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Climate warming and land use change in Heilongjiang Province, Northeast China

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ABSTRACT

This study explores the relationship between climate warming and rice paddy expansion in Heilongjiang Province of China. It is found that paddy fields more than quadrupled from 3479 km^2 in 1958 to 14 564 km^2 in 1980, and increased further to 21,940 km^2 in 2000. The newly gained paddy fields originated chiefly from dry fields (46.35%), swamps (30.22%), and primary forest (nearly 10%) during 1958–1980. During 1980–2000 paddy fields expanded at the expense of dry fields (70.50%), swamp (16.59%), and grassland (10.13%). Analysis of climate data shows a warming of over 2 °C from the 1960s to the 2000s in most places. All 28 meteorological stations except one experienced a warming trend. Spatially, the expansion of paddy fields coincided closely with the spatial distribution of annual temperature. These fields were located mostly between the isolines of 2–3 °C. Sowing area of grain increased at a modest rate during the 1970s and the 1980s when >0 °C area expanded rapidly. However, sowing area of rice rose in the 1990s and 2000s at a rate twice higher than that for sowing area of grain in the preceding decades. Thus, the expansion of paddy fields at the expense of other land covers was made possible owing to climate warming in the preceding decade. On average, it takes about 20 years for agricultural practices to adapt to the warmer climate.

Introduction

There is a complex and mutually interactive relationship between climate change and land cover change (Dale, 1997). On the one hand, anthropogenic factors such as land use change modify climate (Feddema et al., 2005). Land cover changes caused significant changes in regional climate, especially temperature (Zhao, Pitman, & Chase, 2001; Qian & Ding, 2005). The replacement of one land cover by another may be accompanied by changes in surface albedo, latent heat flux, and energy redistribution (Timbal & Arblaster, 2006). Clearance of vegetation causes less evaporation from soil and the formation of cloud in the atmosphere. This explains the rise in temperature and decrease in precipitation at the regional scale. The fact that an overwhelming majority of weather stations exhibited significant warming trends after greatest land cover change, but only relatively few significant temperature trends before periods of greatest land cover change (Hale, Gallo, Owen, & Loveland, 2006) demonstrates that land cover change is a potentially important contributor to the changes in regional climate. On the other hand, the changed climate exerts an influence on land cover change (Liu, Y. S., Wang, & Gao, 2005; Gao, Liu, & Chen, 2006). For instance, drought can induce rapid land cover changes even over a short period of time (Reid et al., 2000; Pitman, Narisma, Pielke, Sr., & Holbrook, 2004). Climate change is even able to dictate the type of land cover change permissible in a geographic region through its influence on the flux of mass and energy balance near the Earth's surface.

So far land use change has been extensively studied at various scales ranging from local to global using modern geoinformatics technologies such as remote sensing and geographic information systems (Lambin & Ehrlich, 1997; Foody, 2001; Petit, Scudder, & Lambin, 2001; Chen, 2002; Loveland et al., 2002; Rogan et al., 2003; Comber, Law, & Lishman, 2004). As early as the 1990s attention was paid to the commercial operation of land cover change detection from satellite data (Green, Kempka, & Lackey, 1994). Owing to their panoramic views and currency, remotely sensed data have proved vital in monitoring land cover change. Multispectral bands of satellite data are usually classified to produce land cover maps that are used to detect land cover change in a post-classification session (Shalaby & Tateishi, 2007; Dewan & Yamaguchi, 2009), or using the raw images directly based on image differencing or ratioing (Lu, Mausel, Batistella, & Moran, 2005). Apart from multi-temporal remotely sensed data (Lunetta, Knight, Ediriwickrema, Lyon, & Worthy, 2006), topographic maps and general land use maps are also used in the change detection (Dimyati, Mizuno, Kobayashi, & Kitamura, 1996; Petit & Lambin, 2001). In addition to detection of changes taking place in the past, it is also possible to predict the future change in land cover based on the past trends (Mertens & Lambin, 2000).

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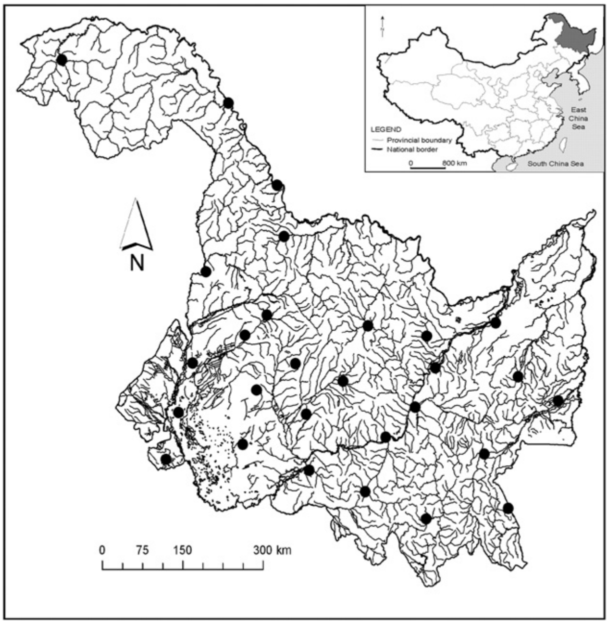

Fig. 1. Location of the study area in China. Line: rivers; dots: weather stations.

In studying the relationship between climate change and land use change, attention has been focused on the influence of the latter on the former, mostly via simulation (Narisma & Pitman, 2003; Salmun & Molod, 2006). Land cover changes are simulated to cause a significant warming in Amazonia (Correia, Alvalá, & Manzi, 2008). Modification of current land cover would bring significant changes to the local and remote climate (Cui, Graf, Langmann, Chen, & Huang, 2006). Simulations show that land cover change caused temperature perturbations only in those regions of land cover modification initially, but in remote regions later (Zhao et al., 2001). By comparison, few have examined the impact of climate change on land cover change, especially benign land cover change. As an example, a warming climate regime is beneficial to primary production in subarctic regions (Nemani et al., 2003). With a fragile and vulnerable environment, the subarctic is a region highly sensitive to climate change, and hence an ideal place to study the impact of climate change on land cover change. Formerly not so productive use of the land may be replaced by more intensive use. Under a warmer climate it is even possible to cultivate rice in the formerly inhospitable environment (Ohta & Kimura, 2007). Nevertheless, nobody has explored the causal relationship between climate change and land use change except at the conceptual level (Dale, 1997).

This research attempts to assess the impact of climate warming on land use change in subarctic China where a slight warming can lead to profound changes in land use intensity. In particular, this paper tries to understand how land cover changes in response to a warmer climate. The focus is placed on change from non-farmland to rice paddy fields that require a certain amount of energy for cultivation. The specific objectives are (1) to ascertain the extent of paddy fields and its temporal variation in Heilongjiang Province of China over the last 60 years; (2) to establish the spatiotemporal pattern of climate warming; and (3) to explore the spatial correlation between the expanded paddy fields and the observed trend of climate warming in the study area.

Study area

The area selected for this study is Heilongjiang province located between 121°13′–135°05′E in longitude and 43°22′–53°24′N in latitude (Fig. 1). This northernmost Province of China has a territory of 454,000 km^2 and a population of 38.17 million with a continental monsoon climate. Annual temperature in Heilongjiang ranges from −4 to 4 °C. Winters are long and frigid, summers short and cool. Annual rainfall averages 500–600 mm, concentrated mostly in the summer season. Mountainous areas account for 59% of the land. Its topography is dominated by a few mountain ranges. Two of the most important ones are the Greater Khingan and Lesser Khingan, both being an important timber base in China. The interior of the province is relatively flat and low in altitude. The most productive land is located in the low-lying terraces formed by the Heilong and Wusu (Ussuri) rivers adjoining Russia. They used to be low-lying wetlands of 50–250 m above sea level that have been claimed as farmland. After decades of land reclamation, Heilongjiang has become one of the most important bases of agricultural products such as grain and timber. Nicknamed as the “Great northern granary”, this subarctic province produced more than 43.53 million tons of grain in 2009 with 2.85 million ha of cultivated land.

Methods

Data used

The data collected include meteorological data, a land use map, satellite data, and grain cultivation area statistics. Temperature data were collected from the DataCenter of the National Meteorological Bureau of China. These observations were made at 28 stations distributed throughout the province (Fig. 1) at a wide range of elevations. Few stations are found in the far north due to a low population there. These data have been aggregated to the monthly interval, covering a period from January 1961 to December 2008. Also contained in the dataset are the location (latitude and longitude) and elevation of each station. A land use map of Northeast China was collected from the Institute of Geographical Science and Natural Resources, ChineseAcademy of Science. It was produced from visual interpretation of aerial photographs taken in 1958 at a scale of 1:3 million. This map displayed ten categories of land covers, the major types being rice paddies, dry fields, grassland, forest, and marshes. In addition, Landsat TM/Enhanced TM Plus (ETM+) images recorded in 1980 and 2000 were also collected from the ground receiving station in Beijing. About 58 images in each year were acquired to cover the entire study area. These images were recorded during the June–September period when spectral disparity between farmland and other covers was maximal.

Data processing

After the 1958 land use map was scanned in Adobe Photoshop, the ten land covers in different colours were extracted by their colour. Each extracted land cover was saved as a separate layer and exported to ArcGIS as a raster image, and projected to the UTM (zone 51 north) coordinate system. These raster images were vectorized and clipped against the provincial boundary layer. Similar steps were taken for each of the land cover layers to ensure that the smallest land use type maintained its presence on the relatively larger layers. Finally, a new shape file was created, to which all the other variables in other land use shape files were added. A new field was added to the attribute table of the newly created shape file for calculating the area of each polygon. The collected satellite images were visually interpreted to map land covers that included paddy fields, dry fields, grassland, and forest using the false colour composites of bands 4, 3 and 2 in PCI® (version 7.0). These land covers were delineated through on-screen digitization according to a pre-determined classification scheme. The accuracy of these

Table 1
Land cover and its change in three periods (unit: km^2)

Land cover	1958	1980	Change 1958–1980	2000	Change 1980–2000
Paddy fields	3479	14, 564	11, 085 (504/yr)	21, 940	7376 (369/yr)
Dry fields	98, 825	127, 982	29, 157	138, 148	10, 166
Woodland	238, 335	216, 782	−21, 553	207, 629	−9153
Grassland/barren	26, 652	37, 988	11, 336	31, 966	−6022
Built-up areas	386	8678	8292	8784	106
Water	1576	15, 615	14, 039	14, 905	−710
Swamp	80, 066	28, 631	−51, 435	25, 203	−3428
Sandy	1777	4046	2269	3976	−70
Sum	451, 096	454, 286	3190	452, 551	−1735

mapped covers was assessed through a combination of field visits and comparison with existing statistics, and was found to be satisfactory (e.g., over 90%).

After they were aggregated to yearly observations in Excel®, the temperature data were averaged over a decade from the 1960s to the 2000s. These point-based data were subsequently imported to ArcGIS together with the easting and northing coordinates. They were interpolated using kriging (with the default settings, e.g., a linear model without the nugget effect) to generate the spatially distribution of temperature over the province at a decadal interval. The interpolated temperature maps were visualized at an interval of 1 °C. This process was repeated for the rise in decadal temperature from the 1960s to the 2000s exactly except the interval of the isolines that was reduced to 0.5 °C.

Spatial analysis

The three land cover maps in 1958, 1980 and 2000 were overlaid spatially with each other to detect the change in rice paddy fields, especially the conversion from other covers, such as woodland, grassland, and dry fields to paddy fields. The overlaid maps were further queried to determine the amount of change quantitatively. The five decadal temperature distribution maps were overlaid with themselves first to identify the northward shift of the 0 °C isoline and the geographic area covered by each shift during each decade. This isoline was singled out for detailed analysis because previous researchers have established that rice grows only in a climate zone with annual temperature above zero degrees (Zhang, Liu, & Zhang, 2003). The area and the distance of shift were measured by tracing the isolines in ArcGIS. The produced decadal temperature distribution maps were also overlaid with the rice paddy distribution maps to relate their patterns and rates of expansion to climate change in an effort to establish the relationship between land cover change and climate warming.

Results

Expanding paddy fields

Back in 1958 there were a small quantity of rice paddy fields at only 3479 km^2 (Table 1), accounting for 0.77% of the province's territory. Most of the paddy fields were distributed in the southern portion of the province in close proximity to the SonghuaRiver. However, this quantity more than quadrupled to 14 564 km^2 by 1980, an increase of 13 814 km^2 at an annual rate of 504 km^2. In 1980 rice paddy fields, however, was still a minor land cover, surpassing only built-up area and sandy land in dominance. The area of paddy fields rose to 21 940 km^2 during the next two decades. The net increase mounted to only 7376 ^{2}, a much slower pace of only 369 km^2 per annum than in the previous period.

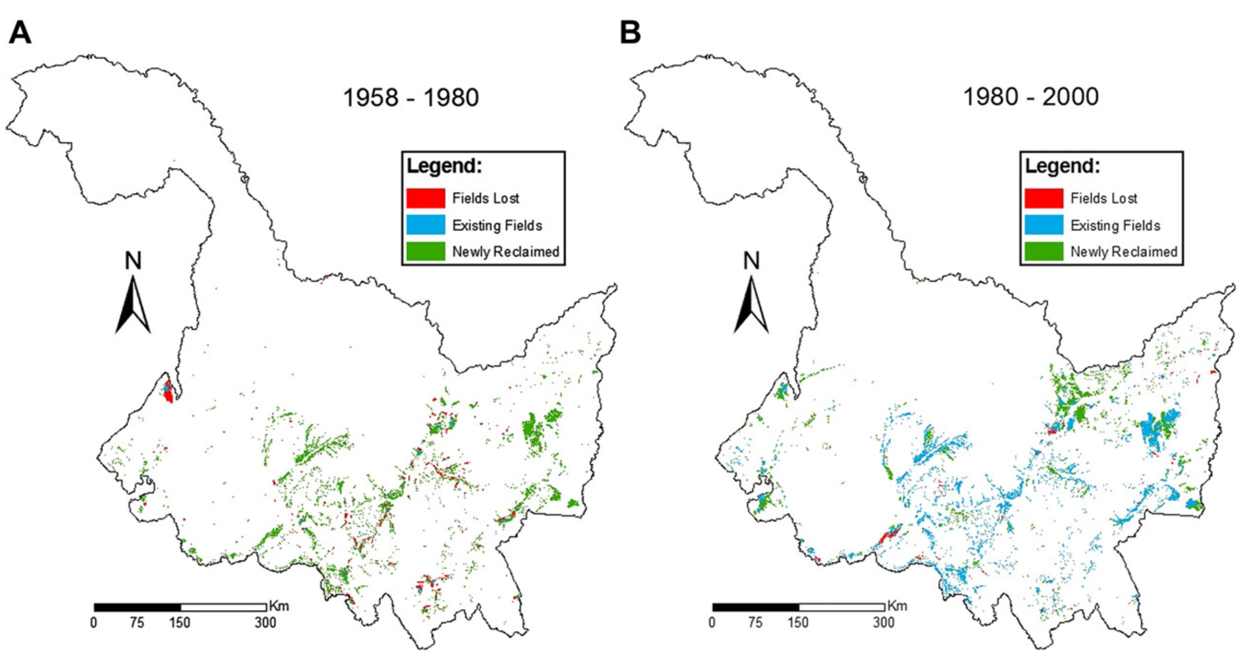

Fig. 2. Expansion and disappearance of rice paddy in relation to existing paddy fields. A: from 1958 to 1980; B: from 1980 to 2000.

Table 2
Source land covers of newly claimed rice paddy in 1980 and 2000.

Land cover	1980		2000	
	km^2	%	km^2	%
Sandy	91.4	0.66	0.0	0.00
Desert	154.3	1.12	8.9	0.11
Dry fields	6403.2	46.35	5968.9	70.50
Primary/dense forest	1306.7	9.46	102.5	1.21
Secondary forest	955.8	6.92	40.2	0.47
Grassland	573.0	4.15	857.2	10.13
Built-up	25.2	0.18	0.0	0.00
Water	130.4	0.94	84.1	0.99
Swamp	4174.0	30.22	1404.2	16.59
Sum	13 814	100.00	8466.1	100.00

Therefore, rice paddy fields expanded at a subdued pace. A potential explanation for this reduction is the declined availability of suitable land resources (e.g., flat and close to water resources). Despite the expansion, rice paddy is still a minor land cover, treading behind grassland and swamp in area. Spatially, from 1958 to 1980 the expansion of rice paddy fields took place in the lower one third of the province where the land is relatively flat and adjacent to water resources (Fig. 2A). The expansion of paddy fields during 1980–2000 was confined to two major locations: in the Songnen plain north of existing paddy fields and in the south adjoining the border with JilinProvince (Fig. 2B). Paddy fields in the Songnen plain are extensive in their distribution, but are small sized elsewhere.

The newly gained paddy fields in 1980 originated mostly from dry fields at 6403 km^2 or nearly half of the total increase (46.35%) (Table 2). Another major contributor was swamps at 4174 km^2 (30.22%). Surprisingly, primary forest contributed 1306.7 km^2 or nearly 10%. These trees probably grew in low-lying swampy land or valley bottoms just above the water level. Thus, the former forestland could be easily converted to paddy fields without much work after trees had been felled. By comparison, secondary forest

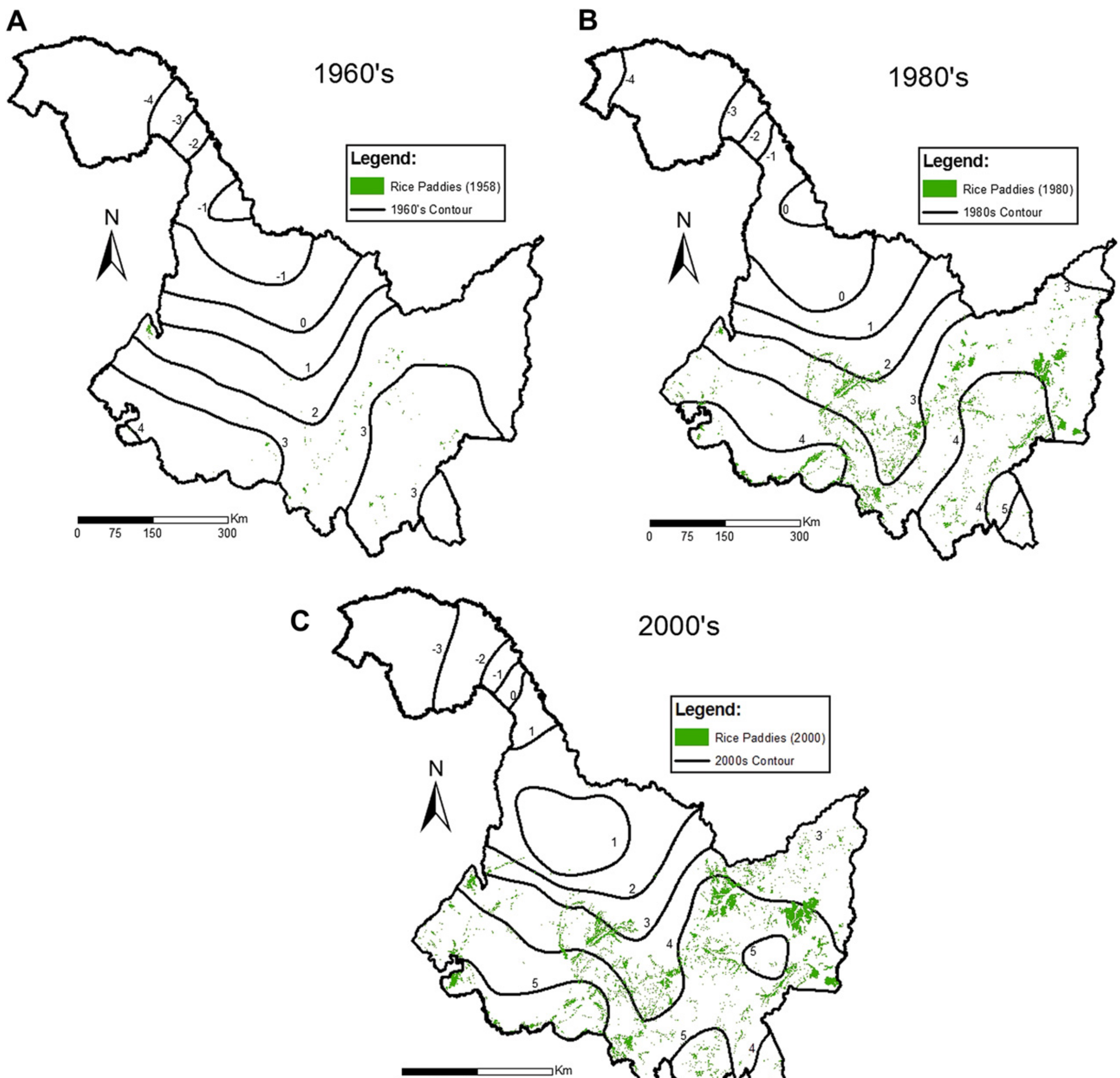

Fig. 3. Distribution of decadal temperature and its spatial relationship with rice paddy location (A) 1960s; (B) 1980s; and (C) 2000s.

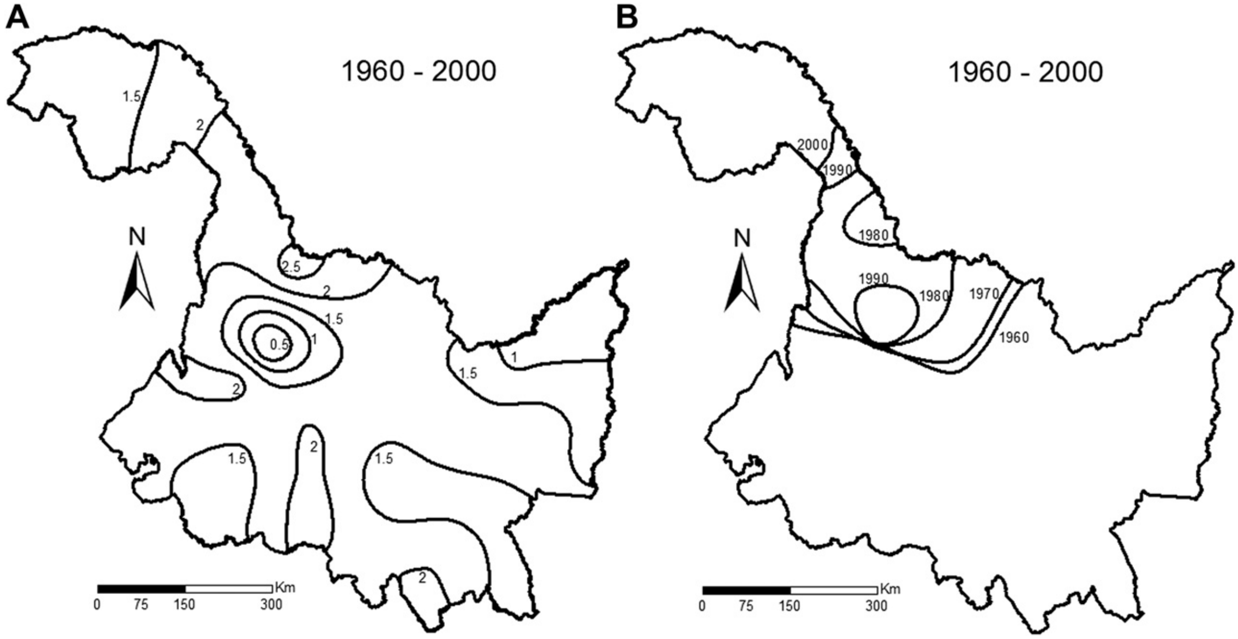

Fig. 4. Spatial pattern of climate warming in Heilongjiang province between the 1960s and the 2000s. (A) Spatial pattern of rise in decadal temperature (unit: °C); (B) Northward migration of the 0 °C isoline of decadal temperature from the 1960s to the 2000s.

contributed less than 1000 km^2 (nearly 7%) to rice paddy fields. All other categories of land cover made a negligible contribution during this period.

During 1980–2000 the major contributors of paddy fields changed only slightly. For instance, the most important contributor was still dry fields that contributed 5969 km^2, or more than 70%. Swamp was still the second most important contributor, even though its contribution reduced to only 1404 km^2 (16.59%) probably because most swamps had already been reclaimed as paddy fields during the first period, leaving few available for further reclamation. By this period forest made little contribution to paddy fields because the remaining forests in a mountainous terrain distant from river channels were ill-suited for reclamation as paddy fields. Instead, grassland replaced primary forest to become the third most important contributor, accounting for 10.13% of the total.

Spatiotemporal pattern of climate warming

Illustrated in Fig. 3 is the spatiotemporal distribution of annual temperature in three decades. In the 1960s decadal temperature had a range from −4 °C to 3 °C with an increasing trend southward (Fig. 3A). The warmest place is located in the southeast and southwest corners, and the coldest place is naturally the northernmost. While some isolines are roughly parallel to latitude, some others bear no definite relationship with latitude due to the presence of mountain ranges. The 0 °C isoline divides the province into two parts, with the bottom half accounting for two thirds of the territory. In the 1980s decadal temperature range was widened to −4–5 °C (Fig. 3B). However, those areas having a temperature of −4 °C or lower shrank remarkably to the very northern tip while those areas with a temperature above 4 °C expanded considerably. Climate warming caused the emergence of the 5 °C isoline, even though those areas having a temperature above 5 °C were extremely tiny. The warming trend continued in the 2000s in that the area having a 0 °C decadal temperature or lower was pushed northward to cause the disappearance of the −4 °C isoline (Fig. 3C). By comparison, the >5 °C areas had expanded, mostly in the lowest part of the province near its southern border.

Spatially, all areas in the province experienced warming at a varying pace between 0.5 °C and more than 2.5 °C (Fig. 4A). The smallest increase is located in the Greater Khigan mountain range due to its higher elevation. The largest increase is found just immediately north of it. These two extremes of change have a limited spatial extent. By comparison, the most expansive increase is between 1.5 and 2 °C. There is no spatially definite pattern of increase, a fact that is attributed to both topography and land cover change (e.g., whether the land has been deforested). Associated with this increase in decadal temperature is the consistent northward migration of the 0 °C isoline (Fig. 4B). In the 1960s the line is located in the upper one third of the province. From the 1960s to the 1970s it moved northward only marginally by about 15 km (Table 3), covering a small ground area of 6602 km^2. Only 30% of the province had a decadal temperature below 0 °C. The pace of northward displacement was noticeably quickened in subsequent decades. For instance, the move exceeded 60 km during the 1970s-1080s, and over 100 km during 1980s-1990s, and 92 km during 1990s-2000s, even though the ground area covered (3804 km^2) was the smallest during the last period among all the decades. Consequently, the area having a 0 °C temperature or lower shrank to about 20% in the 1980s. Thus, the period of 1970s-1990s witnessed the largest expansion of areas with a decadal temperature of >0 °C. Subsequently, the period

Table 3
Statistics of the movement of the 0 °C isoline of decadal temperature in relation to increase in sown grain (rice) area.

Period	Northward shift (km)	Westward shift (km)	Area of shift (km^2) (%)	Sown area of grain[a] (1000 ha)
1961–1970	14.88	10.14	6602 (10.6)	+1259
1971–1980	60.16	40.56	20,024 (32.2)	+309
1981–1990	103.28	59.12	31,699 (51.0)	+338
1991–2000	92.06	218.65	3804 (6.1)	+836.5[b,c]
2001–2009				+784.1[b]
1961–2000	270.39	328.48	62,129	+2089
1993–2009				+1612.3[b]

[a] Data source: China Compendium of Statistics, 1949–2004.
[b] Rice only (e.g., exclusion of wheat and corn); Source: China Statistical Yearbook, 1993-2009.
[c] 1993–2000.

Table 4
Results of Mann-Kendall trend analysis and test of annual temperature, 1961–2000.

Station No.	Min Temp (year)	Max Temp (year)	S	Z	Probability	Trend (99% level)
50136	−75.3 (69)	−33.8(88)	237	2.750	0.9970	Increasing
50353	−39.9 (65)	10.3 (90)	289	3.355	0.9996	Increasing
50468	−28.9 (69)	23.7 (90)	332	3.856	0.9999	Increasing
50557	−22.3 (65)	23.6 (95)	308	3.577	0.9998	Increasing
50564	−37.2 (69)	13.7 (90)	385	4.474	1.0000	Increasing
50656	0 (81)	9.5 (00)	−3	−0.047	0.4814	No trend
50658	−7.1 (69)	38.3 (75)	322	3.740	0.9999	Increasing
50742	7.5 (69)	49.5 (95)	342	3.973	1.0000	Increasing
50745	20.9 (69)	65 (98)	323	3.752	0.9999	Increasing
50756	−1.9 (69)	40.7 (98)	335	3.891	1.0000	Increasing
50758	4 (69)	51.1 (98)	377	4.381	1.0000	Increasing
50774	−13.5 (69)	29.6 (90)	363	4.218	1.0000	Increasing
50775	11.3 (69)	55.8 (95)	276	3.204	0.9993	Increasing
50788	7.6 (69)	54.5 (90)	283	3.286	0.9995	Increasing
50844	28.5 (69)	71.6 (95)	307	3.565	0.9998	Increasing
50853	7 (69)	50 (90)	327	3.798	0.9999	Increasing
50854	22.5 (69)	61.8 (95)	259	3.006	0.9987	Increasing
50862	−5.6 (69)	42.9 (90)	390	4.532	1.0000	Increasing
50873	12.7 (69)	59.7 (90)	356	4.136	1.0000	Increasing
50877	16.3 (69)	59.3 (98)	317	3.682	0.9999	Increasing
50888	17.9 (69)	64.8 (90)	346	4.020	1.0000	Increasing
50963	25.7 (69)	72.6 (98)	329	3.822	0.9999	Increasing
50963	11.2 (69)	47.4 (98)	209	2.423	0.9923	Increasing
50968	10.2 (69)	57.1 (98)	305	3.542	0.9998	Increasing
50978	25.1 (69)	65.1 (90)	331	3.845	0.9999	Increasing
50983	16.7 (69)	56.3 (98)	354	4.113	1.0000	Increasing
54094	26 (69)	71.8 (98)	419	4.870	1.0000	Increasing
54096	12.6 (69)	49.7 (98)	298	3.460	0.9997	Increasing

from safe sowing to heading was prolonged by 12 days in south-central Heilongjiang between 39° and 48°N (Huang et al., 2009) while both heading and maturity stages have been advancing since 1975 (Wang et al., 2008). Although monthly minimum and maximum temperatures were not analyzed in this study, the mean minimum temperature was reported to be about 2.5 °C higher than in the early 1960s (Hijmans, 2007).

Paddy field expansion and climate warming

Illustrated in Fig. 3 is the spatial relationship between the distribution of paddy fields and annual temperature in the nearest decade. In 1958 most of the paddy fields were distributed in southern Heilongjiang between the isolines of 2 and 3 °C (Fig. 3A). There was only a small amount of paddy fields between the isolines of 1 and 2 °C. In 1980 rice paddy fields expanded to much wider areas, mostly outward from the location of 1958 (Fig. 3B). These fields were confined within the isolines of 2 °C and higher, even though some were lying between the isolines of 1 and 2 °C. Since the 2 °C isoline shifted northward during 1958–1980, paddy fields also expanded northward accordingly, in addition to an obvious eastward expansion. The distribution of paddy fields in 2000 was much more extensive than in previous periods. This expansion was made possible by the warmer climate. The expanded paddy fields are located mostly south of the 3 °C isoline (Fig. 3C). In addition, there are some paddy fields between the 2 °C and 3 °C isolines, but much less fields between the 1 and 2 °C isolines than in the previous periods, probably because these isolines have a higher latitude, and thus subject more to seasonal fluctuations in temperature. Obviously, the expansion of the observed paddy fields followed closely the pattern of climate warming.

Discussion

Rice is a crop that requires certain quantity of energy to survive and cultivate. Thus, geographic zones formerly deemed unsuitable for rice cultivation may allow rice to be cultivated productively under a warmer temperature regime. The expanded area of rice cultivation detected in the previous section is a direct response to a variety of factors that may include the demand for more food caused by an enlarged population, and the environment under which certain land use is permissible. As shown in Table 3 (column 5), the sowing area of grain increased drastically in the 1960s, probably in response to a higher food demand. The increase occurred at a subdued pace of about 33,800 ha per annum during 1971–1990. Thus, the demand for more food cannot account for the huge expansion in paddy fields due most likely to the environmental constraint imposed by a chilly climate regime. Rainfall and sunshine hours were not analyzed in this study as temperature is the most important meteorological factor influencing rice cultivation in Heilongjiang Province (Wang et al., 2008), and hence the focus of this study. As illustrated in Table 4, the Mann-Kendall trend analysis results indicate that 27 of the 28 stations experienced a trend of increase in annual temperature, significant at the 99% significance level. The only station (no. 50565) that does not have a warming trend is located at 269.4 m, the fourth highest elevation among all the stations. This increase in annual temperature is subject inevitably to the progressive extension of urban areas into formerly rural areas. Given that those weather stations surrounded predominantly by forest (e.g., 50136 and 50774) also have an increasing trend (Table 4), the contribution of anthropogenic forcings towards the observed warming should be sufficiently minimal so as not to invalidate the warming trend identified. In fact, the large S values in Table 4 testify to the existence of an unmistakable warming trend at 27 out of the 28 stations.

As shown in Table 3, the area having a >0 °C decadal temperature expanded drastically in the 1970s and the 1980s (column 4). The largest increase in sowing area of grain took place in the 1960s when area of >0 °C decadal temperature rose modestly. Thus, no close relationship exists between the two variables. The available data on rice paddy cultivation area from China Statistical Yearbook 1993-2009 reveal that it more than doubled from 0.778 million ha in 1993 to 1.615 million ha in 2000. In the 1990s and 2000s the amount of increase was more than twice higher than the increase in the sowing area of grain in the previous two decades (Table 3, column 5). Of particular notice is the huge amount of increase in paddy fields by 1.6123 million ha during 16 years (1993–2009), highly comparable to the increase in sowing area of grain during 40 years (1961–2000). Therefore, the more convincing explanation for the greater increase in paddy fields in the 1990s and 2000s is due to a warmer growing condition that enables such a huge increase. The fact that extensive climate warming in the 1970s and 1980s is followed by more than double increase in rice paddy fields in the 1990s and 2000s suggests that there is a temporal delay of about 20 years between the rise in decadal temperature and agricultural adaptation.

Conclusions

At 3479 km^2 rice paddy fields accounted for less than 1% of the total area of Heilongjiang province in 1958. During 1958-1980 paddy fields more than quadrupled to reach 14 564 km^2 at an annual rate of 504 km^2. Nearly half of the newly gained paddy fields originated from dry fields. Swamps and primary forest contributed 30.22% and nearly 10% to paddy fields, respectively. During 1980–2000, paddy fields expanded to 21 940 km^2, even though the rate of expansion was reduced to 369 km^2 per annum. The most important contributors of paddy fields expansion are dry fields at 5968.9 km^2 (70.50%), and swamp at only 1404 km^2 (16.59%). Grassland replaced primary/dense forest to become the third most important contributor. The climate of Heilongjiang warmed 2.11 °C during 1961–2001. Spatially, the northern central of the province has the highest rise in excess of 2 °C. In the 1970's only 30% of the province had a decadal temperature below 0 °C. This value shrank to about 20% in the 1980s. Since the 1990s, only the northernmost peninsula had a decadal temperature below 0 °C. The pace of the 0 °C isoline northward expansion was rather slow in the 1960s, but jumped abruptly to hundreds of kilometres during 1990s–2000s. The observed expansion in paddy fields coincided closely with climate warming in the region. Most of the newly gained paddy fields were located within the isolines of 2 and 3 °C, and few within the isolines of 1 and 2 °C. It is concluded that paddy fields in Heilongjiang expanded by more than six fold during the study period, mostly from forest, swamps, dry fields and grassland. This expansion was made possible owing to the rise of more than 2 °C in annual temperature in most places. All 28 weather stations except one experienced an increasing trend of warming. On average, it takes about 20 years for agricultural practices to adapt to the warmer climate. More studies are needed to explore the sustainability of reclaiming more land for rice cultivation in light of a continued trend of climate warming.

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