Future Projection for Areas Suitable for Double Cropping of Silage Corn (*Zea mays* L.) Production in Japan with Two Climate Models under the RCP4.5 Scenario

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Abstract

The future situation of double cropping (DC) of silage corn (*Zea mays* L.) in Japan was projected based on the data simulated with two climate models of MRI-CGCM3 and MIROC5 under the representative concentration pathways (RCP) 4.5 scenario. Annual effective cumulative temperatures (ECT, 10°C basis) in 2040 and 2090 were calculated for every second grid square (approximately 10 km × 10 km), as a mean value between 2031 and 2050, and between 2081 and 2100, respectively. The area suitable for corn-corn DC was distinguished as the area in which ECT was higher than its temperature requirement (2,300°C). It was predicted that the percentage of the areas suitable for corn-corn DC in Japan would increase from 21.4% at the present to 33.4–44.3% in 2040 and to 40.1–48.2% in 2090, and that the suitable areas would expand to the north of the Kanto region until 2090. It was also confirmed that, at Ebina City, Kanagawa Prefecture (one of the suitable areas for corn-corn DC at present), the mean temperatures during the first and second cropping in corn-corn DC were lower than that of the conventional summer-corn cropping, and that corn-corn DC would be one of the countermeasures to alleviate the effect of warming temperatures.

Key words: climate change, double cropping, suitable cultivation area, *Zea mays* L.

Introduction

Agriculture is strongly influenced by weather and climate, and recent climate change also affects agriculture production in the world[3,20]. Projection of the effects of climate change on agriculture production is of crucial importance for the implementation of the countermeasures to adapt the agriculture system to climate change. Corn (*Zea mays* L.) is one of the primary crops both for grain production and silage production, and the effects of recent climate change for the crop should be evaluated from a viewpoint of food security in the world[5,29].

Though corn is a C_4 plant which has high thermal requirement, it has been reported that the temperature increase affects corn production

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negatively in some cases[1,3,4,5,13,14,25,26,27]. Seino (1995) simulated corn silage yield under several climate change scenarios and projected that, if temperatures increase by 2 to 4°C, the corn silage yield would increase at Obihiro in Hokkaido, but decrease at Miyakonojyo in the Kyushu region[25]. Gornall *et al.* (2010) reviewed the literature concerning the effects of climate changes on agricultural productivity, and they indicated that the higher temperature affected negatively on corn yield at low latitudes where temperatures were already close to the physiological maxima for crops[3]. However, they also indicated that, in mid and high latitudes, the suitability and productivity of crops including corn were projected to increase and extend northward[3]. Olesen *et al.* (2007) projected a 30–50% increase in suitable area for corn grain production in Europe by the end of the 21st century, including Ireland, Scotland, Southern Sweden and Finland[19]. Olesen *et al.* (2011) reported that the farmers had already begun to change the areas of corn silage and grain production northwards[20]. On the other hand, in south America, Meza *et al.* (2008) projected the impact of climate change scenarios on corn production in central Chile and indicated that, though corn grain yield would reduce between 10% and 30%, depending on the climate change scenarios and a type of hybrid used, warmer conditions would enable corn-corn double cropping (DC), resulting in an increase in the annual yield[17].

In Japan, silage corn is one of the higher yielding forage crops, and its forage value is at the highest level among the forage crops cultivated[28]. It has been considered that the suitable areas for corn-corn DC in Japan is limited in the southern areas such as Kyushu, and that, in the central and northern areas of Japan, silage corn is usually planted once a year in its monocropping or in DC with winter forage crops like Italian ryegrass (*Lolium multiflorum* Lam.) [28]. However, resulting from the recent warming climate, it is expected that the areas suitable for corn-corn DC will expand. Some livestock farmers in the Kanto region (central Japan) have begun corn-corn DC to improve forage productivity per unit area of their farmlands[9,10,21,23]. Therefore, in this study, the spatial distribution of the corn-corn DC suitable areas at present was examined, as well as the future projection of their expansion.

In the 5th Intergovernmental Panel on Climate Change (IPCC) report, various climate models and four scenarios of the representative concentration pathways (RCP) were introduced as tools to evaluate the effect of climate change[7]. Among the climate models and RCP scenarios, in this study, two climate models of MRI-CGCM3[32] and MIROC5[33] under the RCP 4.5 scenario were utilized for the future projection of corn-corn DC suitable areas in Japan.

Materials and Methods

The future situation of corn-corn DC was projected based on the climate data simulated for the period between 2031 and 2050 and between 2081 and 2100 with the two climate models of MRI-CGCM3[27] and MIROC5[33] under the RCP 4.5 scenario. Both models are the representative climate models developed in Japan: MRI-CGCM3 was developed by the Meteorological Research Institute, Japan Meteorological Agency[32], while MIROC5 was developed by the University of Tokyo, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology[33]. Both of them were utilized in the climate change projection of the IPCC 5th Assessment Report[7], and it is known that the temperature increase projected by MRI-CGCM3 is relatively low, but that by MIROC5 is relatively high among the climate models[7,31]. In this study, the secondary climate mesh data (approximately 10 km × 10 km) were used, and annual effective cumulative temperatures (ECT, 10°C basis) from January to December in all years were calculated for every second grid square. Twenty-year mean values between 2031 and 2050 and between 2081 and 2100 were calculated to predict the suitable area for corn-corn DC in 2040 and 2090, respectively. Historic data at present was calculated with data since 1981 until 2000 in the models of MRI-CGCM3. Then the calculated data was mapped, using ArcGIS (ESRI Japan, Tokyo).

According to the previous report[10], the whole areas were distinguished as unsuitable areas for corn-corn DC (ECT simulated was less than 2,200°C), limiting areas (2,200°C <ECT<2,300°C), and suitable areas (2,300°C <ECT). Moreover, the areas suitable for corn-corn DC were separated into two types of areas: one was the area in which ECT was higher than 2,300°C and corn-corn DC was possible. The other was the area in which ECT was higher than 2,530°C and the dry matter ratio of the whole plant of corn would increase up to 30%, resulting in high-quality silage that could be obtained both in the first and the second cropping. The percentage of the suitable areas was calculated as a ratio of the number of the second grid squares of corn-corn DC suitable areas to the total grid square number of Japan.

Furthermore, to evaluate the effect by changing cropping season on temperature conditions, mean temperatures and ECT (10°C basis) of three different growth periods were calculated with the secondary climate mesh data (Mesh code 533903) in Ebina City, Kanagawa Prefecture where some farmers had already started corn-corn DC[21]. The three periods from May to August, from April to July, and from August to November were assumed as the corn cropping periods of the conventional DC with corn and winter forage crops, and the first and second cropping of corn-corn DC, respectively. The mean temperatures and ECT of the three periods were calculated, using the data of Historic (1981–2000), 2040 (2031–2050) and 2090 (2081–2100).

Results

The average values of mean temperature and ECT at present and in 2040 and 2090 are shown in Table 1. In the models of MRI-CGCM3, it was expected that the average values of annual mean temperature would increase with a rate of 1.23°C and 1.89°C from present to 2040 and 2090, respectively, and that of MIROC5 would be 0.8–0.9°C higher than MRI-CGCM3. Average values of ECT in MRI-CGCM3 was expected to increase from 1,713°C to 1,941°C and 2,087°C in 2040 and 2090, respectively, and ECT projected by MIROC5 was 202–216°C higher than MRI-CGCM3.

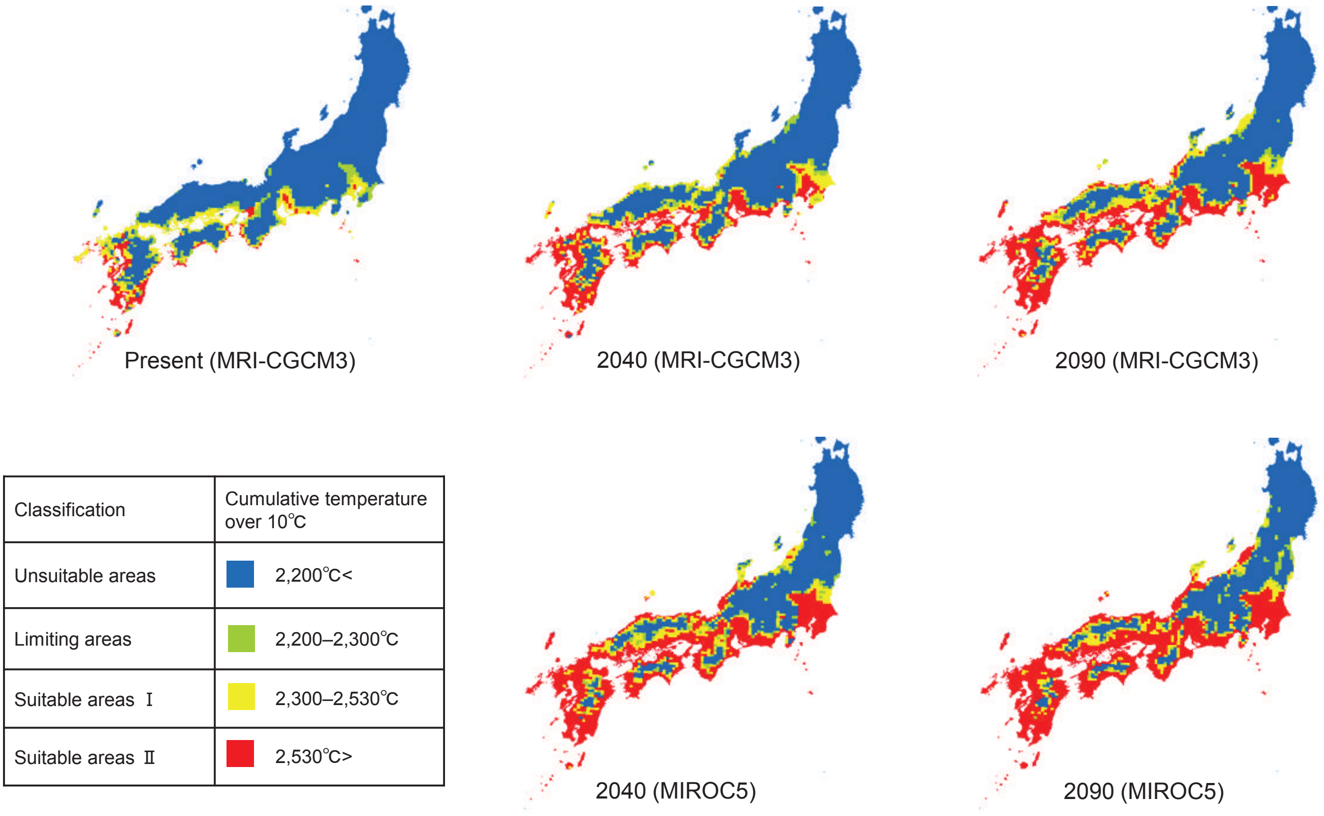
Table 1. Annual mean temperature and cumulative temperature over 10°C throughout Japan in the Historic data (at present) and in 2040 and 2090 projected using two climate models (MRI-CGCM3 and MIROC5) with RCP4.5 scenario.

Period	Climate model	Annual mean temperature (°C)	Cumulative temperature (°C)
Historic	MRI-CGCM3	11.28 ± 0.43	1713.0 ± 101.5
2040	MRI-CGCM3	12.51 ± 0.60	1940.8 ± 119.1
	MIROC5	13.43 ± 0.54	2156.7 ± 115.9
2090	MRI-CGCM3	13.17 ± 0.42	2087.3 ± 81.4
	MIROC5	13.95 ± 0.66	2289.1 ± 161.2

Data shown is a mean value and a standard error among 20 years between 1981–2000, 2031–2050 and 2081–2100 in Historic, 2040 and 2080, respectively.

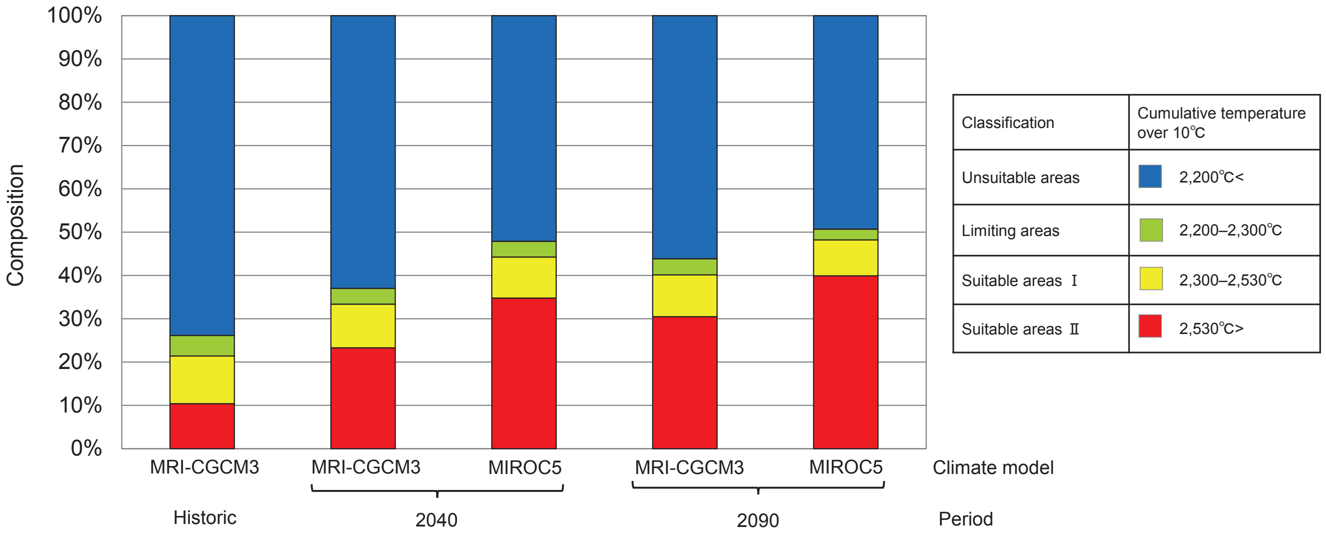
Changes of the spatial distribution of the unsuitable areas, the limiting areas and the suitable areas for corn-corn DC are shown in Figure 1. Since the whole part of Hokkaido was evaluated as unsuitable areas for corn-corn DC, the results only of the areas from Tohoku region to the Kyushu region were described in Figure 1. At present, the suitable areas for corn-corn DC are limited mainly in the lowlands of the Kyushu region, the Setouchi areas, and the coastal areas of the Pacific Ocean in the Shikoku region, Kinki region and Tokai region. However, it was predicted that the areas in which ECT values exceeded 2,300°C would expand in each region until 2040, and the northern limit for corn-corn DC would move to the central parts to the northern parts of the Kanto region. Moreover, the areas in which ECT values exceed 2,530°C will expand to the northern parts of the Kanto region until 2090, and the main part of the Kanto plain will change to the suitable areas for corn-corn DC.

Composition of the second grid squares of the unsuitable areas, the limiting areas and the suitable areas for corn-corn DC is shown in Figure 2. At present, the percentage of the areas in which ECT values exceed 2,300°C and 2,530°C is 21.4% and 10.4%, respectively. In 2040, the areas in which ECT of the two climate models will exceed 2,300°C and 2,530°C will increase to 33.4–44.3% and 23.3–34.8%, respectively. Moreover, in 2090, the areas in which ECT will exceed 2,300°C and 2,530°C will increase to 40.1–48.2% and 30.5–39.9%, respectively.



Classification	Cumulative temperature over 10℃
Unsuitable areas	🟦 2,200℃<
Limiting areas	🟩 2,200–2,300℃
Suitable areas Ⅰ	🟨 2,300–2,530℃
Suitable areas Ⅱ	🟥 2,530℃>

Figure 1. Changes of the spatial distribution of the unsuitable areas, the limiting areas and the suitable areas for corn-corn double cropping from present (Historic; 1981–2000) to 2040 and 2090 projected using two climate models (MRI-CGCM3 and MIROC5) with RCP4.5 scenario.



Classification	Cumulative temperature over 10℃
Unsuitable areas	🟦 2,200℃<
Limiting areas	🟩 2,200–2,300℃
Suitable areas Ⅰ	🟨 2,300–2,530℃
Suitable areas Ⅱ	🟥 2,530℃>

Figure 2. Composition of the second grid squares of the unsuitable areas, the limiting areas and the suitable areas for corn-corn double cropping at present (Historic; 1981–2000) and in 2040 and 2090 projected using two climate models (MRI-CGCM3 and MIROD5) with the RCP4.5 scenario.

In one of the secondary climate mesh data (Mesh code 533903) included in Ebina City, it was projected that annual mean temperature would increase from 15.3°C at present to 16.5–17.3°C and 17.1–17.9°C in 2040 and 2090, respectively (Table 2). Comparing mean temperatures among the three growth periods, that from May to August at present was calculated as 22.8°C, while that from April

Table 2. Mean temperature and cumulative temperature over 10 °C in the Historic data (at present) and in 2040 and 2090 at Ebina City (Meah code 533903) during three different periods and year round data projected using two climate models (MRI-CGCM3 and MIROC5) with RCP4.5 scenario.

Period	Climate model	Mean temperature			
		May-September	April-July	August-November	January-December
		(°C)			(°C)
Historic	MRI-CGCM3	22.8 ± 0.7	19.7 ± 0.6	19.7 ± 0.7	15.3 ± 0.5
2040	MRI-CGCM3	23.8 ± 0.7	20.5 ± 0.8	20.7 ± 0.6	16.5 ± 0.5
	MIROC5	24.7 ± 0.8	21.5 ± 0.7	22.1 ± 0.9	17.3 ± 0.6
2090	MRI-CGCM3	24.5 ± 0.5	21.2 ± 0.5	21.5 ± 0.6	17.1 ± 0.4
	MIROC5	25.2 ± 0.8	22.1 ± 1.0	22.5 ± 0.6	17.9 ± 0.7
Period	Climate model	Mean temperature			
		May-September	April-July	August-November	January-December
		(°C)			(°C)
Historic	MRI-CGCM3	1964.0 ± 99.7	1180.5 ± 77.4	1193.0 ± 84.3	2386.5 ± 141.4
2040	MRI-CGCM3	2108.9 ± 102.7	1286.8 ± 91.6	1308.4 ± 68.7	2633.6 ± 145.4
	MIROC5	2242.9 ± 116.5	1400.2 ± 80.0	1477.8 ± 114.6	2929.4 ± 183.3
2090	MRI-CGCM3	2211.2 ± 70.5	1367.1 ± 64.0	1403.8 ± 70.1	2825.2 ± 116.2
	MIROC5	2328.0 ± 115.8	1475.9 ± 121.8	1527.4 ± 78.6	3096.7 ± 195.8

Data shown is a mean value and a standard error among 20 years between 1981–2000, 2031–2050 and 2081–2100 in Historic, 2040 and 2080, respectively. The periods from May to September, from April to July and from August to November were assumed as the growth period of conventional summer corn and the first and the second cropping of corn-corn double cropping, respectively.

to July and from August to November was 3.1°C lower than that from May to August. Similarly, both in 2040 and 2090, it was expected that the mean temperatures from April to July and from August to November would be 2.5–3.3°C lower than that from May to August both in the two models. On the other hand, ECT from January to December will increase from 2,387°C at present to 2,634–2929°C and 2,825–3,097°C in 2040 and 2090, respectively.

Discussion

In this study, it was expected that the areas suitable for corn-corn DC would expand gradually, due to the warming climate, and that the northern limit for corn-corn DC would move to the northern part of the Kanto region until the end of the 21st century. However, in this study, only the data of temperature simulated was used, and other climate conditions were not taken into account. Besides the higher temperature, the higher atmospheric CO_2 and a change of precipitation will influence agriculture production in the future climate change[3]. Concerning the CO_2 concentration, several authors have reported that elevated CO_2 will not increase biomass or yield of corn significantly, except when water will be limited[11,12,15,22,30]. On the other hand, as for the precipitation, it is expected that the annual precipitation of Japan will not change significantly until the end of the 21st century[8], and any shortage of annual precipitation is not expected in the mean climate of Japan[8]. Therefore, the effects of the higher atmospheric CO_2 and a change of precipitation on corn production were not considered in this study.

Comparing the climate data simulated with the two climate models of MRI-CGCM3 and MIROC5, the annual mean temperature of MIROC5 was 0.92 and 0.78°C higher than that of MRI-CGCM3 in 2040 and 2090, respectively. This result that temperature projected by MIROC5 was higher than that by MRI-CGCM3 was consistent with the previous studies[7,31]. The difference in the results projected by MRI-CGCM3 and MIROC5 suggests a range of variation of the future climate changes. The effects of the temperature increase projected by the MIROC5 model will be at the maximum level in each CO_2 emission scenario[31].

Higher temperature climate sometimes causes a decline of corn yield due to shortening growth period[1,25], preventing pollination[2,4,6,24] and increasing demand for soil water[14]. Badu-Apraku *et al.* (1983) measured the length of the grain filling period of corn in 4 day/night temperature regimes of 25/15°C, 25/25°C, 35/15°C and 35/25°C, and reported that the higher temperature conditions shortened the grain filling periods and reduced whole plant and grain yield[1]. Moreover, as a result of a simulation study, Seino (1995) reported that, in the Kyushu region, a temperature increase of 2–4°C would reduce 9–16% of whole plant dry matter yield of corn, due to shortening its growth period[25]. On the other hand, Herrero and Johnson (1980), Schoper *et al.* (1987) and Dupuis and Dumas (1990) reported that pollen viability of corn decreased when exposure to temperatures above 35–36°C occured[2,6,24], and Gourdji *et al.* (2013) projected that the percentage of global harvested area exposed to at least five reproductive days over 35°C would increase from 15% in the 2000s to 44% in the 2050s[4]. However, Lobell *et al.* (2013) indicated that increasing demand for soil water had a more significant negative effect on the yield reduction of rainfed corn in the United States than the direct heat stress on reproductive organs of corn[14].

It is also known that these negative effects of higher temperature on corn yield can be observed not only in the low latitude areas, but also in mid latitude areas. Using both observed and simulated corn grain yield data in the US, Muchow *et al.* (1990) reported the highest grain yields were from locations with relatively cool growing season mean temperatures (18.0–19.8°C at Grand Junction, Colorado), compared to warmer sites, for example, Champaign, Illinois (21.5–24.0°C), or warm tropical sites (26.3–28.9°C) [18]. To alleviate these negative effects of higher temperature, changing cropping period is one of the effective methods[17]. As shown on Table 2, in Ebina City, mean temperatures of the growth periods corresponding to the first and second cropping of corn-corn DC were 3.1°C lower than that of the conventional corn cropping period. Furthermore, it was projected that, both in 2040 and 2090, the mean temperatures during the first and second corn cropping periods would be 2.5–3.3°C lower than that for the conventional corn cropping period. Therefore, it is concluded that corn-corn DC is one of the effective countermeasures to decrease temperature during the corn growth period[17].

Furthermore, it has been reported that, in the area suitable for corn-corn DC, annual total yield of corn-corn DC is higher than that of corn-winter forage crop DC[16,21]. Meng *et al.* (2017) indicated that, due to significant warming, a corn-corn DC could replace the traditional DC with summer corn and winter wheat (*Triticum aestivum* L.) in the North China Plain, and the corn-corn DC improved yield by 14–31% compared with the conventionally managed summer corn and winter wheat system[16]. In Japan, Orihara (2017) reported that dry matter yield in corn-corn DC was 20% higher than that of the conventional DC with corn and Italian ryegrass in the southern parts of the Kanto region[21]. Therefore, it is expected that, responding to future climate change, corn-corn DC will be adopted as one of the main cropping systems for producing high quality forage, replacing the conventional DC with summer corn and winter forage crops in the wide areas from the Kyushu region to the Kanto region.

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RCP4.5 シナリオのもとでの２つの気候モデルを用いたサイレージ用トウモロコシ（*Zea mays* L.）の二期作適地の変化予測

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摘　要

代表的濃度経路（RCP）シナリオ 4.5 のもとで２つの気候モデル（MRI-CGCM3 および MIROC5）を用いて得られた気象予測データを用い，我が国におけるサイレージ用トウモロコシ（*Zea mays* L.）の二期作栽培適地の将来予測を行った。2040 年および 2090 年の年間の 10℃基準有効積算温度を 2031 年から 2050 年の平均値および 2081 年から 2100 年の平均値として二次メッシュ（約 10 km × 10 km）ごとに計算した。トウモロコシ二期作の栽培適地は 10℃基準有効積算温度が 2,300℃以上の地域として判定した。我が国におけるトウモロコシ二期作の栽培適地となる二次メッシュの割合は現在（1981 年～ 2000 年）の 21.4% から，2040 年には 33.4 ～ 44.3% へ，2090 年には 40.1 ～ 48.2% に増加し，2090 年までに栽培適地は関東地方北部まで拡大することが予測された。また，既にトウモロコシ二期作の栽培適地となっている神奈川県海老名市の二次メッシュ予測データより，2040 年および 2090 年においても，トウモロコシ二期作の１作目，２作目の栽培期間の平均気温は慣行二毛作における夏作トウモロコシの栽培期間の平均気温よりも低く，トウモロコシ二期作は生育期間中の高温による影響を緩和する対策技術として有効であると考えられた。

キーワード：気候変動，栽培適地，トウモロコシ二期作，*Zea mays* L.