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Hotspots of Yield Loss for Four Crops of the Belt and Road Terrestrial Countries under 1.5 °C Global Warming

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Abstract: The Fifth Assessment Report of the Intergovernmental Panel on Climate change (IPCC) shows that climate change poses severe risks to the Belt and Road region and could cut future crop production. Identifying the positions and features of hotspots, which refer to regions with severe yield loss at 1.5 °C global warming, is the key to developing proper mitigation and adaptation policies to ensure regional food security. This study examined yield loss hotspots of four crops (maize, rice, soybean and wheat) at 1.5 °C global warming under RCP8.5. Yield data were derived from simulations of multiple climate-crop model ensembles from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). Hotspots were identified by setting a threshold of the 10th percentile of crop yields during the reference period (1986–2005). To quantify the likelihood of crop yield loss hotspots within multi-model ensembles, the agreement of model combinations for hotspots was calculated for each crop at the grid scale with 0.5° × 0.5° spatial resolution. Results revealed spatial heterogeneity of cultivation structure and hotspot likelihood for four crops. The four crops' production of SA (South Asia) and SEA (Southeast Asia) accounts for more than 40% of the total production in the Belt and Road region, roughly four times the amount produced in CEE (Central and Eastern Europe) and NEA (Northeast Asia). Besides, the hotspots likelihood of maize, rice and soybean is generally larger in SA/SEA than that in CEE/NEA which means the risk of yield reduction is higher in the current main agricultural area. According to IPCC's classification rules for likelihood, four crops' hotspot patterns were displayed under the 1.5 °C global warming. As the highest-yielding crop, maize shows the largest proportion of "likely" hotspots (hotspot likelihood > 66%), which is about 6.48%, accounting for more than four times that of the other three crops. In addition, four crops' hotspots are mainly distributed in SEA and SA. Overall, SEA and SA are vulnerable subregions and maize is the vulnerable crop of the Belt and Road region. Our results could provide information on target areas where mitigation or adaptations are needed to reduce the adverse influence of climate change in the agricultural system.

Keywords: the Belt and Road; global warming; 1.5 °C; crops; yield; hotspots; likelihood; ISI-MIP

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1. Introduction

The Belt and Road is a global initiative led by the Chinese government to promote win-win international cooperation in the new era. Since 1951, the warming rate in the Belt and Road region is approximately 0.22 °C per decade, nearly twice the global average [1]. According to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate change (IPCC), most regions along the Belt and Road would experience a significant temperature increase by the end of the 21st century (2081–2100), which will be higher than the global average. In addition, World Bank's statistics show that the total population of the Belt and Road terrestrial countries reached 4.7 billion in 2018, accounting for approximately 62% of the total population of the world, despite over 40 Belt and Road countries having a per capita GDP less than $10,000 (current US dollars). Therefore, countries along the Belt and Road would face a higher level of warming risk than the global average, especially for those underdeveloped countries with large populations.

Agriculture is an important sector closely linked to human livelihoods. The World Bank's statistics on employment show that the agricultural sector has supported the income of more than 1 billion people worldwide in 2019. However, the changing climate is affecting global agricultural productivity and threatening food security [2–4] and will therefore hamper the UN Sustainable Development Goals to end hunger [5]. To reduce the adverse effects of warming, the goal set by the United Nations Framework Convention on Climate Change (UNFCCC) emphasizes that the concentration of greenhouse gases in the atmosphere should be stabilized at a level that guarantees secure food production. The Paris Agreement also sets a target to limit global mean temperature to "well below 2 °C" above pre-industrial levels and to pursue efforts to limit it to 1.5 °C by the end of this century, considering that 1.5 °C warming would significantly reduce climate change risks. Therefore, 1.5 °C warming has become an important target for climate change studies.

Future populations will face a number of climate change-related effects, varying in both intensities and locations. However, some 'hotspots' will be at greater risks than others [6]. To promote efficient adaptations, it is crucial to identify and quantify these hotspots and consider their uncertainties at the same time. Many climate-related hotspot analyses are conducted through purely climatic metrics [7–9], with limited consideration about the linkage between climate change and its social impacts. To move forward, some researchers have conducted hotspots analysis covering several sectors, such as agriculture, water, energy and so on [10,11] at a global scale. They have implemented a general analysis for the agricultural hotspots by integrating multiple crops as a whole. But local stakeholders usually need more detailed hotspot information for specific crop varieties when they are making adaptive measures. Through a keyword search for the terms "yield AND hotspot * AND Belt and Road" in the Web of Science, we find analysis on specific crops yield loss hotspots for the Belt and Road region especially under 1.5 °C global warming is still missing.

To fill this gap, we evaluated yield loss hotspots of four main crops (maize, rice, soybean and wheat) separately using the results of ISI-MIP multi-model ensembles in the 65 terrestrial countries of the Belt and Road under 1.5 °C global warming. We took multiple ensembles because the median or average of model ensembles is thought to be more accurate in simulating the crop temperature response compared with any single mode [12–14]. Besides, it enables an uncertainty estimation for yield loss hotspots as well. Before the hotspots analysis, it is also essential to have a basic knowledge of the historical cultivation pattern of the study area. Thus, our research mainly aims to (1) clarify the characteristics of the cropping structure and production levels of crops in the study area in the past; and (2) explore the crop yield reduction hotspots in different subregions and reveal the pattern of crop yield loss hotspots under 1.5 °C global warming. These findings can contribute to the awareness of severe yield loss risks of the four main crops and provide reference to regional agricultural adaptations.

2. Materials & Methods

2.1. Study Area

The "Belt and Road" is the abbreviation of "the Silk Road Economic Belt" and "the 21st-Century Maritime Silk Road". The study area is located primarily in Asia, Europe and northern Africa and is characterized by complex and diverse environmental conditions. It has a variety of climates, including tropical, arid, temperate, cold and polar climates, and most of the region shows a warming trend [15]. In this paper, we considered 65 countries under the Belt and Road Initiative and divided the study area into 7 subregions (Table 1) according to the website of the Belt and Road Portal of China (https://www.yidaiyilu.gov.cn/, accessed on 13 September 2021).

Table 1. Subregions of the Belt and Road countries.

Subregions	Abbreviation	Detailed List
China	CH	China
Central Asia	CA	Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, Tajikistan
Northeast Asia	NEA	Mongolia, Russia
Southeast Asia	SEA	Vietnam, Laos, Cambodia, Thailand, Malaysia, Singapore, Indonesia, Brunei, Philippines, Myanmar, Timor-Leste
South Asia	SA	India, Pakistan, Bangladesh, Nepal, Bhutan, Sri Lanka, Maldives
Central and Eastern Europe	CEE	Poland, Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Romania, Bulgaria, Serbia, Montenegro, Macedonia, Bosnia and Herzegovina, Albania, Estonia, Lithuania, Latvia, Ukraine, Belarus, Moldova
West Asia and North Africa	WAN	Turkey, Iran, Syria, Iraq, Afghanistan, United Arab Emirates, Saudi Arabia, Qatar, Bahrain, Kuwait, Lebanon, Oman, Yemen, Jordan, Israel, Palestine, Armenia, Georgia, Azerbaijan, Egypt

2.2. Data Description

Four major crops were analyzed, including maize, rice, soybean and wheat. Their yield (unit: t/ha) simulations with a resolution of 0.5° × 0.5° were provided by the Fast Track of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, www.isimip.org, accessed on 22 September 2021). The simulated crop yields were computed by seven global gridded crop models (GGCM) (EPIC, GEPIC, GAEZ-IMAGE, LPJGUESS, LPJml, PEGASUS, and pDSSAT). Each GGCM was forced with bias-corrected climatic data [16] of five global climate models (GCM) (GFDL-ESM2M, HaDGem2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) under four Representative Concentration Pathways (RCPs, including RCP2.6, RCP4.5, RCP6.0, RCP8.5) from the Fifth Coupled Model Intercomparison Project (CMIP5). In order to reveal hotspots of crop yield loss under a severe greenhouse gas emission scenario, only simulations under RCP8.5 were considered. All GGCMs were run for different parameter settings (with or without CO_2, with or without irrigation). As a result, there are 116, 96, 116 and 116 model pairs available for maize, rice, soybean and wheat, respectively.

This study contains two 20-year time slices, including the baseline period (1986–2005) which is a commonly used reference period to derive warming level and assess climate impacts [1,17], and the period when the global mean temperature will be 1.5 °C higher than pre-industrial levels under RCP8.5 (Table 2) [18]. In terms of the spatial range, the cultivated area of four crops during the reference period (1986–2005) were derived from MIRCA2000 data [19]. Due to data availability, the cultivated ranges were supposed to be consistent in the future within ISI-MIP's simulations. Therefore, each crop's simulated yield was then extracted by its historical cover, respectively.

Table 2. The respective 20-year time slices for 1.5 °C global warming calculated by the ISI-MIP model ensembles under RCP8.5 scenario [18].

Name	Time Slices for a 1.5 °C Global Warming
GFDL-ESM2M	2028–2047
HaDGem2-ES	2010–2029
IPSL-CM5A-LR	2016–2035
MIROC-ESM-CHEM	2010–2029
NorESM1-M	2022–2041

2.3. Research Methods

The climate hotspots could be a concept relevant to vulnerability, which can be defined as a region being especially responsive to climate change and suffering pronounced impacts [8,9]. In this study, we defined hotspots as regions with severe yield loss. To identify the yield loss hotspots of the Belt and Road region, we took the yield of four main crops as the index to recognize the adverse effects of global warming. Figure 1 shows the workflow of this study.

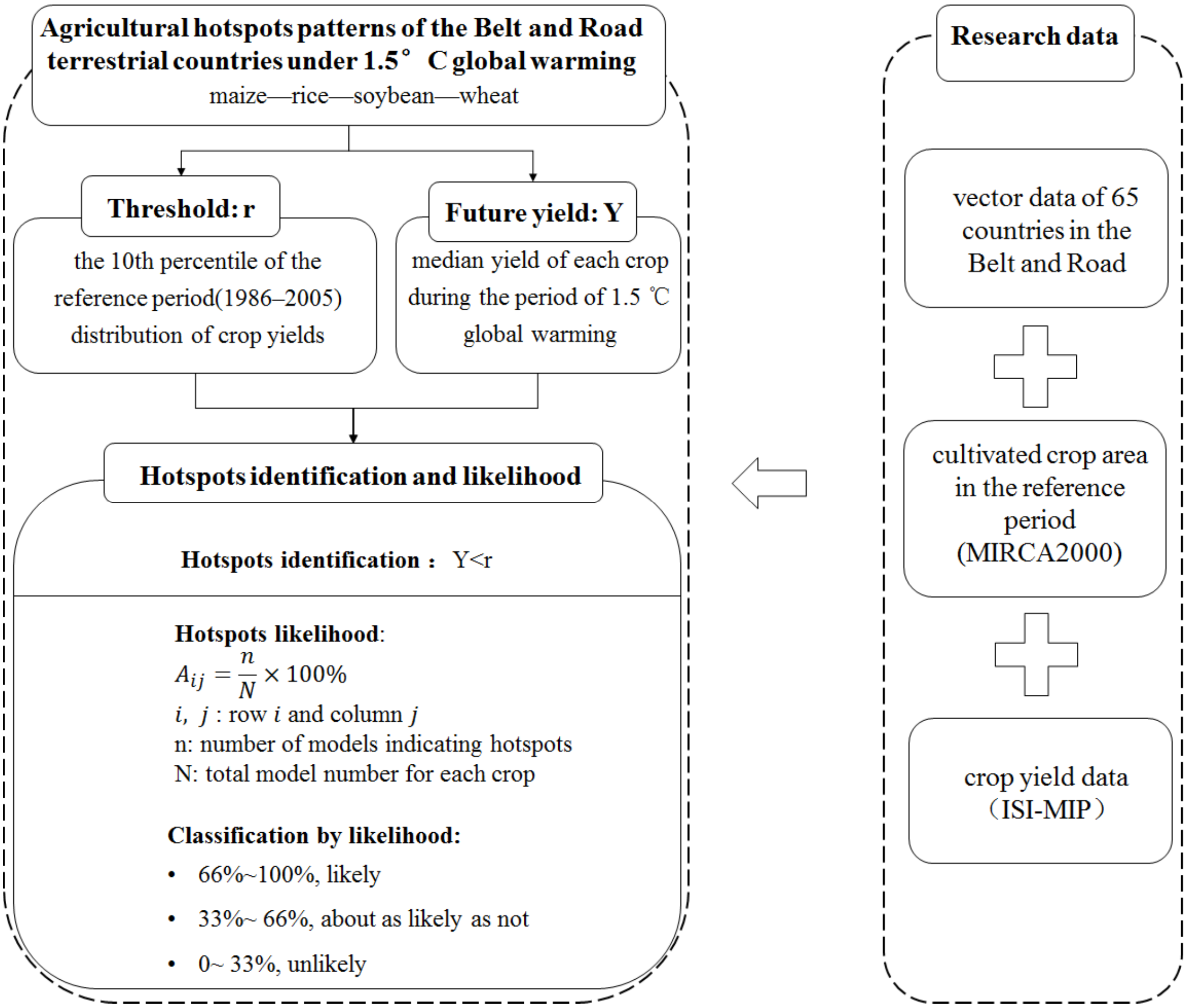

Figure 1. The workflow of research methods.

In line with Piontek et al. [11], the 10th percentage point of yield distribution in the baseline period (1986–2005) was taken as the threshold to identify each crop's hotspots. This threshold means a shift in average conditions into what is considered moderately extreme, happening in about 10% of all historical years. Average conditions are measured as each crop's yield median over the 20-year time slices for 1.5 °C warming under RCP8.5. Moreover, multi-model simulations also enable an assessment of likelihood. The model agreement of hotspots at each grid can indicate how large the likelihood of hotspots is by dividing the number of models indicating hotspots by the total number of models. And according to IPCC AR5, the likelihood can be described quantitatively through the following terms: likely, 66~100%; about as likely as not, 33~66%; unlikely, 0~33%. Thus, three classes of hotspots were divided.

3. Results

3.1. Cultivation Structure and Crop Production of Different Subregions

Figure 2 shows four crops' cultivated area and past productions in each subregions of the study area. The total planted area for CH and SA were the largest, being around

9×10^5 km^2. However, CA's total planted area was the smallest, being no more than 15% of CH's. Besides, the ratio of planted area for four crops varied among subregions. For CH, the proportions of planted area for wheat, rice and maize were around 30%, while the ration was around 10% for soybean. In SA, rice and wheat were the major crops with the total proportion being over 80% of planting area. The major crop of SEA was rice, covering about three-quarters of the total planted area. CEE was almost occupied by wheat and maize with little soybean. As for the last three subregions (WAN, NEA and CA), wheat was the dominant crop and the proportion of which was above 80% of the total cultivated area. The ranking of total crop productions in different subregions is consistent with the ranking of the total cropped area. CH had the highest crop production (accounting for over 38% of the study area's total production), followed by SA and SEA (taking about 29% and 13% of total production, respectively). In contrast, CA showed the lowest crop production (about 1.99×10^7 t), less than 2% of the total production in the study area.

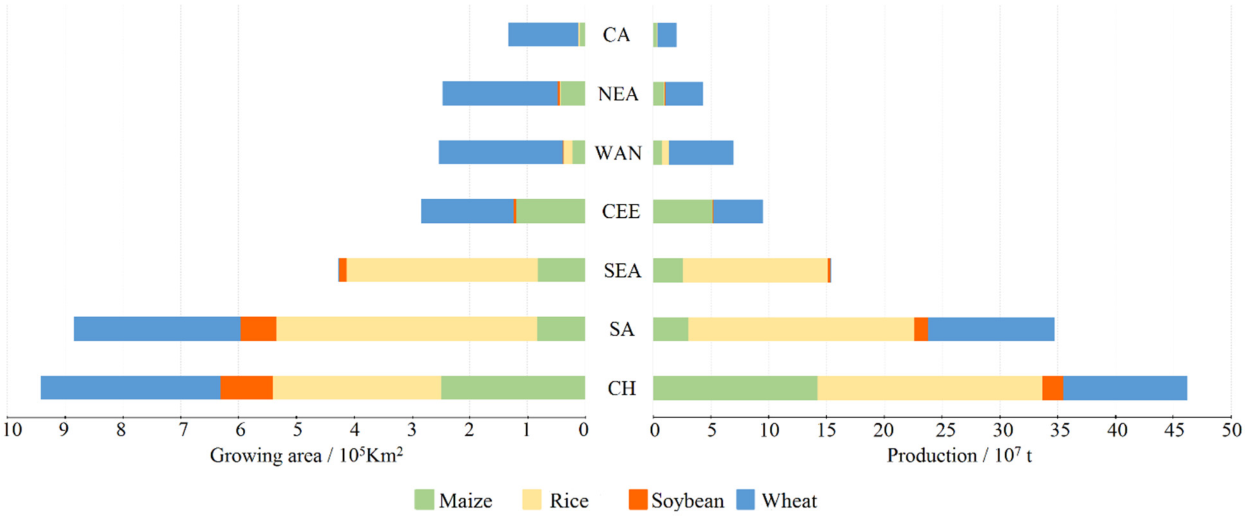

Figure 2. Cultivated areas and production for maize, rice, soybean, and wheat of subregions in the Belt and Road during the reference period (1986–2005).

3.2. Crops Yield Analysis of Different Subregions

Figure 3 presents the mean yield of maize, rice, soybean and wheat in seven subregions of the Belt and Road during the reference period (1986–2005), indicating that crop yields vary across crop types and subregions. For the whole region of the Belt and Road (BR), the yields of the four crops, in descending order, were 4.58 t/ha (maize), 3.64 t/ha (rice), 2.66 t/ha (wheat) and 1.92 t/ha (soybeans). For most subregions, the average yield of maize was the highest while the yield of soybean was the lowest. Besides, there are also variations in crop yields among different subregions. For example, the average yield of the four crops in CH was higher than that of BR, whereas the crops yield of NEA, WAN and CA were lower than BR's averages. As for CEE, the mean yield of maize, soybean and wheat is similar to that of BR. However, its rice yield was slightly low, being smaller than BR's average value. For SEA and SA, the yield of maize, rice and soybean were very close to each other. However, the wheat yield in SA was almost twice as high as that in SEA.

Therefore, CH, SA and SA are the main crop production area of the Belt and Road region, with the production of four crops accounting for more than 80% of the total production of the Belt and Road region. And the yield of maize is the highest among the four crops in BR as well as in most subregions.

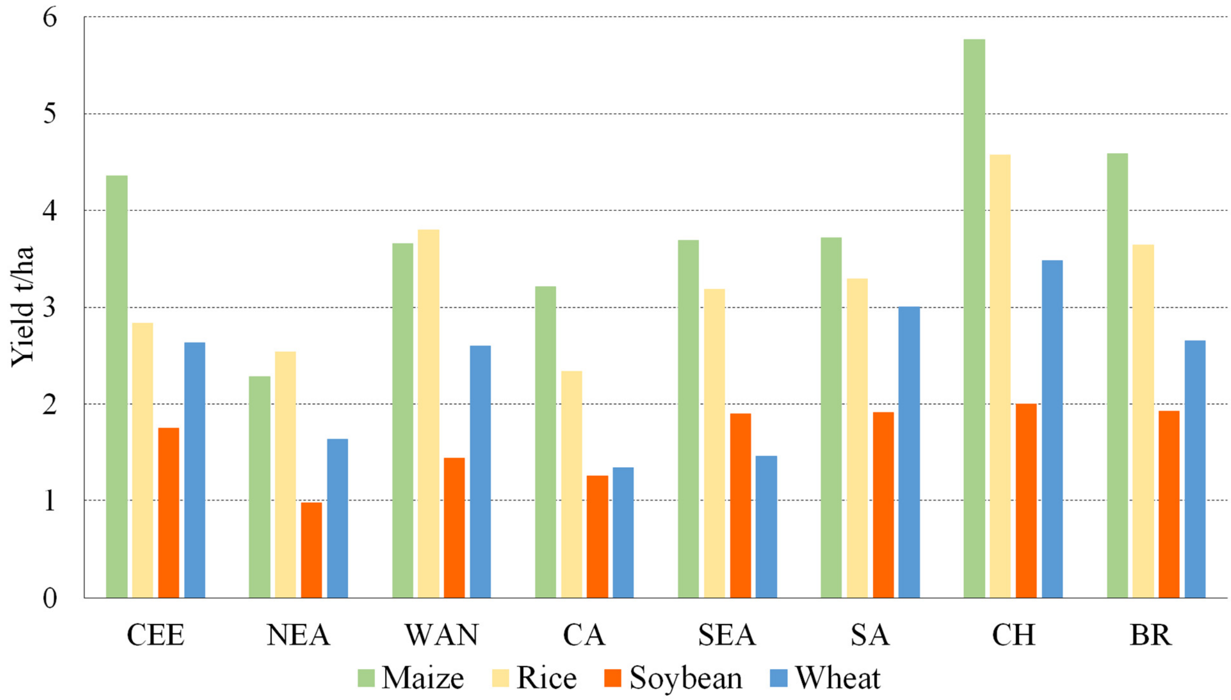

Figure 3. The mean yield for maize, rice, soybean, and wheat of subregions in the Belt and Road during the reference period (1986–2005).

3.3. Characteristics of Hotspots Likelihood in Different Subregions

Figure 4 displays the distribution of hotspot likelihood for four crops in seven subregions of the Belt and Road for 1.5 °C global warming under RCP8.5. There is a large deviation in the hotspot likelihood for each crop in almost every subregion, indicating great variation in hotspot likelihood within subregions. For maize, rice and soybean, the median hotspot likelihood is relatively low in CEE and NEA compared with other subregions. However, NEA shows a high level of median hotspot likelihood (>50%) for wheat, although with a high latitudinal location. Unlike CEE and NEA, SA and SEA located at low latitudes usually have a high level of hotspot likelihood, being around 50% or even more than 60% for maize, soybean and wheat. For WAN and CA, where wheat is the major crop, the median hotspot likelihood of wheat is higher than 50% for CA, a little higher than that of WAN. As for CH, its median hotspot likelihood for four crops is at a moderate level, ranging from 30% to 40%.

The difference in likelihood among subregions is consistent with previous studies saying that tropical regions at lower latitudes experienced a greater magnitude of impact and likelihood of reduced crop yields than temperate regions [3,12]. The tropical area's temperature is very close to the threshold suitable for grain growth, so the temperature rising by 1–2 °C will adversely affect grain yields [20–22]. As for the high hotspot likelihood of wheat in NEA, it could be reasonable due to the increase of extremely high temperature, aridity in these regions under global warming [23,24].

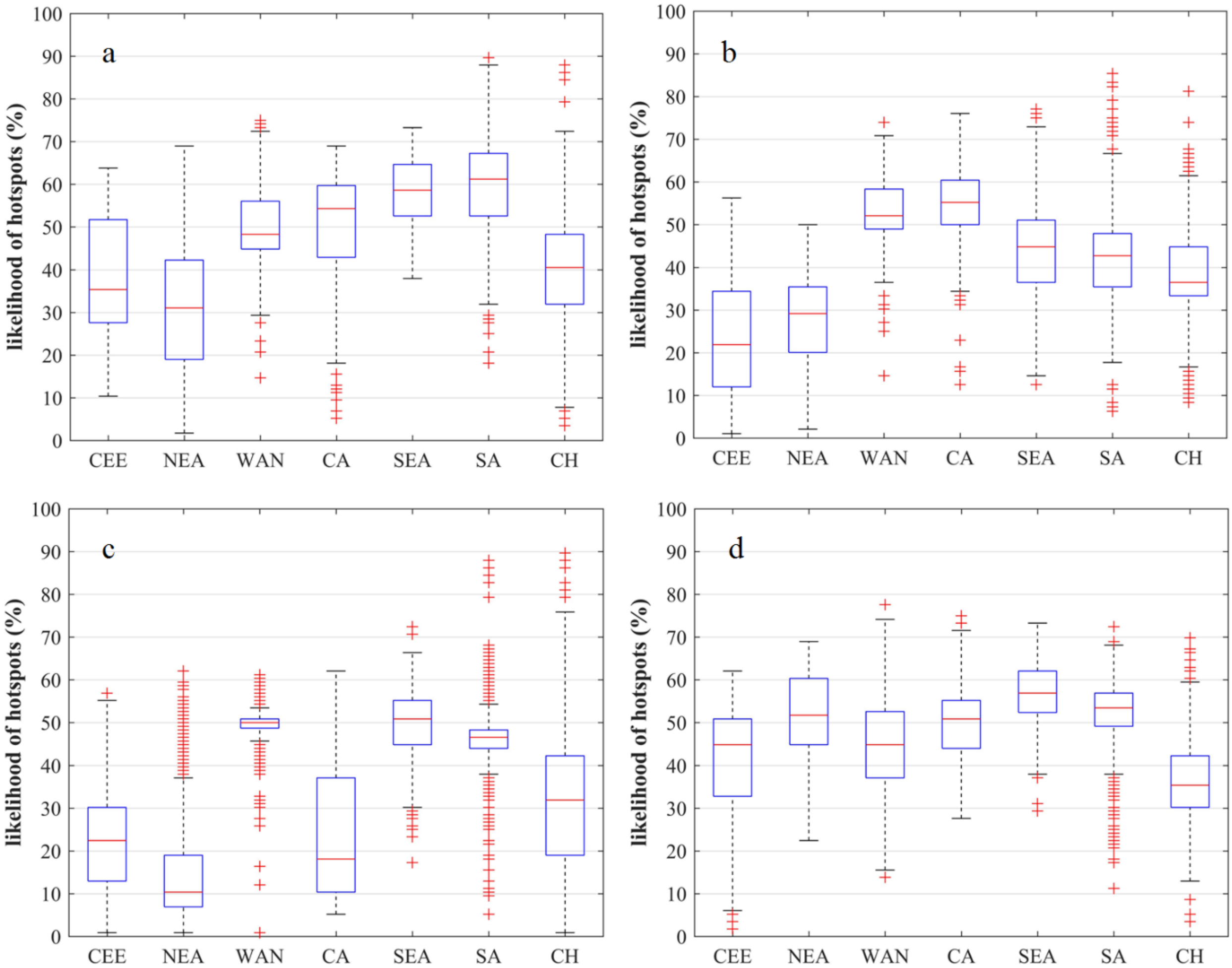

Figure 4. Box plot distribution of hotspot likelihood for maize (**a**), rice (**b**), soy (**c**), wheat (**d**) at subregions of the Belt and Road for 1.5 °C global warming under RCP8.5. "+" indicates abnormal values.

3.4. Hotspots Patterns of Four Crops for 65 Countries of the Belt and Road

As shown in Figure 5, regions being "likely" or "about as likely as not" or "unlikely" to become hotspots are identified for four crops under 1.5 °C global warming (considering RCP8.5), and their proportions are displayed in Table 3. For maize, these "likely" hotspots account for around 6.48% of the total maize growing area in the baseline period, mainly located in SA and SEA. While for the other three crops, the proportions of the "likely" hotspots are 1.51%, 0.11% and 0.69% for rice, soybean and wheat, respectively, scattered in mid-to-low-latitudes. As for "unlikely" hotspots, their proportions of historical cultivated area range from 12.29% to 35.23%, with the smallest value for rice and the biggest for soy. These are mainly distributed in CEE, NEA and some parts of CH. The last kind of hotspots, "about as likely as not", takes the largest percentage of these crops' growing area, and the proportion is 64.66~86.20%.

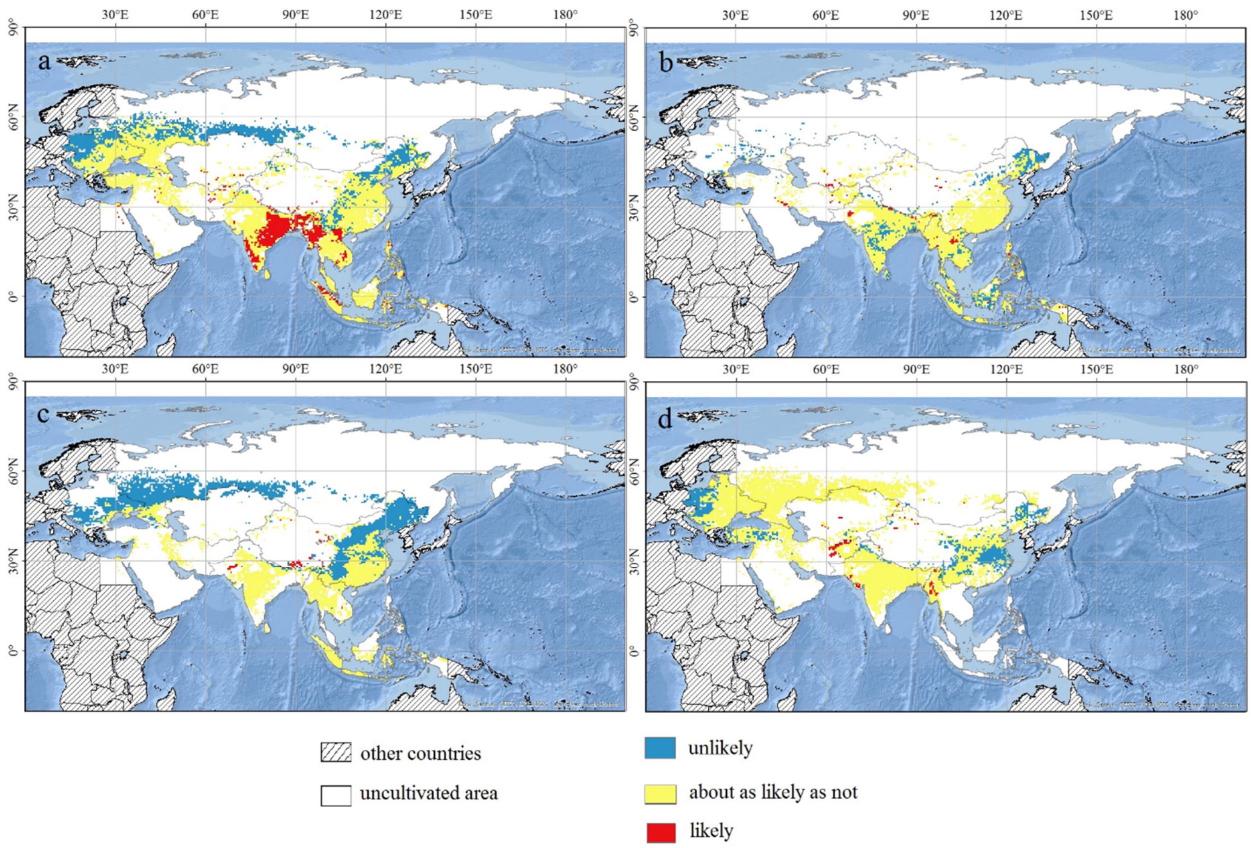

Figure 5. The spatial distribution of maize (**a**), rice (**b**), soybean (**c**), and wheat (**d**) hotspots in the Belt and Road for 1.5 °C global warming under RCP8.5. The hotspots are divided into three classes according to the magnitude of likelihood: >66% "likely", 33~66% "about as likely as not", <33% "unlikely".

Table 3. Proportions of each kind of hotspots for maize, rice, soybean and wheat in the Belt and Road.

Crop	Likely (%)	About as Likely as Not (%)	Unlikely (%)
maize	6.48	69.33	24.19
rice	1.51	86.20	12.29
soybean	0.11	64.66	35.23
wheat	0.69	82.05	17.26

Maize is a type of C4 plant, while rice, soy and wheat are C3 plants. It has been proved that the C4 plant profits less from increased CO_2 concentrations than the C3 plants because the C4 crop's photosynthesis is already CO_2 saturated at the current CO_2 level [25,26]. Therefore, it is reasonable that maize shows the largest proportion of 'likely' hotspots under 1.5 °C global warming. According to Figure 5, SEA and SA are likely to suffer extremely low maize production, even under a slight warming level, namely the 1.5 °C global warming. These two subregions are mainly composed of developing countries with large populations. Therefore, to meet people's food demand and ensure food security, crop and regional specific adaption strategies must be taken in SEA and SA.

4. Discussion

The yield loss hotspots of the Belt and Road region under 1.5 °C global warming depend on crop species and geographic locations since the response of crops to climate change varies. Warming is going to accelerate the growth rate and shorten the crop cycle, reduce pollen viability resulting in a reduction of kernel number, and ultimately reduce yields of crops [27,28]. However, elevated CO_2 concentration shows a beneficial impact on C3 crops (i.e., wheat, rice, and soybean). As a C4 plant, maize gains less benefit from the increased CO_2 concentration than C3 plants because its photosynthetic pathway is unresponsive to elevated CO_2 [29,30]. As a result, the CO_2 fertilization effect cannot offset adverse climate impacts on the maize yield [31]. Therefore, maize in the Belt and Road region is more likely to experience yield reduction under 1.5 °C global warming than the other three C3 crops. The likelihood of yield loss hotspots varies across subregions. For instance, the hotspot likelihood of crops is greater in SA and SEA, whereas it is smaller in CEE and NEA. This is because subregions in the tropical environments, which are already characterized by high temperature and variable rainfall conditions, are more likely to have yield loss under a warming scenario unless adaptation measures are taken. This is in line with previous reports indicating that climate impacts on tropical croplands are generally more negative than the mid- and high-latitude impacts [22,32,33]. Our analysis confirmed past studies and will also help inform more details about the locations of these vulnerable sites by identifying hotspots of crops.

In order to maintain economically acceptable yields under the future climate in the study area, adaptations of crops to future warmer conditions are required, especially for tropical subregions. Passive effects of warming can partly be compensated through optimizing sowing date and switching variety [28]. The growth rate of crops will decrease by sowing earlier in the season when temperatures are cooler, which allows more time for grain filling and would therefore be expected to increase yield [34,35]. Another possible adaptation under warming conditions would be switching to improved high-temperature-tolerant varieties [36]. Considering drought and heat stress levels in the tropical environment, incorporating drought and heat tolerance into maize germplasm also has the potential to offset predicted yield loss and sustain maize productivity under climate change in vulnerable sites [37].

Our study still involved some limitations. Firstly, due to data limitations, our estimates did not consider the variations in crops' cultivated area, for example, the expansion of crop area in some cooler places. However, we focus on the hotspots of crop yield loss, namely the adverse outcome of increased temperature on crop yield. Therefore, the expansion of the grown area, a favorable effect of warming is beyond the study scope. In addition, our results on hotspots may be overly pessimistic because they did not include agricultural adaptations as mentioned above. On the other hand, these crop models can not explicitly simulate the effects of extreme events, which have significant impacts on final crop yields [38–40]. Thus, the assessment results based on yield predictions of ISI-MIP may underestimate the impact of extreme weather events on crop yields [26,41]. These limitations indicate the scope and need for future studies on the impacts of changing crop cultivation, extreme climate events and potential adaptations.

5. Conclusions

Using the multi-model simulated results of crop yields provided by ISI-MIP, this article explored the features of cultivation, crop hotspots and the patterns of four crops in 65 countries of the Belt and Road under 1.5 °C global warming by a threshold of historical yield distribution and model agreement of multi-model ensembles. The major conclusions of the study include:

The analysis shows the spatial heterogeneity of crops' cultivation structure and hotspots likelihood for four crops. For maize, rice and soybean, the value of hotspots likelihood is generally smaller in mid-to-high-latitude regions like CEE and NEA than that in low-latitude parts such as SA and SEA. However, except for the low latitudinal region, NEA with a high latitudinal location also shows a high level of median hotspot likelihood (>50%) for wheat.

The results also reveal hotspot patterns of four crops under 1.5 °C global warming considering RCP8.5. The proportion of "likely" hotspots for maize is about 6.5%, being at least four times larger than that of the other three crops. These "likely" hotspots are mainly situated in SEA and SA, while the "unlikely" hotspots are mainly distributed in CEE and NEA (except for wheat).

SA and SEA are the main crop producing area of the Belt and Road region and the majority of people here still rely on agriculture for their livelihoods. However, these subregions will remain vulnerable to climate warming for the foreseeable future. Maize, as the most productive crop, will also be exposed to the largest extent of hotspots than other crops. Our research reveals the yield reduction hotspots of four crops and indicates that the warming climate will continue reshaping the production pattern of agriculture in the Belt and Road region unless adaptations are taken.

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