented as a set of real-value variables called “characteristics,” the restrictions are that the expected value of each characteristic must match its empirical average (the average value for a set of sample points taken).

In this way, the mode for a species is determined from a set of environmental or climate characteristics for a set of cells or fan areas, together with a set of sample locations where the species has been observed. The results of the modeling express the suitability or aptitude of each cell to host the species. A high value in a grid cell in particular indicates that it is predicted that the cell will have adequate conditions for that species (Phillips et al., 2008). The calculated model is a probability distribution over all the grid cells and the chosen distribution is the one that has the maximum entropy subject to some restrictions: it must have the same expectation for every characteristic (derived from the environmental layers) as the average of the sample locations.

Maxent has shown to have a Good performance and shows various advantages as it only needs presence data, it allows to show the results of the model in different maps, it allows to quantify the importance of each variable through a jackknife test, it allows the use of continuous or categorical value variables and it allows to re-project the potential distribution in other spaces or regions and throughout time (Elith et al., 2006); (Qiao et al., 2015); (Wei et al., 2018), (Molinos et al., 2017); (Charre-Medellín et al., 2019).

3.2.2 Spatial analysis

Spatial analysis, which in its broadest sense can be considered as the analysis of spatial and non-spatial information of phenomena in spatial or spatial-temporal systems as an aid to their description, explanation and prediction, and involves a series of steps for the verification, valuation, evaluation and modeling of the characteristics of special data (Fischer & Nijkamp, 1992), (Agoha et al., 2024). Spatial analysis aims to convert unprocessed spatial data into meaningful information that can be used for decision-making. This implies the use of methods like mapping, spatial statistics, and Geographical Information Systems (GIS) for examining relations, patterns, and tendencies in the data (Agoha et al., 2024).

3.3 Harmful biological interactions for the potato crop (*Solanum tuberosum*)

The potato crop can be affected by many types of biological agents that are natural to the mountain agricultural ecosystems in the north of the Andes. Among the important ones are insects, fungi, bacteria, nematodes, and viruses. These wild populations feed directly from and/or affect structures such as leaves, stalks, or tubers, directly impacting the growth of plants. These crop plagues or pathogens can also cause rotting or malformations that affect the commercial attractiveness and yield of the harvests and the general quality of the tubers, creating an important economic impact (Egúsquiza, 2013).

Even though the documented diversity of biological factors that affect the *Solanum tuberosum* is broad, in this study we focus on the four more common population models whose presence and affectation in the department of Nariño is well documented, with robust and significant information in the databases of biological and geographic records in the neotropical region: *Phytophthora infestans* (mushroom gout, or tardive smut), *Ancognatha scarabaeoides* (beetle larva, or potato botfly), *Liriomyza huidobrensis* (Potato mining fly, and *Tecia solanivora* (Guatemalan moth, potato moth, puss moth).

Methodology

This study generated habitat suitability models for the potato and its most common aggressors in this context. Models were generated for future climate periods from 2024 to 2040 (short-term), 2041 to 2060 (medium-term), and 2061 to 2080 (long-term) under the SSP370 climate change scenario (Shared Socioeconomic Pathway), which contemplates a forcing of 7 W/m² until 2100 and shared socioeconomic conditions of regional rivalry, inequality, and drastic environmental damages in some regions (Deutsches Klimarechenzentrum, 2022).

The habitat-suitability models were created with the maximum entropy methodology, through the MAXENT software (Phillips et al., 2006b), whose objective is to estimate a target probability distribution by finding the maximum-entropy probability distribution, subject to a set of restrictions that represent incomplete information about the target distribution. Bio-climate data from the GISS-E2.1H of NASA (NASA Goddard Institute for Space Studies (NASA/GISS), 2019) Project were employed, biodiversity data (presences) from the Global Biodiversity Information Facility (GBIF) (GBIF, 2022) platform, and localization data of the potato crops in Nariño, provided by the CONTACTAR (CONTACTAR, 2022) corporation, as well as topographical surveys. Through the QGIS software (QGIS 2022), numerical values on habitat suitability provided by the models were re-classified into the following categories: *Inadequate*, *Deficient*, *Good*, *Optimal*, and *Ideal*, both for crops as well as for aggressor species. Afterward, crop and aggressor organism models were overlaid to categorize the results of inter-relationships of habitat adequacy as *Critical*, *Unfavorable*, *favorable*, and *Very favorable* for the crop, with which it was possible to carry out the crop/organism interaction analysis (Fig. 1) for current conditions, and at the short, medium, and long term and elaborate the corresponding maps.

The processing of bioclimate data provided by the CMIP6 platform, as well as the results of habitat suitability models through Maxent, was carried out through the QGIS 3.30 geographical information system tools. This tool allowed for the classification of numerical values for habitat suitability in the categories: *Inadequate*, *Deficient*, *Good*, *Optimal*, and *Ideal*, for the crops and aggressor species. Likewise, numerical values were categorized for the results of the interactions as *Critical*, *Unfavorable*, *Neutral*, *Favorable*, and *Very favorable*, which allowed us to describe, analyze, and better explain the predictions for future scenarios.

Results

5.1 Modeling of the niche for *Solanum tuberosum*

The potato's niche-modeling data reflect ideal crop conditions (23% of the Department's area) in a wide range of Nariño's Andean region. Concerning the short-term SSP370 scenario, the results show an increase of the area in ideal conditions (25.8%) for the development of the plant, especially for the tuberization process that occurs with temperatures between 14 and 22°C. In this scenario, growth for the potato crop in Nariño can be evidenced in the range of optimal occurrence. However, in the following twenty years of climate evolution, that is, medium-term (2041-2060), ideal conditions of occurrence for the crop reduce considerably, and in a somewhat rapid way in practically the entire Andean region of Nariño. In the long-term (2061-2080), a dramatic scenario of a total loss of adequate conditions for the harvest of *Solanum tuberosum* is presented (Figure 2 and Graph 1).

5.2 Models for biotic agents of agricultural importance.

The biological characteristics of different organisms that interact with potato crops produce contrasting responses for the presence and ecological consolidation of the crops. Thus, the generated model shows that in some areas, in the long term (2060-2080), the Andean region of the department of Nariño would turn into an ideal habitat for fungi populations such as *Phytophthora infestans*, which causes gout or late blight disease, as well as for the lepidopteran *Tecia solanivora* (the potato moth) (see Figure 3 *Tecia* model, as an example of the maps). In both cases, the projection of the ecological niche in the short and medium term presents a stable trend where the range of availability of ideal habitats for the species remains more or less constant with minor geographic variations. However, the long-term climatic scenarios show a prosperous panorama,

where, especially in the case of the potato moth, the entire Andean area of the department will have ideal conditions for its establishment and proliferation. In the long term, *Phytophthora infestans* would have good to optimal climatic conditions in the areas of interest for the present study.

In the case of *Ancognatha scarabaeoides* (beetles), the tendency is more or less stable in the short and medium term (Figure 4b and 4c). However, in the long term, the reduction of the potential habitat for this species is very evident (Figure 4d). Nevertheless, the occurrence of this insect in potato crop areas shows relative stability despite the climatic variations. For this reason, their populations must be considered as one of the risk factors for the production of the potato crop in the Department, although unlike the fungus or the Guatemalan moth, the habitat would tend to decrease the beetle's potential niche in the long-term. This panorama for the beetles does not take into consideration that, both in the medium and long term, the availability of good places for the growth of its host, *Solanum*, would reduce drastically.

The mining population, *Liriomyza huidobrensis*, shows greater resilience regarding their potential niche's answer to the climatic scenarios considered in this study. The habitat suitability for this species in Nariño's potato crop areas remains stable in the range Good for the areas of interest. Unlike the case of beetles, which can maintain a good to optimal habitat until 2050,

5.3 Crop interactions with the fungus and the insects

When we consider the interactions between the ecological niches of the potato crop and its main pathogens and plagues, we can see a highly contrasting response since there are organisms with very particular lifestyle strategies where ecology, physiology, and metabolism establish a peculiar susceptibility to climatic variability:

5.3.1 *Solanum tuberosum* vs *Phytophthora infestans*

The spatial analysis shows that the pattern of potential-niche overlapping for the plant and the fungus that causes late blight or late blight *Phytophthora infestans* (figure 5) reflects an intensification of interactions (infections), particularly in the short-term scenario, which means, in terms of the next 20 years or less, especially in the areas of marginal distribution of the optimal niche for *Solanum tuberosum*. The general conditions might favor the fungi slightly, considering the overlapping of climatic niches in current times (Figure 5 a and b). This is despite the high level of sensitivity of fungi to environmental and particularly climatic factors.

In the medium term, the analysis showed that for the *Solanum tuberosum* crop, the niche conditions are deficient, but still habitable, while for the late blight fungus (*Phytophthora infestans*) the conditions are optimal, therefore, an interaction between these two species would be unfavorable to *Solanum tuberosum* and may pose a notable risk for the productivity of its crop. Nevertheless, in the long term, the conditions of the climatic niche for the late blight fungus are unfavorable. However, they would not be for sowing *Solanum tuberosum* at profitable productive levels.

5.3.2 *Solanum tuberosum* vs the insects

Regarding the relationship of the potential niches of the Guatemalan moth or the *Tecia solanivora* potato moth, in the short term, that is, in less than 20 years, thermic variations in high mountain conditions that limit the activity of the insects could, in general terms, create a rather beneficial relationship for the crop (Figure 6 a and b).

Nevertheless, medium and long-term scenarios show how this herbivore could have evermore adequate conditions for its proliferation, meaning that the ideal conditions for the infestation of crops by moth would be given for it to be a factor to be considered beyond purely climatic effects that the potato crop would face in this region of the north of the Andes, where, under this scenario, potatoes would be almost uncultivable and where herbivore insects such as the *Tecia solanivora* could proliferate more efficiently (Figure 6 c and d).

This is how, by the end of this century, most of the Andean region of the department of Nariño will have optimal conditions for the occurrence of insects, which benefit from greater temperatures, which favor their activity and metabolism with *Tecia solanivora*.

The tendency described for the moth is consistent with the overlapping pattern of niches for both species of insects studied, Ancognatha scarabaeoides and Liriomyza huidobrensis. Nevertheless, the effects of the decrease in the optimal range of climatic niche for the beetle, in the long-term climatic scenario also present notable restrictions, with a relict and fragmented distribution (Figure 7 c and d), as well as for the potato-mining fly (Figure 8 c and d).

Discussion

Our results from the long-term model suggest that the conditions of the climatic niche are not very favorable for the *Phitophthora infestans* fungus as well as for the cultivation of *Solanum tuberosum* in profitable production levels, which is congruent with the conclusions of Wilches Ortiz et al., (2022) in the sense that the gout epidemic in the *Solanum tuberosum* crop could be reduced before the possible climate change scenarios in which high temperatures ($\geq 23^{\circ} \pm 1^{\circ} \text{C}$) are present since the maximum temperature was a climatic variable that presented a negative relation to the development of the disease (Wilches Ortiz et al., 2022).

These recent studies suggest that while global warming in high latitudes would favor the production of *Solanum tuberosum*, in tropical and subtropical regions, it would have a negative effect (Wilches-Ortiz et al., 2022; Hijmans, 2003), which is consistent with our results for the modeling for the climatic niche. Warming in mid and high latitudes will allow for the extension of the growth season of the potato crop, thus favoring its cultivation in countries like Canada and Russia, because the sowing season could be anticipated and increase the number of cycles in a season. Contrarily, in regions closer to tropical zones, the plant's cultivation will be more unfavored, and yields could be reduced by up to 50% (Hijmans, 2003) according to recent analyses. In fact, during the last seasons, with drought and high temperatures, 130.000 hectares were affected in Colombia, causing losses of up to 50% (Wilches-Ortiz et al., 2022).

For its part, the International Potato Center (CIP, for its acronym in Spanish) has suggested that the sustained increase in temperature is exerting a high selection pressure on wild potatoes; close to 20% of them are at risk of going extinct by 2055. Likewise, studies by the CIP in the last ten years, based on surveys of potato producer and satellite images, reveal that during the last 30 years, Peruvian agricultures of Andean zones have had to move their crops to areas of greater latitude (Wilches-Ortiz et al., 2022). This is to escape the increase of disease and plagues due to the thermic increase. However, if climate change continues this rhythm, potato producers will not have land at higher latitudes to cultivate (CIP, 2012). Thus, changes in plague cycles and diseases are also projected with temperature changes. In *Solanum tuberosum*, the incidence of pathogens like tardive smut, virus vectors, and nematodes will be accentuated. For example, in Europe, an earlier attack of the tardive smut, an increase in the number of cycles by season for some nematodes, and a greater incidence of aphids are projected. In Chile, this type of response is also observed in the potato crop (Wilches-Ortiz et al., 2022). Based on the temperature, this climate change scenario for the next 50 years projects that the potato crop will experience a decrease in its yield, between 18 and 33% if the necessary adaptation measures are not taken regarding the new scenario. However, these losses could be significantly less – up to 9%- if adaptation measures are implemented (Hijmans, 2003; Schafleitner et al., 2011).

The scenario chosen to obtain the data for the future bioclimatic variables for this research was the ESPP 370, which best represents the current socio-political reality; however, the scenario could change in the future to better or worsen the current environmental situation. Therefore, it is necessary to recognize the need to create models for the other scenarios available in the CMIP6, which would make it possible to have a broader scope and more information for decision-making.

On the other hand, since future climate changes involve more than increases in temperature and alterations in precipitation patterns (Bonifácio-Anacleto et al., 2024), it is essential to broaden the reach of the investigations, consider other relevant

factors in the crop models, such as soil adequacy, and study other important bioclimatic variables for each particular species.

From the agro-systems point of view, the establishment and consolidation of organisms (plants, animals, microorganisms) depends on the expression of many interactions that go beyond those linked to purely physical variables (temperature, precipitation, relative humidity, etc.), for which it is necessary to consider the association and coexistence with predators, herbivores, and even human action as limiting factors. Also, it is vital to study the presence of pollinizers, dispersers, and natural enemies of plagues and crop diseases. These aspects are also of great significance for creating more realistic and precise models about the impact of climate change since they can facilitate the establishment of species in the ecosystem. In this measure, it is recommendable not only to broaden the investigation to other agro-systems and other geographical areas but also to include ecological variables in the analysis, which can improve the reach and robustness of future models.

Studying the interaction of ecological niches of crops and their biotic interactions of agricultural interest through spatial analysis (intersection) and suitability categories is the first approach to jointly observe the affectation of crops regarding climate changes and fungi, insects, and other organism affectation. However, despite that the most important variables are considered, it may not be enough...

It is necessary to continue investigating climate change's effects on future food security, including studying whether climate change increases the number and type of plagues that attack crops. The natural hypothesis might be that the productivity of these crops decreases ostensibly, but what happens if the number of plague predators also increases? Also, because some cultivation regions expand and others reduce, it is difficult to predict the destiny of certain foods.

Conclusion

The methods employed in this study allow for studying the possible affectation of the habitat of potato crops in the department of Nariño, starting from the increase in temperature and the precipitation variation due to climate change, through the relation of climate changes and the future suitability of the habitat for this species and its most important aggressor organisms.

The niche modeling data for *Solanum tuberosum* reflect very favorable current conditions for the establishment of the species in a broad range of the Andean region of the department of Nariño because, in all municipalities of Andean influence, appropriate altitudinal and climate ranges exist that are appropriate for the development of the plant and especially the process of tuberization. In the short-term, that is, an Interval of less than twenty years, if the climatic tendency continues and particularly the increase in temperature, the ideal conditions of the environmental niche would be favored and even increase the range of optimal occurrence for the cultivation of potatoes in the department of Nariño. Nevertheless, in the following years of climatic evolution, that is, in the medium-term (2041-2060), according to the simulation models, the climatic conditions appropriate for the crop reduced considerably in practically all of the department's Andean region. The long-term niche projection data of 2061-2080 show a dramatic scenario of loss of adequate conditions for the establishment of *Solanum tuberosum*.

The overlaying pattern of potential niches for the potato and gout or tardive smut-causing fungus *Phytophthora infestans* shows that in the next 20 years, more or less, the general conditions will favor the pathogen more, with regards to the current scenario, despite the high degree of sensitivity of the fungi to environmental and particularly climatic factors. In the medium term, the interaction between niches shows deficient but still habitable conditions for the potato since the optimal conditions for the fungus could prevail, constituting a latent risk for the crop. Nevertheless, in the long term, the conditions for the gout-causing fungus do not notably support their presence.

Regarding the relationship of the potential niches of the *Tecia solanivora* Guatemalan moth or potato moth, the situation of this insect differs regarding the relationship with the gout fungus. In the short-term, that is, less than 20 years, thermic variations in high mountain conditions, which limit the activities of the insects, could promote a more beneficial relationship

for the crop regarding moth occurrence. Nevertheless, medium and long-term scenarios show how this herbivore could have evermore adequate conditions for its proliferation, that is, the ideal conditions for moth infestation to be an essential factor would be provided.

A similar situation is given in the case of the *Ancognatha scarabaeoides* (Beetle larva, beetle, or potato botfly) and *Liriomyza huidobrensis* (potato mining fly) insects. Nevertheless, in the long-term climatic scenario, the decrease in the optimal niche range for the beetle also presents notable restrictions, with a relict and fragmented distribution, as for the potato mining fly.

Scientific efforts to predict, with decades of anticipation, how agriculture will change are of priority. Thus, scientists can help farmers know what to expect and can advise the responsible politicians on how to motivate them to use more efficient cultivation methods, such as the use of cover crops to avoid erosion or plantation rotation of new crops when necessary.

Declarations

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Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval/declarations:

This research does not used any human or tissue as experimental subjects.

Consent to participate:

The authors declare that they have voluntarily participated in the research.

Consent for publication:

The authors give consent for information about themselves to be published in the Theoretical and Applied Climatology

Availability of data and material/ Data availability:

The datasets generated during and/or analysed during the current study are available in the [Climatic_impact_solanum-pests] repository, https://zenodo.org/records/14680530?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6ImU4ZWVhNmM2LWJmMWMtNDc0ZS1hNTQ1LWQxMWMxM2U0Nzk2MSIsImRhdGUiOiJ9LCJyYW5kb20iOiJiYjhmNzNmMWIwNjQzZW00DE2NzYwN2FMDMzNzA5MyJ9.GW5nPhh6Cpwd8E1tKZnpqgtTE-YfBJ4WqLJPWnD53bftRa-0ptXwpTbIPGuRTMUGZ_LNar2HFCfMXqkJHwumXg

Authors' contribution

R. C.: Methodological development, climate data processing, generation and analysis of habitat suitability models, analysis of results, writing and editing of the manuscript.

A. G.: Biological study of the species *Solanum tuberosum*, *Phytophthora infestans*, *Ancognatha scarabaeoides*, *Liriomyza huidobrensis* and *Tecia solanivora* and analysis of model results.

G. C.: Model review, results analysis and resource management.

All authors contributed to the study conception and design

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Footnotes

1. The special edition of the Agricultura magazine “Modeling the Adaptation of Agricultural Production to Climate Change (MAAPCC)”, compiles a number of investigations on the evaluation of climate change impact on the production of crops, among other aspects (Xiao & Shi, 2023).
2. A revision of the available literature on SDM for plagues, weeds, pathogen species, and biological control agents can be found in Lantschner et al. (2019).

Graph 1

Graph 1 is available in the Supplementary Files section.

Figures

		Crop				
		Inadequate	Deficient	Good	Optimal	Ideal
Aggressor organism	Ideal	Critical	Critical	Unfavorable	Neutral	Neutral
	Optimal	Critical	Critical	Unfavorable	Neutral	Neutral
	Good	Critical	Critical	Neutral	Favorable	Very favorable
	Deficient	Unfavorable	Unfavorable	Neutral	Favorable	Very favorable
	Inadequate	Unfavorable	Unfavorable	Neutral	Favorable	Very favorable

Figure 1

Crop vs aggressor organism interaction matrix

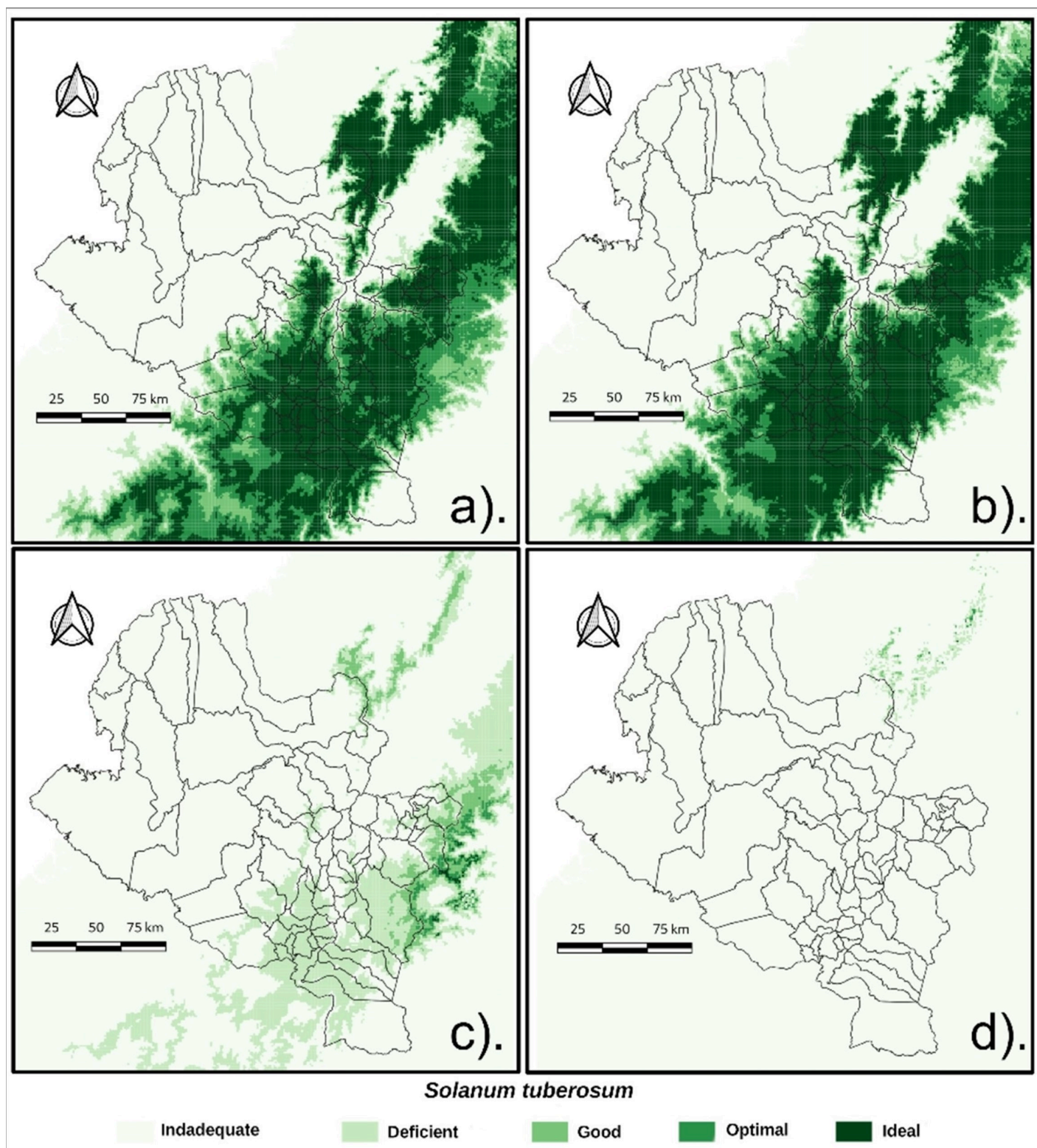


Figure 2

Habitat suitability for *Solanum tuberosum* in different climate scenarios: a) current time, b) short-term (2023-2040), c) medium-term (2041-2060), d) long-term (2061-2080)

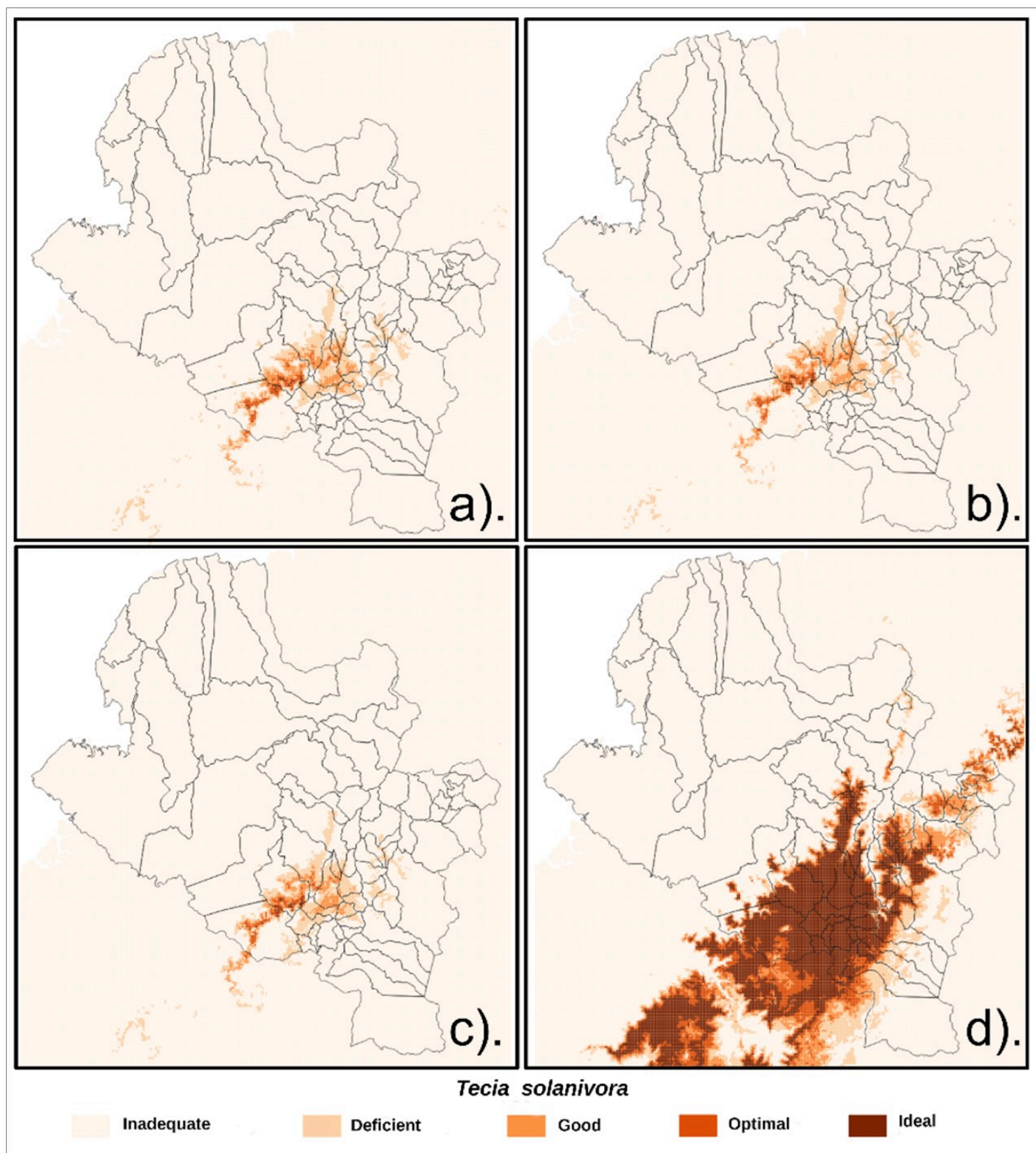


Figure 3

Habitat suitability for *Tectia solanivora* (potato moth) in different climatic scenarios: a) current time, b) short-term (2023-2040), c) medium-term (2041-2060), d) long-term (2061-2080).

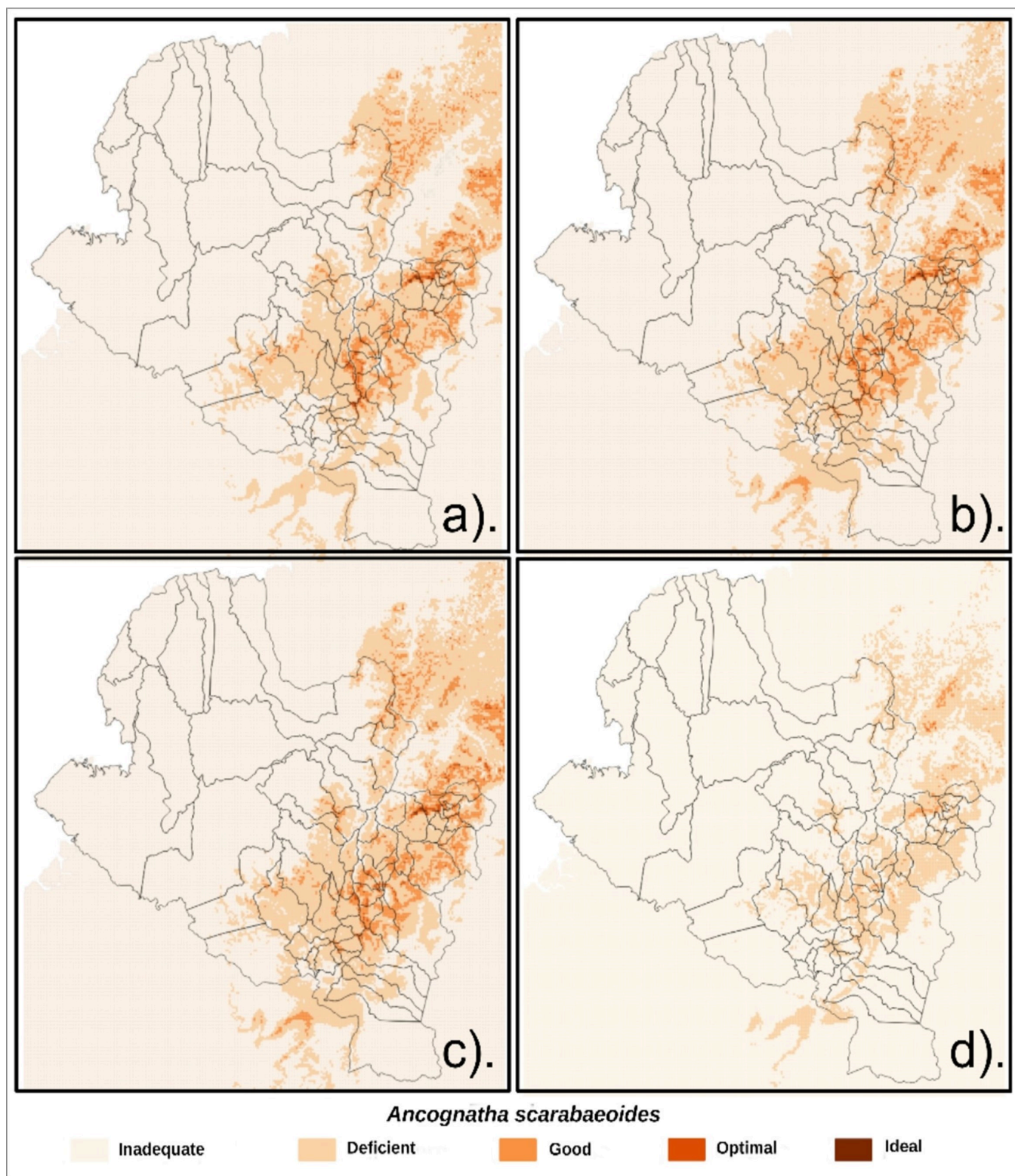


Figure 4

Habitat suitability for *Ancognatha scarabaeoides* in different climatic scenarios: a) current time, b) short-term (2023-2040), c) medium-term (2041-2060), d) long-term (2061-2080).

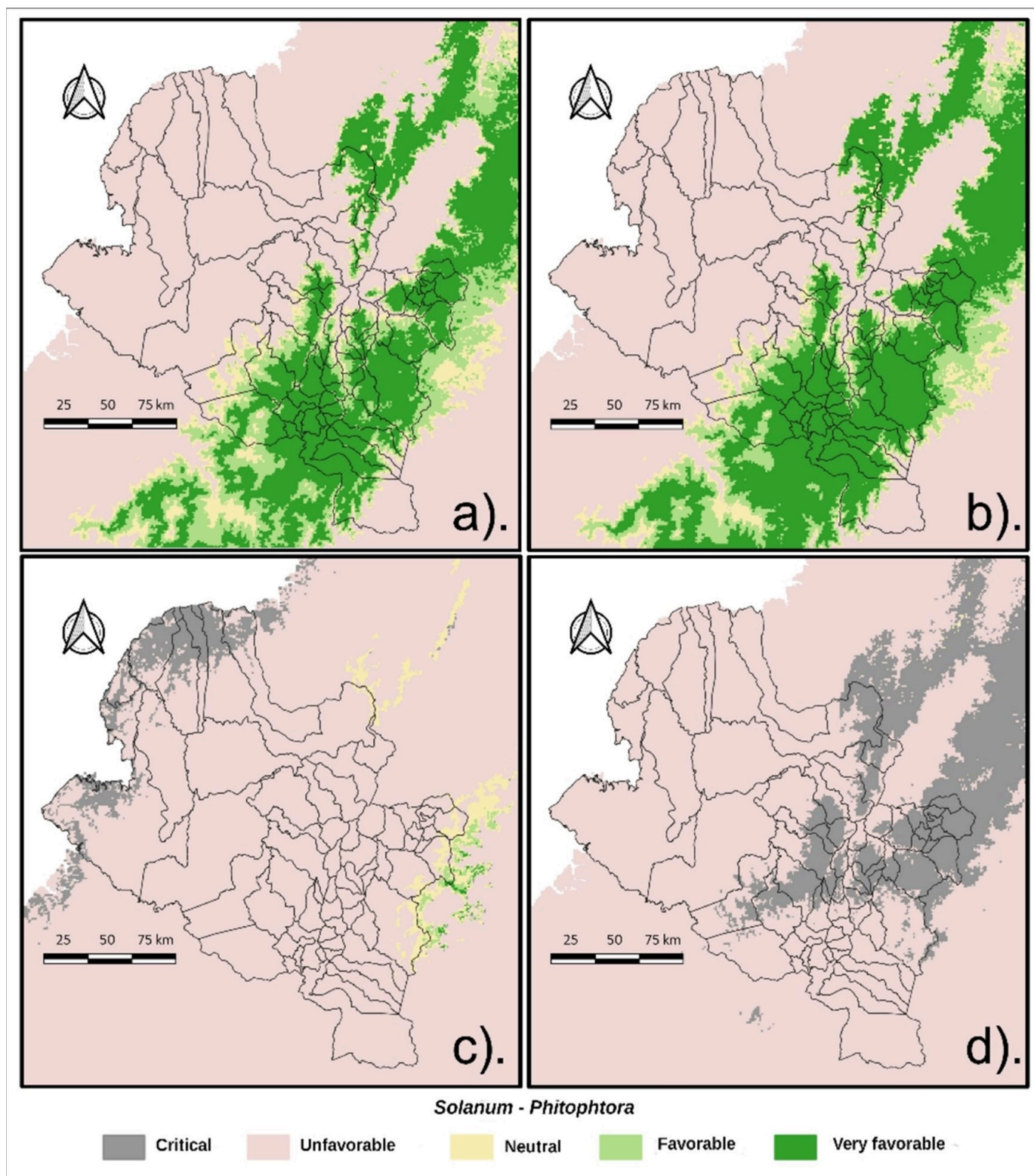


Figure 5

Interactions with the habitat suitability for *Solanum tuberosum* Vs *Phytophthora infestans* (gout fungus) in different climatic scenarios: a) current time, b) short-term (2023-2040), c) medium-term (2041-2060), d) long-term (2061-2080).

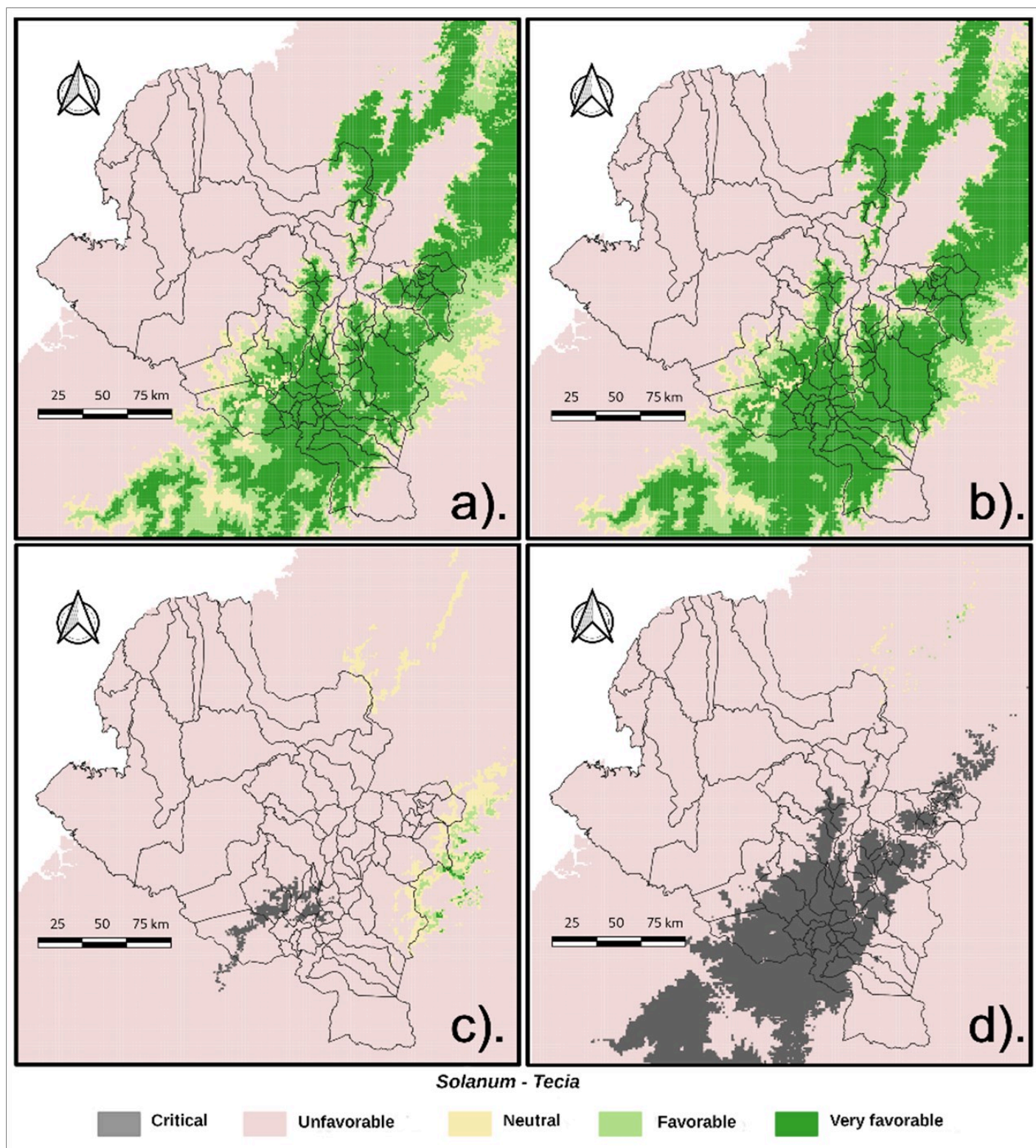


Figure 6

Interaction of habitat suitability for *Solanum tuberosum* Vs *Tecia solanivora* (potato moth) in different climatic scenarios: a) current time, b) short-term (2023-2040), c) medium-term (2041-2060), d) long-term (2061-2080).

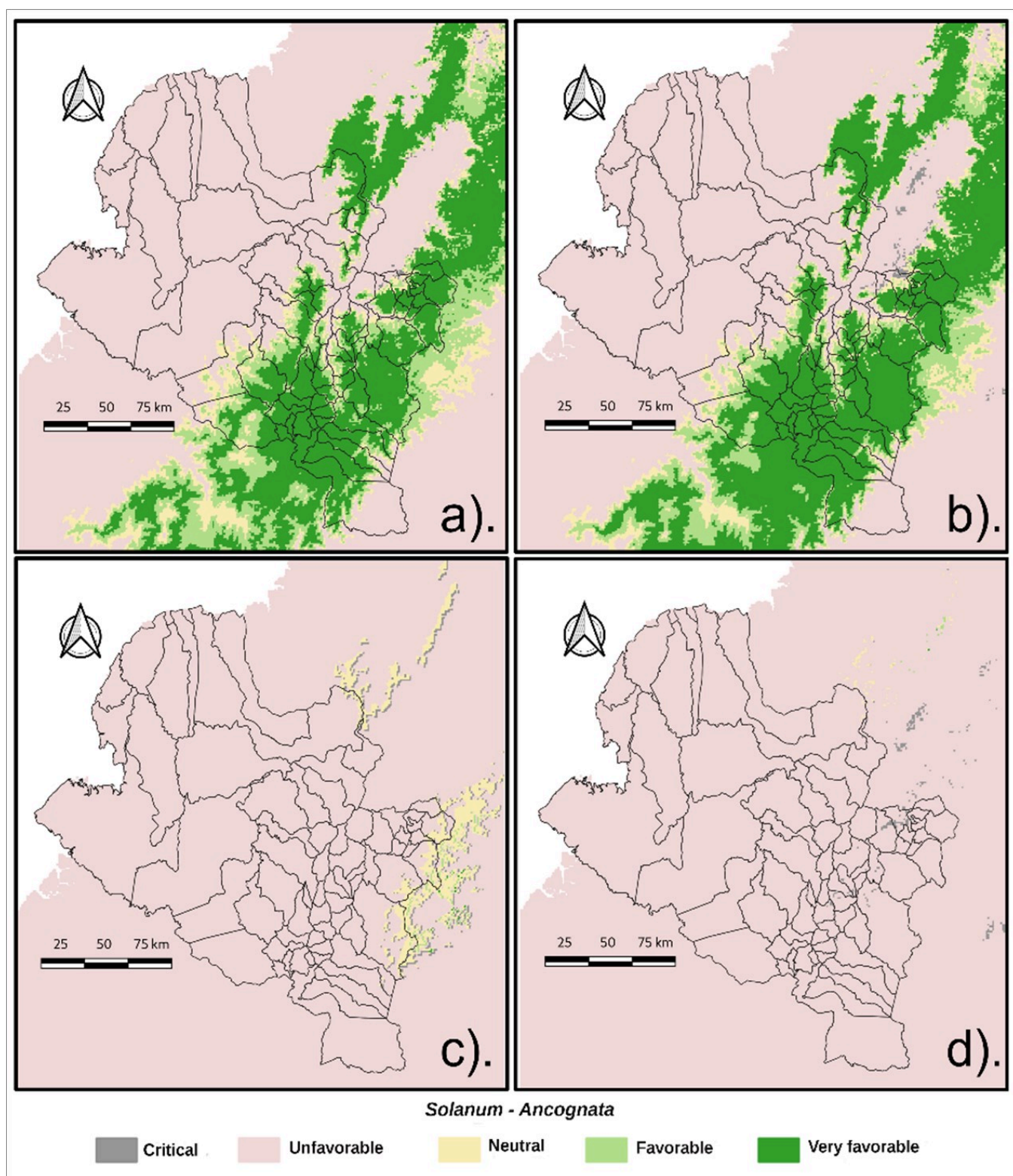


Figure 7

Interaction of the habitat suitability for *Solanum tuberosum* Vs *Ancognatha scarabaeoides* (Beetle larva, beetle or potato beetle in different climatic scenarios: a) current time, b) short-term (2023-2040), c) medium-term (2041-2060), d) long-term (2061-2080).

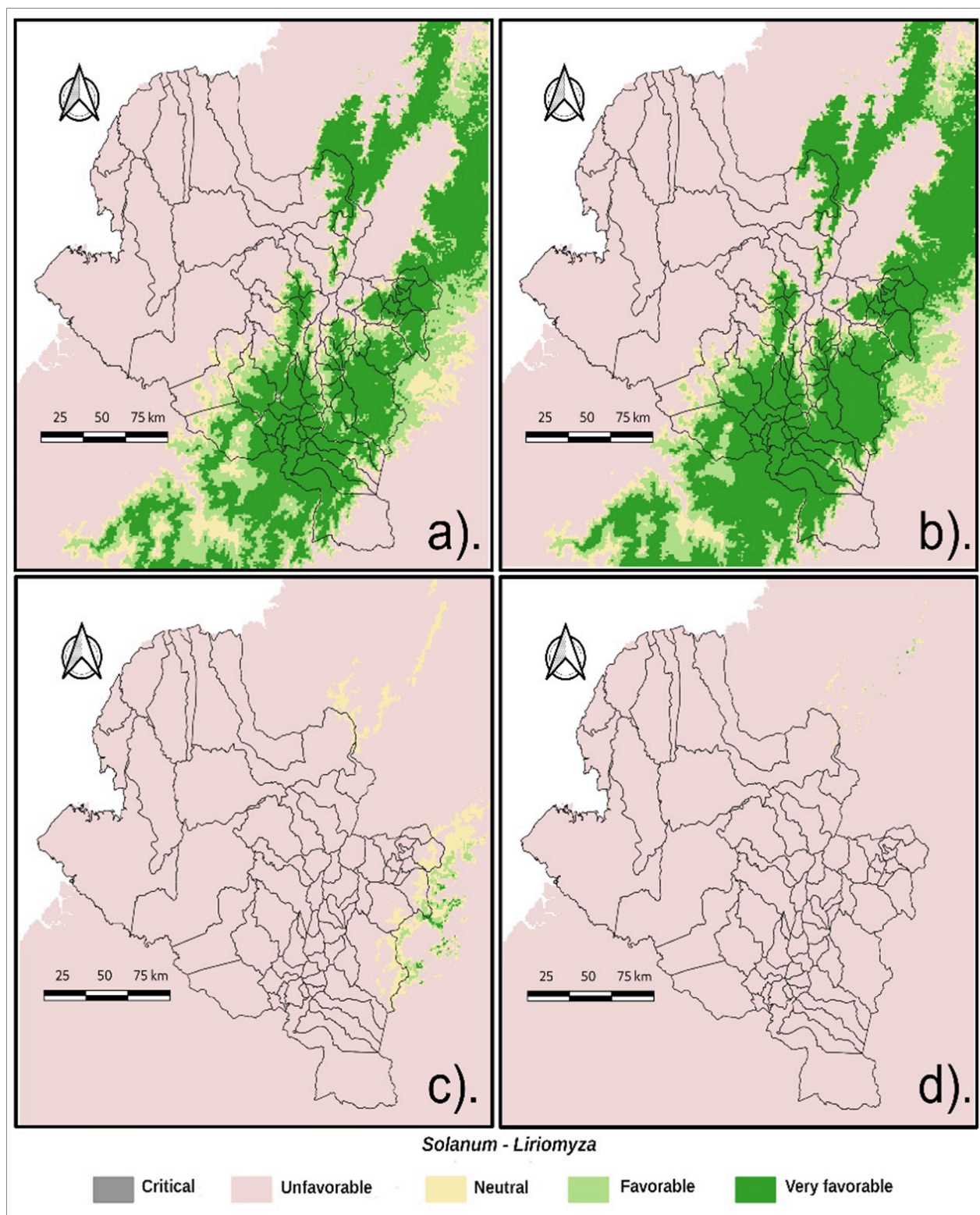


Figure 8

Interaction of the habitat suitability for *Solanum tuberosum* Vs *Liriomyza huidobrensis* (potato-mining fly) in different climatic scenarios: a) current time, b) short-term (2023-2040), c) medium-term (2041-2060), d) long-term (2061-2080).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Graph1.docx](#)