Research Article

Impacts of Future Climate Changes on Shifting Patterns of the Agro-Ecological Zones in China

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An agroecological zone (AEZ) is a land resource mapping unit, defined in terms of climate, landform, and soils, and has a specific range of potentials and constraints for cropping (FAO, 1996). The shifting patterns of AEZs in China driven by future climatic changes were assessed by applying the agroecological zoning methodology proposed by International Institute for Applied Systems Analysis (IIASA) and Food and Agriculture Organization of the United Nations (FAO) in this study. A data processing scheme was proposed in this study to reduce systematic errors in projected climate data using observed data from meteorological stations. AEZs in China of each of the four periods: 2011–2020, 2021–2030, 2031–2040, and 2041–2050 were drawn. It is found that the future climate change will lead to significant local changes of AEZs in China and the overall pattern of AEZs in China is stable. The shifting patterns of AEZs will be characterized by northward expansion of humid AEZs to subhumid AEZs in south China, eastward expansion of arid AEZs to dry and moist semiarid AEZs in north China, and southward expansion of dry semiarid AEZs to arid AEZs in southwest China.

1. Introduction

The world is facing a crisis in terms of food security [1, 2]. The challenge is from not only the growing global population but also the sustainability of nutritious food supply. In order to meet global demands, food production should increase 60–70% by 2050 compared with that at the beginning of the 21st century [3]. Climate change is now widely recognized as one of the most critical influences on sustainability of food supply. It changes the suitability of crop and investment structure in agriculture. Researchers have confirmed that the crop suitability shifts in the context of climate change [4–7]. Lane and Jarvis [8] predicted the impact of climate change with current and projected future climate data and found that the suitable area of main food crops including rice, wheat, potato, and some cash crops such as apple, banana, coffee, and strawberry would reduce along with climate change. According to the evaluation of Easterling et al. [9], even in the scenario of Intergovernmental Panel on Climate Change (IPCC) low emissions (B1, with a 2°C rise in global mean temperatures by 2100) the current farming systems will be destabilized. If the increasing suffering from

chronic hunger is frustrating today, the further difficulties, risks, and challenges for achieving food security will make people desperate, especially for those in South Asia and sub-Saharan Africa [10, 11].

China, which experienced rapid growth and increased integration with the global economy in recent years, has significant potential to contribute to global food security not only by alleviating hunger among its own citizens, but also by increasing trade and financial linkages as well as technology and knowledge exchanges with other developing countries [12]. China has made remarkable progress in reducing poverty, cutting the share of people living on less than \$1.25 a day from 84 percent of the population in 1981 to 13 percent in 2008 and reducing the number of poor people from 835 million to 174 million [13]. In recent years, the development of China's agricultural production is very stable which significantly contributes to global security [14, 15]. But there are still some potential challenges for China's food supply. One of the most probable challenges is climate change. Now and in the future, China's food supply will be a key issue for the world food market.

There are various ways such as the frequency and intensity changes of disasters (including flood, drought, hail, and typhoon) and the changes of precipitation, accumulated temperature, and solar radiation that climate changes influencing China's agricultural production. Though most of these influences are occasional and small-scaled, there are still some influences that are persistent and massive [16–18]. The variation of AEZs may be one of the most notable responses of climate changes that can alter the pattern of crop and agricultural management. The AEZ concept was originally developed by the FAO [19]. It has widespread applications in land use planning, design of appropriate agricultural adaptations, reducing vulnerability, as well as crop water requirements and long-term frost protection measures determination [20, 21]. There are many researches on agroecological zoning in China and relevant topics [22–27]. Chen [28] classified China into twelve AEZs based on the mode of agricultural production, the productivity of farmland, heat, water, and landform. Jin and Zhu [29] divided Northeast China into three AEZs and found that the maize yields are reduced significantly along with climate change. Yang et al. [30] applied the method proposed by Chen [28] to classify Northwest China into thirteen AEZs and analyzed the climate-induced changes in crop water balance in each AEZ. He et al. [31] divided Chinese wheat producing area into three major regions and ten AEZs depending on the produced grain traits, ecological factors, soil properties, cropping system, and so on. On the basis of these ten AEZs, Kong et al. [32] proposed a number of potential strategies to increase the grain protein content and protein-based grain processing quality. Jia et al. [33] studied the variation of precipitation and found the AEZ-based research help to master the precipitation patterns of different agricultural regions. As a determinant of cropping pattern and agriculture management, the pattern of AEZs may change significantly under the background of global climate changes. There is no doubt that an assessment of shifting patterns of AEZs in China is helpful to guide the nation's future agricultural development and guarantee global food security.

The global agroecological zones (GAEZs) were developed in order to provide a prediction for crop potential productivity in a specific environment under limiting factors including climate and soil [34]. They were used as the main analysis units of agricultural production in Global Trade Analysis Project (GTAP) as well as a lot of other researches [35]. For example, Atehnkeng et al. [36] analyzed the distribution and toxigenicity of *Aspergillus* species isolated from maize kernels from three AEZs in Nigeria. Palm et al. [37] analyzed environmental and socioeconomic barriers for plantation activities on local and regional levels and investigated the potential for carbon finance to stimulate the increased rates of forest plantation on wasteland in southern India combined with AEZs. IIASA and FAO had published the GAEZ version 3.0 aiming to include practical applications such as a significantly updated version, including expanded crop coverage and dryland management techniques. This dataset provides climate change impacts on agroecological suitability and productivity for three time horizons, 2020s, 2050s, and 2080s, for 11 combinations of GCMs and IPCC emission scenarios, which is

global significance [38]. But it is a little bit sketchy for guiding national and regional agriculture developments because more detailed and accurate data can always be obtained to support agroecological zoning at such scale. Mugandani et al. [39] reclassified the AEZs of Zimbabwe based on the climatic data from meteorological stations to cover the shortage of GAEZ. Kurukulasuriya and Mendelsohn [40] compared the observed distribution of AEZs from FAO and the calculated distribution of AEZs given climate and found there were significant local differences. These studies imply that it makes sense to access the impacts of future climate changes on shifting patterns of the AEZs by using more detailed and accurate data at regional and national levels.

This study aims to assessing the shifting patterns of AEZs in China driven by future climate changes. The major contribution of this paper is that it provides future AEZs in China which contains decision making information for agriculture development in China and global food security. Compared with GAEZ, this study takes full advantage of observed climate data from meteorological stations. And compared with other static assessment results based on historical period data such as Chen [28], this study provides more predictive information of shifting patterns of AEZs. In addition, the data processing scheme of integrating observed and predicted data of this study has high reference value for similar studies. AEZs in China of four periods: 2011–2020, 2021–2030, 2031–2040, and 2041–2050 were drawn in this study based on the projected climatic changes. It is found that the future climate changes will lead to significant change of AEZs in China, while the overall pattern of AEZs in China is stable. The northward expansion of humid AEZs to subhumid AEZs in south China, eastward expansion of arid AEZs to dry and moist semiarid AEZs in north China, and southward expansion of dry semiarid AEZs to arid AEZs in southwest China are the major characteristics of future AEZs changes in China.

2. Data and Methodology

2.1. Agroecological Zoning Methodology. The AEZ is a zone characterized by specific length of growing period (LGP) and climatic attributes. Several agroecological zoning methods have been previously used for agricultural purposes [41, 42]. The Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin derived six global LGPs by aggregating the IIASA/FAO GAEZ data into six categories of approximately 60 days per LGP: (1) LGP1: 0–59 days, (2) LGP2: 60–119 days, (3) LGP3: 120–179 days, (4) LGP4: 180–239 days, (5) LGP5: 240–299 days, and (6) LGP6: more than 300 days [43]. These six LGPs roughly divide the world along humidity gradients, in a manner that is generally consistent with previous studies in global agro-ecological zoning [44]. They are calculated as the number of days with sufficient temperature and precipitation/soil moisture for growing crops. In other word, LGPs are calculated as the number of days in the year when average daily temperature (T_a) and precipitation plus moisture stored in the soil (P) are above their thresholds. In GAEZ, three standard temperature

TABLE 1: Definition of agroecological zones used in Global Trade Analysis Project.

AEZs	LGP	Climatic zone	AEZs	LGP	Climatic zone
AEZ1	0–59	Tropical	AEZ4	180–239	Tropical
AEZ7		Temperate	AEZ10		Temperate
AEZ13		Boreal	AEZ16		Boreal
AEZ2	60–119	Tropical	AEZ5	240–299	Tropical
AEZ8		Temperate	AEZ11		Temperate
AEZ14		Boreal	AEZ17		Boreal
AEZ3	120–179	Tropical	AEZ6	≥300	Tropical
AEZ9		Temperate	AEZ12		Temperate
AEZ15		Boreal	AEZ18		Boreal

thresholds for temperature growing periods are used: (1) periods with $Ta > 0^\circ\text{C}$, (2) periods with $Ta > 5^\circ\text{C}$, which is considered as the period conducive to plant growth and development, and (3) periods with $Ta > 10^\circ\text{C}$, which is used as a proxy for the period of low risks for late and early frost occurrences. In this study, we choose the second standard temperature threshold ($Ta > 5^\circ\text{C}$) for calculating LGPs in China. We set the threshold of precipitation plus moisture stored in the soil as half the potential evapotranspiration (ET) ($P > 0.5 \text{ ET}$) to keep it consistent with FAO [45]. Therefore, LGP used in this study is defined as follows:

$$\text{LGP} = \text{Card} \{(Ta_i, P_i) \mid Ta_i > 5^\circ\text{C}, P_i > 0.5 \text{ ET}_i\}, \quad (1)$$

where Ta_i ($^\circ\text{C}$) is the average daily temperature of the i th day in the year; P_i (mmday^{-1}) is the precipitation plus moisture stored in the soil of the i th day in the year; ET_i (mmday^{-1}) is ET of the i th day in the year; Card is the cardinality function counting the number of elements of a set.

In addition to the LGP breakdown, the world is subdivided into three climatic zones, tropical, temperates and boreal, using criteria based on absolute minimum temperature and growing degree days (GDD), as described by Ramankutty and Foley [46]. Concretely, the climatic zone rules are as follows:

zone

$$= \begin{cases} \text{tropical,} & \text{if } t_{\min} > 0^\circ\text{C}, \\ \text{temperate,} & \text{else if } t_{\min} > -45^\circ\text{C}, \text{ GDD}_5 > 1200, \\ \text{boreal,} & \text{else,} \end{cases} \quad (2)$$

where $t_{\min}$ ($^\circ\text{C}$) is the absolute minimum temperature; GDD_5 is the annual number of accumulated growing degree days above 5°C . GDD_5 are calculated by taking the average of the daily maximum and minimum temperatures compared to the base temperature, 5°C .

$$\text{GDD}_5 = \sum_{i=1}^{365} \left(\frac{Td_{i,\min} + Td_{i,\max}}{2} - Td_{\text{base}} \right), \quad (3)$$

where $Td_{i,\min}$ and $Td_{i,\max}$ are the daily maximum and minimum temperatures, respectively; Td_{base} ($=5^\circ\text{C}$) is the

base temperature. We employ the definition of AEZs used in the GTAP land use database [35], which divides the world into 18 AEZs (Table 1).

2.2. Data and Process. Both observed and projected climate data were used in this research to assess the shifting patterns of AEZs in China driven by climatic changes. This dataset includes climatic data, moisture stored in the soil, and ET. Historically observed climate data including average daily temperature, precipitation, absolute minimum temperature, and daily maximum and minimum temperatures were collected by the China Meteorological Administration for the year 2006. The spline interpolation method is used to interpolate these data using a 100 m digital elevation model developed by Chinese Academy of Sciences. This interpolative method is selected because it takes into account the climatic dependence on topography by using a trivariate function of latitude, longitude, and elevation [47–50] and balances the smoothness of fitted surfaces and the fidelity of the data by minimizing the generalized cross-validation automatically [51]. Observed data of moisture stored in the soil comes from soil categories and soil composite data sets at the scale of 1:1,000,000. This data set were developed according to the survey results of the second national soil census data, covering 1,572 soil profiles in 100 cm depth layer [52–55]. The ET data comes from the MODIS (Moderate Resolution Imaging Spectroradiometer) Global Evapotranspiration Project (MOD16). This project aims to estimate global terrestrial evapotranspiration by using satellite remote sensing data [56, 57]. The missing values of ET data are complemented using the spline interpolation method.

The projected climate data including average daily temperature, daily precipitation, absolute minimum temperature, and daily maximum and minimum temperatures from 2006 to 2050 comes from the data sets produced from Hadley Centre Coupled Model version 3 (HadCM3) GCM (Global Circulation Model) under greenhouse-gas emission scenario of B2. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels [58]. The data is

originally obtained with a spatial resolution of $2.50^\circ \times 3.75^\circ$ and downscaled to $1\text{ km} \times 1\text{ km}$ using the spline interpolation method. A data processing scheme is designed to reduce systematic errors generated by HadCM3 and improve the assessment accuracy of the shifting patterns of AEZs in China (Figure 1). First, the changes of average daily temperature, daily precipitation, absolute minimum temperature, and daily maximum and minimum temperatures of each year from 2011 to 2050 compared with those of 2006 are calculated using the projected climate data:

$$\Delta K_{i,y} = K_{i,y} - K_{i,2006}, \quad (4)$$

where $K_{i,2006}$ refers to the projected average daily temperature, daily precipitation, daily maximum and minimum temperatures of the i th day, and absolute minimum temperature, in 2006; $K_{i,y}$ ($y = 2011, 2012, \dots, 2050$) refers to the projected average daily temperature, daily precipitation, daily maximum and minimum temperatures of the i th day, and absolute minimum temperature, in the y th year and $\Delta K_{i,y}$ refers to the changes of average daily temperature, daily precipitation, absolute minimum temperature, and daily maximum and minimum temperatures of each year from 2011 to 2050 compared with those of 2006. Second, the corrected climate data can be generated by adding $\Delta K_{i,y}$ to the observed climate data of 2006:

$$Q_{i,y} = Q_{i,2006} + \Delta K_{i,y}, \quad (5)$$

where $Q_{i,2006}$ refers to the observed average daily temperature, daily precipitation, daily maximum and minimum temperatures of the i th day, and absolute minimum temperature, in 2006; $Q_{i,y}$ refers to the corrected average daily temperature, daily precipitation, daily maximum and minimum temperatures of the i th day, and absolute minimum temperature, in the y th year. By these two steps, the systematic errors in projected climate data generated by HadCM3 are reduced. Considering that climate change is a long-term shift in weather conditions, we then take the average for ten years of the corrected climate data to assess the shifting patterns of AEZs driven by future climate changes:

$$Q_{i,p-(p+9)} = \frac{1}{10} \sum_{y=p}^{p+9} Q_{i,y}, \quad (6)$$

where $Q_{i,p-(p+9)}$ ($p = 2011, 2021, 2031, 2041$) refers to the ten-year averaged climate data including average daily temperature, daily precipitation, daily maximum and minimum temperatures of the i th day, and absolute minimum temperature, in the periods of 2011–2020, 2021–2030, 2031–2040, and 2041–2050. Finally, future AEZs in China are obtained with the ten-year averaged climate data and data of moisture stored in the soil and ET.

3. Results and Discussion

The assessment results show that there are totally fourteen AEZs in China, most of which will experience pattern shifting from 2011 to 2050 (Figure 2). The AEZ4, AEZ5, and AEZ6

FIGURE 1: Data processing scheme for assessing the shifting patterns of agroecological zones in China.

characterized by tropical climate will be mainly found in the extreme south of China (Figure 2). The AEZ4 will be stable in pattern and area over time and covers 0.16 million hectares, and this translates to no more than 0.02% of the whole country (Table 2). The area of AEZ5 will increase from 1.08 million hectares to 1.76 million hectares from 2011 to 2050 with an area expansion of 63.73%. This area increase will mainly happen in the period of 2021–2040. The new area of AEZ5 will be mainly transferred from AEZ6 (Table 3). The AEZ6 will experience an area decreasing from 10.44 million hectares to 9.57 million hectares during the period from 2011 to 2050 (Table 2). Besides the conversion to AEZ5, the area decrease of AEZ6 will be also due to the southward expansion of AEZ11 (Table 3, Figure 2).

The AEZ11 and AEZ12 will occupy most area of south China (Figure 2). The AEZ12 will cover about 16% of the whole of China and expand by 3.88 million hectares from 2011 to 2050 (Table 2). This expansion will be mainly because of the westward expansion being larger than the southward shrink of AEZ12 (Figure 2). And the newly added area of AEZ11 cannot counterbalance the reduced area from AEZ12 expansion (Table 3). Consequently, the area of AEZ11 will reduce from 85.50 million hectares in 2011 to 82.48 million hectares in 2050 (Table 2). Moreover, the northward movement of northern side boundary of AEZ11 implies that there will be LGP reduction that happened in central China. The area of AEZ10 will decline from 53.52 million hectares to 47.34 million hectares from 2011 to 2050 mainly due to the southward expansion of AEZ11 in central China and the expansion of AEZ9 in northwest China (Table 3). The center of gravity of AEZ9 will shift to the east due to the overall northward movement of AEZ10 but its area which is about 60.00 million hectares will keep stable (Table 2).

Most of the area of northern China will belong to AEZ7 and AEZ8 (Figure 2). The AEZ7 will cover 200.23 million

FIGURE 2: Future agroecological zones in China, 2011–2050.

hectares in the period of 2011–2020 and expand to 207.76 million hectares in the period of 2041–2050 (Table 2). This area increase is mainly because of the conversion from AEZ8 to AEZ7 (Table 3). And there will be significant area reduction of AEZ7 due to the expansion of AEZ13 in northwest China (Table 3). The area of AEZ8 will decrease from 90.05 million hectares to 83.41 million hectares from 2011 to 2050 mainly due to the eastward expansion of AEZ7 (Table 2 and Figure 2). The boundary change of AEZ7 and AEZ8 implies that there will be LGP reduction in northern China and temperature decrease in northwest China. Another significant change in northeast China will be the area reduction of AEZ15 (Table 2 and Figure 2). About one-fifth of the AEZ15

in northeast China will convert to AEZ8, AEZ9, and AEZ10 due to temperature rise (Table 3).

The AEZ13 will cover about 15% of the whole China and more than a half of southwest China (Table 2 and Figure 2). Its area will expand by 15.00 million hectares from 2011 to 2050 mainly due to the conversion from AEZ14 (Table 3). This indicates that the LGP in southwest China will be generally increased driven by future climate change. And AEZ14 will become more continuous along with climate change (Figure 2). The total area of AEZ15 will be reduced by 2.95 million hectares mainly due to its area decrease in northeast China (Table 2 and Figure 2). The AEZ16 and AEZ17 will mainly spread over southwest China (Figure 2).

TABLE 2: Areas of future agroecological zones in China.

AEZs	Area (unit: million hectares)			
	2011–2020	2021–2030	2031–2040	2041–2050
AEZ4	0.16	0.16	0.16	0.16
AEZ5	1.08	1.08	1.71	1.76
AEZ6	10.44	11.08	9.62	9.57
AEZ7	200.23	199.37	203.73	207.76
AEZ8	90.05	89.85	85.72	83.41
AEZ9	60.26	58.38	60.29	60.53
AEZ10	53.52	55.80	48.39	47.34
AEZ11	85.50	81.78	88.18	82.48
AEZ12	151.90	155.90	149.59	155.78
AEZ13	141.05	136.86	143.84	156.05
AEZ14	86.57	90.65	88.98	74.27
AEZ15	55.60	53.83	51.94	52.64
AEZ16	15.96	17.58	19.71	20.10
AEZ17	0.49	0.49	0.96	0.97

The AEZ16 will cover 15.96 million hectares in the period of 2011–2020 and expand to 20.10 million hectares in the period of 2041–2050 (Table 2). These newly expanded areas of AEZ16 will mainly come from AEZ15 (Table 3). The area of AEZ17 in China will be almost doubled due to future climate change though it will still cover an area of not more than 1 million hectares (Table 2).

On the whole, the pattern of AEZs in China will change significantly due to future climate change. The changed area will reach 32.00 million hectares accounting for 3.36% of the country's total area (Table 3). Certainly, the changes of AEZs in China are not monotonous. The direction inversion of boundary movement of AEZ12 in southwest China from the period of 2011–2040 to the period 2041–2050 is one of the most prime examples of such changes (Figure 2). But the overall change trend of AEZs in China including northward expansion in south China, eastward expansion in north China, and southward expansion in southwest China is persistent. These results are obtained using data sets produced from HadCM3 under greenhouse-gas emission scenario of B2. It is sure that some new results will be found by applying data set from other models and scenarios. And we will address them in future studies.

4. Conclusions

The shifting patterns of AEZs in China driven by climatic changes were assessed. The projected climate data and historically observed climate data as well as moisture stored in the soil and ET data are used in this study. By using the agroecological zoning methodology proposed by IIASA and FAO, we draw AEZs in China of each of the four periods:

2011–2020, 2021–2030, 2031–2040, and 2041–2050. The main conclusions from this study could be summarized as follows.

- (i) The overall pattern of AEZs in China will be stable in the future. The AEZ4, AEZ5, and AEZ6 will distribute mainly in the extreme south of China. The AEZ12, AEZ11, AEZ10, AEZ9, AEZ8, and AEZ7 will sequentially spread from north to south. The AEZ13 and AEZ14 will occupy most of the southwest of China. And besides AEZ15 partly distributing in the northeast of China, most of other AEZs (including AEZ15, AEZ16, and AEZ17) will distribute mainly in the southwest of China.
- (ii) The future climate change will lead to significant local changes of AEZs in China. The changes of AEZs will be not monotonous over time, but the overall change trend of AEZs is persistent. The future change of AEZs in China is characterized by area expansion of AEZ7, AEZ12, AEZ13, and AEZ16 and area reduction of AEZ8, AEZ10, AEZ11, AEZ14, and AEZ15. The shifting patterns of AEZs in China are characterized by northward expansion of humid AEZs to subhumid AEZs in south China, eastward expansion of arid AEZs to dry and moist semiarid AEZs in north China, and southward expansion of dry semiarid AEZs to arid AEZs in southwest China.
- (iii) The data processing scheme proposed in this study is helpful in reducing systematic errors in projected climate data which has high reference value for similar studies. Its feasibility has been proved by our empirical analysis. The application of observed data from meteorological stations will improve the assessment accuracy of impacts of future climate changes on shifting patterns of the AEZs in principle.

TABLE 3: Transition matrix of agroecological zones in China (unit: million hectares).

Transition from	Transition to															
	AEZ4	AEZ5	AEZ6	AEZ7	AEZ8	AEZ9	AEZ10	AEZ11	AEZ12	AEZ13	AEZ14	AEZ15	AEZ16	AEZ17		
AEZ4	—															
AEZ5		—	0.25 ^c													
AEZ6		0.63 ^b 0.30 ^c	—					0.42 ^b	0.40 ^b							
AEZ7				—						2.44 ^a 3.29 ^b 2.14 ^c						
AEZ8		6.63 ^b 5.08 ^c			—	0.72 ^b				0.31 ^b	0.20 ^a 0.87 ^b					
AEZ9					3.29 ^b 2.77 ^c	—	3.37 ^a 1.17 ^c					0.21 ^b				
AEZ10						1.09 ^a 4.37 ^b 2.30 ^c	—	2.82 ^b 1.02 ^c				0.24 ^b				
AEZ11			0.24 ^a					—	4.68 ^a 0.24 ^b 7.85 ^c			0.44 ^b 0.24 ^c	0.28 ^b	0.47 ^b 0.29 ^c		
AEZ12			0.40 ^a					0.57 ^a 8.81 ^b 1.66 ^c	—				0.26 ^b			
AEZ13		1.58 ^a 1.02 ^b 1.10 ^c								—	5.53 ^a 9.8 ^b	2.61 ^a 0.25 ^b 3.12 ^c				
AEZ14					0.91 ^b					3.10 ^a 14.43 ^b 13.74 ^c	—	1.41 ^a 2.00 ^b 0.98 ^c				
AEZ15					0.20 ^b	0.40 ^a 0.32 ^b 1.88 ^c	1.10 ^c	0.27 ^a		0.02 ^b 0.55 ^c	2.86 ^a 3.54 ^b 0.01 ^c	—	2.26 ^a 3.78 ^b 0.72 ^c			
AEZ16								0.35 ^a 0.40 ^b	0.29 ^a		1.45 ^b	2.83 ^b	—	0.33 ^c		
AEZ17												0.61 ^c		—		

Notes. ^a From period of 2011–2020 to period of 2021–2030; ^b from period of 2021–2030 to period of 2031–2040; and ^c from period of 2031–2040 to period of 2041–2050.

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