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A Study of the Effects of Natural Fertility, Weather and Productive Inputs in Chinese Agriculture

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A Study of the Effects of Natural Fertility, Weather and Productive Inputs in Chinese Agriculture

Richard S. Eckaus and Katherine Kit-Yan Tso[†]

Abstract

In this paper the variations across China of climate, other natural growing conditions and anthropogenic farm inputs are used as a natural experiment to identify the contributions of each to the production of corn, potatoes, rice, soybeans and wheat. Crop production functions are estimated across prefectures using land, labor, fertilizer, machinery and irrigation inputs, as well as estimates of the average net primary productivity (NPP) for each prefecture during the growing seasons. NPP is the net assimilation of carbon into the plants as a result of natural growing conditions and the estimates are taken from projections of the Terrestrial Ecosystems Model. The results indicate that through the use of anthropogenic inputs farmers have made effective adaptations to differences in natural outputs of NPP in each crop. Thus, the research suggests that there is a substantial potential for adjustments to climate change. In addition, the results also suggest that there is substantial scope for further increases in food production in China.

1. INTRODUCTION

This paper reports on an investigation for China of the relations between farm output, the natural fertility of agricultural land, including the effects of climate, and the use of anthropogenic farm inputs. The original motivation derives from concern about the potential consequences for agricultural production of global warming associated with the accumulation of atmospheric greenhouse gases. The study uses the variations across the prefectures of China of climate, soil and topographic conditions, as well as direct farm inputs, as a "natural experiment" to determine their effects on the output of particular crops. A key and somewhat novel element in this study is the use of estimates of the, "net primary productivity," or NPP of the land in each prefecture to simulate the effects of climate and other natural growing conditions. NPP is the net assimilation of carbon into organic matter and is a function of atmospheric CO_2, plant CO_2 respiration rates, the photosynthetically active radiation, moisture availability, mean air temperature, nitrogen availability, the relative synthetic capacity of the vegetation and the topography of the land.

Among the potential effects of climate change, the consequences for agricultural production have, perhaps, been studied most intensively.[1] That is partly because of the very natural interest in these issues and, perhaps, partly because the analysis of these consequences seem relatively susceptible to conventional tools. Several approaches have been developed of which the most direct is the estimation of changes in agricultural outputs as the result of specific climate changes. This has been undertaken for particular regions, for which detailed data on outputs and

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[†] This paper derives from the Master of Science thesis by Katherine Kit-Yan Tso, "Effects of Climate on Agricultural Productivity in China," submitted to the MIT Department of Electrical Engineering and Computer Science, May, 1996. Tso is now with Morgan Stanley Asia Limited; R.S. Eckaus is Ford International Professor *Emeritus*, MIT Department of Economics.

[1] For a careful review of the literature see Reilly, J., 1995.

inputs are available, but has also been done, with heroic effort, for the entire world.[2] A somewhat more basic procedure is the estimation of agricultural production functions that include climate variables. However, neither approach, in itself, provides the information necessary to assess all the effects of climate change on agriculture. That is because climate change would not only induce changes in the particular farm product for which a production function may be estimated, but changes in land use among field crops, orchards, animal husbandry, etc. That is why reliance on production function estimates of the consequences of climate variables has been called the, “dumb farmer,” or, more politely, the, “naive farmer,” approach, as it neglects the adjustments in land usage that would occur.

An ingenious, alternative methodology, called by its authors a, “Ricardian,” technique has been applied to U.S. agriculture.[3] It estimates farm land prices as a function of climate variables, as well as other natural and human controlled variables. In good markets these prices will reflect the productivity of land in its best use, including optimal adjustments to different local climates. This might be called the, “smart farmer,” approach. The independent variables in the estimated equations include soil and topographical characteristics, as well as climate and some conventional input variables, so it is not necessary to assume that each piece of land is equally suitable for any purpose.[4] Yet, since it is a “partial equilibrium” relation, it cannot be used to project the effects of a climate change that would be significant enough to change the relative prices of the different outputs and services potentially provided by agricultural land. Thus, it does not, for example, permit analysis of the consequences of changes that would occur in world demands for U.S. agricultural grain crops as a consequence of general climate change. Another limitation of the approach is that it is unable to take into account the important fertilizing effects of increased atmospheric CO_2 because it is based on data for which there has been no substantial atmospheric CO_2 augmentation.

A third approach to the assessment of the effects of climate change on agriculture is the estimation of the effects of climate change on the assimilation of carbon in organic matter. This methodology is based directly on plant biology. The analysis has focused on estimating the net primary productivity of “natural” vegetation, which is pre-agricultural and without human intervention, but takes into account the conditions of soil quality, topography and, of course, climate.[5] Thus, it is a kind of production function analysis for natural vegetation. It has not as yet been extended to cultivated ecosystems and is only distantly related to agricultural production. First, the relation of plant biomass to the harvestable output varies across crops. Secondly, and as will be emphasized below, there are many intensive human interventions between “natural” growing conditions and actual farm practices. Yet the methodology has, with painstaking detail,

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[2] See Rosenzweig, C., *et al.*, 1993, and Pearce, D.W., *et al.*, 1996.

[3] See Mendelsohn, R., *et al*., 1994.

[4] In effect, the method attempts to estimate a demand function for agricultural land from cross section land market data, with a number of shifting variables, including climatological indices. This demand function is, of course, the market value of the partial derivative of a production function that is linear, since land, itself, does not appear among the independent variables. There is the very important difference that it is a kind of envelope curve that includes only the best uses of the land, given all the input and output prices. Since it is a partial equilibrium relation, it cannot be used to estimate the effects of a climate change that was strong enough to change the relative prices of other inputs.

[5] See Raich, J.S., *et al*., 1991.

been applied on a global scale and has been used in an integrated assessment of climate change origins and consequences.[6]

The study reported upon here estimates crop production functions with conventional land, labor, fertilizer and mechanical inputs and the NPP projections of the Terrestrial Ecosystems Model developed by the Ecosystems Center of the Marine Biological Laboratory (in Woods Hole, Mass.) to reflect climatic conditions. The NPP estimates used are those calculated as if the vegetation was entirely natural grasslands, which, of course, are not agricultural crops, except when used for animal forage. These NPP values are used as proxies for the NPPs for the particular crops studied and serve as an index with which to adjust specific land areas for their fertility with the current climate. In addition weather variables are used to register the actual growing conditions in the particular year for which data are used.

China was chosen as the country to be investigated for several reasons. First of all, it has features that make it a relatively good object of a cross section study. It is a large country with considerable variability in growing conditions, both natural and anthropogenic. While the economic and social environments across regions are far from uniform, they are less variable than among many countries. Secondly, China is an important country in several dimensions other than, most obviously, the size of its population. In particular, it has a large and growing international trade, including trade in agricultural products. It has even been argued, quite controversially, that China's potential demand for food grains will soon overpower world grain markets.[7] Finally, China is now an important source of greenhouse gas emissions and will become more so. This is partly because of its increasing economic size, but also because of its heavy dependence on coal, which is an intensive emitter of carbon dioxide, and its large area of paddy rice, a major source of methane.

There are also disadvantages in using China as a test case, most of which are associated with the relative recency of the marketization of its economy. Although its economic reforms started in the agricultural sector in 1978, important government interventions remain, whose significance varies across provinces as well as over time. For example, the agricultural procurement process and the distribution of farm inputs such as fertilizer is still, to a considerable extent, in government hands or is heavily influenced by government policy. Moreover, many market practices and institutions that would improve the efficiency of resource allocation in agriculture, such as land titles and land markets, do not yet exist. So market prices are not as yet completely accurate reflections of the real relative scarcities of farm inputs and outputs. On the other hand, because China's agricultural sector has responded with great vigor to market incentives, farm prices must be having important allocation effects. Nonetheless, while it may still be true that each farmer uses the inputs available in an efficient manner, unless there is efficient allocation of inputs among farm, overall efficiency cannot be achieved. If this is not approximated reasonably well, then the estimated relationships do not lie on "frontier" of production efficiency, but rather reflect some conventional patterns that do not reflect optimal adjustments to local climates.

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[6] Prinn, R.G., *et al*., 1999.

[7] See Brown, L., *et al*., 1995, and Crook, F.W., 1996.

There are problems in the Chinese data as well. It is widely believed that there is substantial underestimation, both of cultivated land and of grain output.[8] For example, one aspect of Chinese grain data that has raised many eyebrows is the extremely large size of reported grain inventories, which, according to official reports, were roughly equal to annual production in 1991, a very much larger ratio than is customarily found. Since the inventory data should be consistent with the production and consumption data, doubts about the former necessarily raises some questions about the latter as well.

Given the deficiencies in the data, as well as questions as to the economic efficiency of production in China in 1990, the following analysis should be treated with some skepticism. It is presented as a potential increment to the methodology of the analysis of the effects of climate change in agriculture. As will be shown, however, the critical regressions are both reasonably reliable by the conventional statistical measures and, in a number of ways, conform in a general way to expectations based on economic reasoning. All of which provides reasons to be encouraged about both the concepts and the data.

The next sections will describe in somewhat more detail the functions and the variables that are estimated and the data that were used. The results of the estimation will be presented in Section 3.

2. THE DATA AND THE VARIABLES FOR GRAIN PRODUCTION FUNCTIONS

There are 30 provinces in China, each of which is divided into prefectures and counties. Data for 1990 were abstracted from provincial statistical yearbooks for 175 prefectures in 16 provinces, distributed as shown in **Table 1**.[9] However, not all the prefectures had information for all the crops studied and, in some cases, data had to be censored because of obvious reporting errors. It will also be noticed that the southern most provinces are not well represented in the sample.

The Terrestrial Ecosystem Model (TEM) is a monthly, time-stepped, process-based model that predicts the major carbon and nitrogen fluxes and pool sizes. Estimates are based on an extensive data base on monthly climate (precipitation, mean temperature and mean cloudiness), soil texture (sand, clay and silt proportions), elevation, water availability for the cells of a global grid of 0.5 degree latitude by 0.5 degree longitude.[10] Each prefecture was located on the grid and the NPP for the prefecture was averaged across all grids in the prefecture. The TEM model calculates NPP under three alternative assumptions with respect to water and nitrogen availability: (1) limitations on both water and nitrogen; (2) limitation on water only, (3) limitations on nitrogen only. Regression results are reported below only with NPP estimates

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[8] See Johnson, D. Gale, 1994.

[9] Beijing and Tianjin each include only the city and immediately surrounding agricultural area, which could be misleading if the regressions were at the provincial level. Since these regressions are based on data at the prefecture level, it is appropriate to include them.

[10] The Terrestrial Ecosystem Model (TEM) has six state variables and eleven carbon and nitrogen fluxes:
State Variables: 1. carbon in vegetation, 2. structural nitrogen in vegetation, 3. labile nitrogen in vegetation, 4. organic carbon in soils & detritus, 5. organic nitrogen in soils & detritus, 6. available inorganic soil nitrogen.
Carbon and Nitrogen Fluxes: 1. gross primary productivity, 2. autotrophic respiration, 3. heterotrophic respiration, 4. carbon litterfall, 5. nitrogen litterfall, 6. nitrogen uptake into structural nitrogen of vegetation, 7. nitrogen uptake into labile pool of vegetation, 8. nitrogen resportion from dying tissue into labile nitrogen pool of vegetation, 9. net mineralization of soil organic nitrogen, 10. nitrogen inputs from outside ecosystem, 11. nitrogen losses from ecosystem. (For a description of TEM, see Xiao, X. *et al*., 1997, 1998.)

calculated with the first of the limitations, but these regressions are not substantially different from those calculated with the other limitations.

All the variables used in the production function estimates and their definitions are shown in **Table 2**. The resource inputs listed in Table 2 are those conventionally used in agricultural production functions. Unfortunately, the "degree" of irrigation, that is, the proportion of water supplied by irrigation as compared to the proportion relying solely on rain, is not specified, only the amount of land that is, to some degree, irrigated. Even more unfortunately, the outputs from the non-irrigated and irrigated lands were not separately identified.

Table 1. Prefecture Observations by Crop

		Number of Prefectures				
	Provinces	**Wheat**	**Rice**	**Corn**	**Potatoes**	**Soybeans**
1	Anhui	16	16	-	16	-
2	Beijing	1	1	1	1	1
3	Guangdong	-	19	-	-	19
4	Hainan	-	2	2	-	2
5	Heilongjiang	13	12	13	13	14
6	Henan	17	17	17	17	17
7	Hubei	16	16	16	16	16
8	Jianxi	11	11		11	11
9	Ningxia	4	4	4	4	4
10	Qinghai	7	-	-	-	-
11	Shaanxi	10	10	10	-	-
12	Shandong	16	16	16	-	16
13	Tianjin	1	1	1	1	1
14	Xinjiang	14	12	12	-	12
15	Xizang	5	-	-	-	-
16	Yunnan	17	17	17	17	17
	Total	**148**	**154**	**109**	**96**	**130**

Table 2. Variables used in the Production Function Estimates

PROD	Output (metric tons)
EFFNONIRRLAND	Nonirrigated sown area (hectares) * NPP (PG C/year)
EFFNONIRRLAND2	Nonirrigated sown area (hectares) * NPP2 (PG C/year)
EFFIRRLAND	Irrigated sown area (hectares) * NPP (PG C/year)
EFFIRRLAND2	Irrigated sown area (hectares) * NPP2 (PG C/year)
IRRLAND	Irrigated sown area (hectares)
LABOR	Labor used (persons)
NPP	Net Primary Productivity of land (PgC/year)
NONIRRLAND	Nonirrigated sown area (hectares)
MECH	Power of mechanized equipment (kw)
FERT	Fertilizer used (10,000 tons)
TMEAN	Average daily mean temperature in growing seasons (˚C)
TMIN	Average daily minimum temperature in growing seasons (˚C)
EPCP	Total precipitation in growing seasons (mm)
EPCPN	Total precipitation in non-growing season (mm)
APET	Average pan evapotranspiration (mm)
AMINRH	Average minimum relative humidity (percent)
IGDD	Total growing degree days (˚C * days)

In addition, only the total amounts of machine horsepower, fertilizer, irrigated area, and labor force were recorded for each prefecture. These were allocated among the crops in same proportions as the sown area for the crop in relation to total sown area, which is another major data deficiency. Twenty two different types of machines are included in the machine power variable, *e.g*., cotton gins, grain drying machines, including some without relevance to the crops analyzed, such as motorized fishing boats, whose power could not be separately identified and, therefore, could not be excluded. The effective weights of the different types of fertilizers were summed to create the fertilizer variable, again because of inability to allocate each type of fertilizer to particular crops.

The problems of distinguishing the actual labor inputs used in farm production from the total labor available are particularly severe in China and were not overcome in this study. It is widely believed among economists and policy makers in China that the agricultural labor force includes a large number of, "disguised unemployed," workers, *i.e.* workers who are not full time, fully effective agricultural workers. Indeed, there is a conventional estimate of 100 million workers in a floating population that moves between agricultural and urban labor. By comparison, the total agricultural labor force in China in 1990 was estimated at 341 million. The allocation of the reported labor force among the crops in the same proportions as sown area introduces a further distortion. In effect, the labor variable serves as a proxy for the population in the prefecture.

The climate that NPP reflects is an average of weather conditions. Since the average differed from the actual weather within each prefecture in 1990, separate variables were used to reflect the 1990 weather. These weather variables are the last six listed in Table 2. Ideally the weather variables should enter as deviations from similar variables included in the TEM estimation of NPP. This could be done only for mean temperature and total precipitation. The other weather variables do not appear in the TEM calculations. The only one of the weather variables which is not self explanatory is the average pan evapotranspiration, which is the sum of the evaporation of surface water and the transpiration of water through plants into the atmosphere.

The weather data were abstracted from that collected by the National Center for Atmospheric Research from weather stations in each prefecture. Where there were more than one such weather station within a prefecture, the data from each were averaged. Where there was no weather stations, data from adjoining prefectures with weather stations were averaged.

For the estimation process two new variables, EFFNONIRRLAND, and EFFIRRLAND were created for each crop. EFFNONIRRLAND is the product of the nonirrigated sown land area cultivated for the crop and the average NPP for the prefecture. EFFIRRLAND is the irrigated sown land area multiplied by the NPP for the crop and prefecture. While effective land may seem to be a anomalous concept, it can be argued that it is exactly the input variable that has economic significance. The rents charged for land never distinguish between that part of the rent which is for the land area alone and that part which is due to the land's fertility. Thus, when agricultural production functions are estimated from their dual relations with input prices, as is now most common, the quantity variable, which is dual to the land rent variable, is some version of the effective land variables. The concept is quite analogous to that of "efficiency labor," which implies adjustments for education and training and other conditions which differentiate labor inputs from the simple measure of hours worked.

Table 3 provides an overview of the characteristics of the data, with the input variables normalized by land area. There are differences in the distribution of crops among the prefectures and over the year and, in general, there is relatively less variability in the weather variables than in the farm input variables.

The variation in NPP deserves special comment, since it is serves as an indicator of natural fertility, including the effects of climate. The range of NPPs across the prefectures for any one crop seems quite large, but its coefficient of variation, which is the standard deviation divided by the mean to adjust for differences in units of the variables, is the smallest of all the variables. Rice, soybeans, wheat and potatoes have about the same mean NPP values. Surprisingly there is relatively little variation across all the crops in the intensity in which the input variables are used in relation to land, the major exception being the relatively low use of mechanical power in growing rise. There is also relatively little variation in the weather variables across all the crops, the exceptions being EPCP and IGDD, precipitation and degree days.

Table 3. Data Characteristics

	Mean	**Standard Deviation**	**Minimum**	**Maximum**	**Coef. of Variation**
Corn					
NPP (Pg C/year)	373.552	127.593	100.438	621.207	0.342
Production/Land (T/ha)	4.110	1.381	0.622	7.005	0.336
Irrigated Land/Total Land	0.361	0.237	0.035	1.132	0.656
Labor/Land (persons/ha)	2.131	1.045	0.388	5.766	0.490
Fertil/Land (10^4 tons/ha)	0.156	0.076	0.015	0.437	0.489
Mechaniz/Land (kW/ha)	4.226	5.338	0.453	25.484	1.263
Mean Temperature (˚C)	18.603	3.060	10.552	23.214	0.164
Min. Temperature (˚C)	13.746	3.443	5.919	19.300	0.250
Precipitation (mm)	140.614	114.575	0.763	371.228	0.815
Evapotranspiration (mm)	3.894	0.693	0.130	5.353	0.178
Rel. Humidity (min., %)	49.061	10.634	20.250	68.357	0.217
Degree days (˚C * days)	3791.963	1516.257	977.000	11780.00	0.400
Rice					
NPP	460.984	158.948	100.438	775.800	0.345
PROD/LAND	5.671	1.377	2.819	9.917	0.243
IRRIG L./TOTAL LAND	0.368	0.207	0.018	1.132	0.562
LABOR/LAND	2.338	0.919	0.407	5.766	0.393
FERTILIZER/LAND	0.182	0.098	0.015	0.804	0.535
MECHANIZ/LAND	2.428	1.913	0.453	12.656	0.788
TMEAN	15.772	4.423	3.995	24.838	0.280
TMIN	11.448	5.015	-0.880	21.539	0.438
EPCP	45.849	59.798	0.015	324.200	1.304
APET	3.056	0.543	0.708	4.264	0.178
AMINRH	53.879	9.340	23.625	68.917	0.173
IGDD	4975.253	2043.058	197.000	9420.500	0.411
Soybeans					
NPP	458.981	160.525	100.438	775.800	0.350
Production/Land	1.533	0.757	0.010	6.833	0.493
Irrigated L./Total Land	0.309	0.167	0.000	1.000	0.542
Labor/Land	2.190	1.062	0.009	5.766	0.485
Fertilizer/Land	0.187	0.140	0.000	1.197	0.752
Mechanization/Land	4.095	6.006	0.039	39.935	1.467
TMEAN	23.966	3.339	13.542	28.600	0.139
TMIN	19.580	3.777	9.733	25.463	0.193
EPCP	225.465	172.945	0.317	1112.433	0.767
APET	4.576	0.803	0.985	7.025	0.176
AMINRH	56.521	9.854	17.000	75.500	0.174
IGDD	2922.446	683.015	765.500	3857.500	0.234

Table 3. (continued)

	Mean	Standard Deviation	Minimum	Maximum	Coef. of Variation
Wheat					
NPP	390.149	142.661	92.744	621.207	0.366
Production/Land	2.714	1.206	0.108	5.383	0.444
Irrigated L./Total Land	0.376	0.230	0.035	1.179	0.613
Labor/Land	2.187	0.978	0.388	5.766	0.447
Fertilizer/Land	0.153	0.072	0.015	0.437	0.468
Mechanization/Land	4.675	11.342	0.100	128.059	2.426
TMEAN	13.044	4.833	0.158	23.633	0.371
TMIN	7.475	6.012	-7.842	15.775	0.804
EPCP	49.968	111.467	0.020	795.700	2.231
APET	2.881	0.553	0.236	3.759	0.192
AMINRH	49.144	11.803	4.112	65.500	0.240
IGDD	4265.249	1441.722	693.000	8746.500	0.338
Potatoes					
NPP	461.428	121.138	222.150	775.800	0.263
Production/Land	3.029	1.160	0.161	6.839	0.383
Irrigated L./Total Land	0.296	0.139	0.014	0.803	0.469
Labor/Land	2.223	1.021	0.388	5.766	0.459
Fertilizer/Land	0.156	0.071	0.015	0.437	0.457
Mechanization/Land	4.395	6.560	0.453	39.935	1.493
TMEAN	22.980	3.903	12.840	33.238	0.170
TMIN	18.363	4.067	7.253	26.685	0.221
EPCP	129.661	288.807	0.001	1659.196	2.227
APET	4.121	0.787	1.524	6.371	0.191
AMINRH	58.059	12.519	35.200	117.769	0.216
IGDD	3714.171	1708.309	925.667	11533.50	0.460

Table 4 presents correlation matrices for the input variables for the various crops. The correlation of NPP with land productivity is negative for all the crops. Of course, a positive correlation does not prove causality and neither does a negative correlation. It does suggest, as should really be obvious, that there must be other important influences on land productivity. The correlation of NPP with the degree of irrigation is positive only for potatoes. The correlations of NPP with the farm inputs that are subject to annual decisions, fertilizer and mechanization, are always positive for the former and always negative for the latter. This suggests that the relations are, respectively, those of complements and substitutes.

Land productivity is always positively related to the degree of irrigation, fertilizer and mechanization intensity, but negatively related to labor per hectare for corn, wheat and potatoes, a surprising result, explained, perhaps, by the problems of accurate measurement of labor inputs, as pointed out above. Irrigation intensity is positively associated with fertilizer intensity, as would be expected from the general complementarity of these two inputs. The correlation between irrigation intensity and labor intensity is not uniform, but for labor intensity and the intensity of use of fertilizer it is always positive. The correlation of labor intensity and the degree of mechanization is always negative, as would be expected, and suggests that measurement of labor inputs may not be completely erroneous.

The relations between NPP and the labor and other inputs provide a partial test of the validity of using NPP estimated for natural vegetation as an index of the productivity of land under cultivation. In spite of the emergence of the large, “floating population,” of farm workers, there are still barriers to the movement of labor from rural to urban areas and greater barriers to the movement of labor across rural areas. There are also no land markets that would help in the adjustment of labor intensities on the land. Land and labor in agriculture are, therefore, not resources whose relative intensities can be adjusted like other farm inputs. Since there have been no recent large scale population resettlements, the high correlation of NPP and the labor/land ratio reflects the historical pattern of land settlement and population growth. It is a plausible hypothesis that, in the past, population simply moved to and/or stayed in more fertile areas and has also grown relatively rapidly in these areas. If the hypothesis is tested by a simple regression of the labor/land ratio on NPP, it is not rejected for any of the crops.

Overall the correlations suggest that inputs are used rationally in Chinese agriculture. That does not mean that they are used with perfect efficiency, only that they are not used counterproductively.

Table 4. Data Correlation Matrices

	NPP	**Prod/ Land**	**Irrig Land/ Total Land**	**Labor/ Land**	**Fertilizer/ Land**	**Mechan/ Land**
Corn						
NPP	1.0000					
PRODUCTION/LAND	-0.5257	1.0000				
IRRIGATED LAND/TOTAL LAND	-0.5491	0.3593	1.0000			
LABOR/LAND	0.4899	-0.2761	-0.2327	1.0000		
FERTILIZER/LAND	0.1828	0.2752	0.1463	0.3314	1.0000	
MECHANIZATION/LAND	-0.2106	0.2849	-0.2054	-0.4162	-0.1348	1.0000
Rice						
NPP	1.0000					
Production/Land	-0.1074	1.0000				
Irrigated Land/Total Land	-0.4786	0.0799	1.0000			
Labor/Land	0.3198	0.0871	-0.3478	1.0000		
Fertilizer/Land	0.3188	0.2282	0.1130	0.2581	1.0000	
Mechanization/Land	-0.1576	0.2227	0.1344	-0.0673	0.2939	1.0000
Soybeans						
NPP	1.0000					
Production/Land	-0.0796	1.0000				
Irrigated Land/Total Land	-0.1593	0.1680	1.0000			
Labor/Land	0.3801	0.1006	0.0578	1.0000		
Fertilizer/Land	0.3644	0.0409	0.3627	0.2911	1.0000	
Mechanization/Land	-0.3086	0.1058	-0.2619	-0.3907	-0.1327	1.0000
Wheat						
NPP	1.0000					
Production/Land	-0.5432	1.0000				
Irrigated Land/Total Land	-0.4707	0.4088	1.0000			
Labor/Land	0.3093	-0.0161	-0.1695	1.0000		
Fertilizer/Land	0.2663	0.4027	0.0979	0.2226	1.0000	
Mechanization/Land	-0.1294	0.1878	0.0624	-0.0615	-0.1112	1.0000
Potatoes						
NPP	1.0000					
Production/Land	-0.2138	1.0000				
Irrigated Land/Total Land	0.0569	0.2337	1.0000			
Labor/Land	0.2779	-0.3143	0.1695	1.0000		
Fertilizer/Land	0.1977	0.3001	0.5664	0.2588	1.0000	
Mechanization/Land	-0.4845	0.1868	-0.2849	-0.4703	-0.2397	1.0000

3. THE EFFECTS OF NPP, FARM INPUTS AND WEATHER ON OUTPUT: REGRESSION RESULTS

The logarithmic form of Cobb-Douglas production functions for each crop was estimated in several alternative specifications, with physical measures of output being related to measures of physical inputs, rather than through the dual relation of production functions with cost functions. The first function estimated is:

$$\begin{aligned} \ln PROD = \; & a_1 * \ln EFFNONIRRLAND + a_2 \ln EFFIRRLAND + a_3 * \ln LABOR \\ & + a_4 * \ln FERT + a_5 * \ln MECHANIZATION + a_6 * \ln TMEAN \\ & + a_7 * \ln TMIN + a_8 * \ln EPCP + a_9 * \ln APET + a_{10} * \ln AMINRH \\ & + a_{11} * \ln IGDD + constant. \end{aligned} \qquad \text{[Eq. 1]}$$

The results of estimating Eq. 1 for each of the crops are shown in **Table 5**, where the variables are in logarithmic form. The estimation has adjusted for heteroscedasdicity, which was, however, not acute.

The estimated coefficients on the effective land variables are positive and significant at either the 5 or 10 percent level with one exception, which the coefficient on effective irrigated land used in wheat production, for which there is no obvious explanation. The estimates of the coefficients on the current input variables also correspond to expectations and are significant at the 5 or 10 percent levels, again with one exception, which is the negative coefficient on labor used in producing potatoes.

The estimated coefficients on the weather variables are often not significant, but, in some cases, tell an interesting story. Average mean temperatures above the climate average are usually bad for grains, but not for potatoes, while average minimum temperatures that are above the climate average are generally good for crop output. Precipitation levels above the climate average are also generally good for crops. The estimated coefficients on the evapotranspiration and humidity variables are often negative and usually not significant, as is true also of the coefficients on the degree day variables.

Table 5. Coefficient Estimates for Equation 1

Independent	Corn		Rice		Soybeans		Wheat		Potatoes	
Variables	Coef.	t	Coef.	t	Coef.	t	Coef.	t	Coef.	t
EFFIRRLAND	0.138	1.869	0.263	4.598	0.209	2.982	-0.106	-1.706	0.405	4.333
EFFNONIRRLAND	0.197	3.405	0.325	6.324	0.079	1.517	0.218	2.283	0.384	3.197
FERTILIZER	0.404	5.060	0.097	1.604	0.330	3.376	0.450	3.849	0.215	1.810
MECHANIZATION	0.144	2.971	0.067	1.408	0.209	3.475	0.236	3.287	0.331	4.561
LABOR	0.109	1.376	0.203	3.101	0.156	1.529	0.299	2.786	-0.207	-2.016
TMEAN	-2.387	-2.229	-1.834	-2.276	-2.266	-0.965	-0.172	-0.294	2.463	0.764
TMIN	1.267	1.878	0.650	1.218	1.314	0.790	-0.061	-0.552	-1.220	-0.786
EPCP	0.098	3.210	0.077	3.249	0.043	1.434	0.041	1.565	0.029	1.208
APET	0.094	1.057	-0.056	-0.501	-0.177	-0.792	-0.154	-1.084	0.151	0.559
AMINRH	-1.446	-5.812	-1.147	-4.517	-0.648	-1.599	-0.229	-1.293	-0.164	-0.308
IGDD	-0.136	-0.808	0.031	0.758	-0.321	-0.920	-0.333	-0.905	-0.572	-0.728
CONSTANT	10.100	5.548	6.529	4.242	7.614	2.145	5.067	2.790	-1.973	-1.049
R^2	**0.976**		**0.990**		**0.931**		**0.963**		**0.964**	

There is a strong logic, as argued above, for consolidating measures of the natural fertility of land with measures of land area in an effective land variable, since these features of any particular plot particular plot cannot be separated. The consolidation effectively forces the coefficients measuring the contribution of each variable to be the same. There is, however, a natural interest in trying to identify the distinct contributions of land area and land fertility and climate. In particular, an assessment of the separate consequences of climate change is the essence of the analysis of the impact of potential global warming on agricultural production. For this reason, tests were made in which land and NPP enter individually in production functions for each of the crops. The equation estimated is:

$$\begin{aligned} PROD = \; & a_1 * \ln NONIRRLAND + a_2 * \ln IRRLAND + a_3 * NPP + a_4 * \ln LABOR \\ & + a_5 * \ln FERT + a_6 * \ln MECHANIZATION + a_7 * \ln TMEAN \\ & + a_8 * \ln TMIN + a_9 * l\, n\, EPCP + a_{10} * \ln APET + a_{11} * \ln AMINRH \\ & + a_{12} * \ln IGDD + constant. \end{aligned} \quad \text{[Eq. 2]}$$

The coefficient estimates for Eq. 2 are shown in **Table 6**.

The apparently counterintuitive results in the regressions are that the estimates of the coefficients on the NPP variable are all negative, but highly significant only for corn, rice and wheat. In effect the regressions seem to be saying that better natural land characteristics, including climate, are bad for these crops. This is difficult to believe, yet the results are quite robust to many changes in specification. They are also, however, consistent with the negative correlation between NPP and the Product/Land ratio for all the crops except rice, for which the correlation was positive but weak.

The coefficients on the land variables are positive and significant at the 5 or 10 percent levels. The signs on the coefficients on the current input variables correspond to expectations, except for the labor used in growing corn and potatoes. The estimated coefficients on the weather variables are usually less significant than in the previous regressions.

Table 6. Coefficient Estimates for Equation 2

Independent Variables	**Corn**		**Rice**		**Soybeans**		**Wheat**		**Potatoes**	
	Coef.	**t**	**Coef.**	**t**	**Coef.**	**t**	**Coef.**	**t**	**Coef.**	**t**
NPP	-0.287	-1.715	-0.099	-0.531	-0.242	-0.939	-0.505	-3.023	-0.109	-0.365
NONIRRLAND	0.208	3.033	0.423	7.849	0.076	1.490	0.232	2.628	0.569	5.693
IRRLAND	0.394	5.781	0.260	4.825	0.292	3.714	0.322	3.588	0.355	3.125
FERTILIZER	0.363	4.969	0.074	1.284	0.305	3.159	0.298	2.678	0.226	2.019
MECHANIZATION	0.066	1.383	0.071	1.588	0.172	2.801	0.198	2.990	0.292	4.212
LABOR	-0.018	-0.229	0.138	2.173	0.115	1.134	0.044	0.394	-0.319	-3.136
TMEAN	-1.836	-1.875	-0.668	-0.825	-0.841	-0.351	0.413	0.753	3.136	1.030
TMIN	0.805	1.296	0.191	0.371	0.655	0.394	-0.008	-0.080	-0.407	-0.275
EPCP	0.043	1.423	0.077	3.457	0.034	1.145	0.053	2.203	0.022	0.971
APET	0.112	1.375	-0.066	-0.631	-0.271	-1.209	-0.125	-0.960	0.023	0.091
AMINRH	-0.604	-2.065	-0.194	-0.583	0.233	0.412	-0.073	-0.439	0.573	1.052
IGDD	0.035	0.224	0.009	0.234	-0.318	-0.928	-0.357	-1.060	-1.052	-1.397
CONSTANT	9.121	5.475	4.891	3.257	4.908	1.326	6.657	3.936	0.340	0.180
R^2	**0.981**		**0.991**		**0.933**		**0.968**		**0.964**	

In trying to explain the counterintuitive negative sign on the NPP variable the possibility must be considered that the variable itself is not the right one. It will be recalled that the NPP values used are not those that would be estimated for each crop, since those have not been calculated. Rather they are the NPP values for each prefecture for the growth of grasses under natural conditions, which were taken to be the closest available approximations for the field crops. But the field crops are not grasses and are certainly not grown under natural conditions. Yet the NPP values do meet certain important tests of plausibility, as pointed out above. NPP and the labor/land ratios are positively correlated and regressions of the labor/land ratios on NPP yield significant positive coefficients. The other correlations also conform to intuition. So the results cannot be discarded as simply the result of the misspecification of one of the variables.

As noted above, it may be especially erroneous to assume for China that the observed points represent efficient uses of resources on a production frontier, except for random influences. If this is the case, then the observed values for crop outputs, especially, may reflect different degrees of inefficiency. While quite plausible, it would not account for the strong, though counterintuitive results, which require a specific, systematic pattern of inefficiency.

The negative sign on NPP in most of the preceding regressions need not indicate that natural fertility and climate are bad for output, as there is a plausible interpretation that is consistent with a positive contribution of NPP to agricultural production. There have been many modifications of the natural qualities of land and its climates in China over many centuries and current inputs have been adjusted to the changed qualities. Hills have been terraced; sparse rainfall has been supplemented with irrigation; current inputs have been adjusted and suitable seeds and crops have been chosen for use. As a result, observations of the current relations of output to "natural" NPP may be quite misleading. The data may, in fact, indicate an indirect influence of NPP through a relationship between NPP and adjustments to other inputs.[11]

In order to test the hypothesis of such a relationship, two stage least squares regressions were calculated. For the first stage, irrigation was used as an indicator of human adjustments to natural climate and fertility. Though not an exhaustive measure, it was the only one available in the data; a measure of the extent of land terracing was, for example, not available. Thus, the ratio of irrigated land to total land was regressed on NPP. The shares of nonirrigated land in total land were then calculated. In the second stage these shares were regressed on the full range of other independent variables, including land. The results of the first stage are shown in **Table 7**. There is a negative relation between irrigation and NNP for all crops except soybeans and the estimated coefficient on NNP is highly significant. Since NNP takes into account the average natural rainfall and the more of that, the less the need for irrigation. The estimated coefficient for soybeans is positive and not significant.

Table 7. First Stage Regressions for Irrigated Land

	Corn		**Rice**		**Soybeans**		**Wheat**		**Potatoes**	
	Coef.	**t**	**Coef.**	**t**	**Coef.**	**t**	**Coef.**	**t**	**Coef.**	**t**
NPP	-0.745	-4.801	-0.554	-4.807	-0.259	-0.981	-0.527	-4.736	0.431	2.059
CONSTANT	3.125	3.433	2.197	3.137	0.115	0.072	1.934	2.948	-3.983	-3.121

[11] The authors are indebted to John Reilly for stressing the importance of these adjustments.

The results help explain the negative sign on the coefficients for NPP in the previous regression. Obviously, irrigation has been used to make up for relatively low levels of precipitation in the climate indicators embodied in low NNPs. Thus, when the irrigation variable, as well as NPP, enter separately in the previous regressions for output, the regression shows indirectly the negative relation between NPP and irrigation by making the coefficient on NPP negative.

In the results from the second stage of the regressions, as shown in **Table 8**, the estimated coefficients for the derived variables, the shares of irrigated and nonirrigated land, have the exception of the results for soybeans. The estimated coefficients on the land variable are always positive and significant as is true also for fertilizers and mechanization, with the exception of those for corn and rice, for mechanization. The estimated coefficients for labor are often of the wrong sign and almost never significant. The estimated coefficients on the weather variables are mostly not significant, with the exception of the precipitation variable, EPCP, which is always positive and significant, except in the case of corn and soybeans.

Table 8. Second Stage Regressions

	Corn		**Rice**		**Soybeans**		**Wheat**		**Potatoes**	
	Coef.	**t**	**Coef.**	**t**	**Coef.**	**t**	**Coef.**	**t**	**Coef.**	**t**
IRRIG/LAND	1.138	3.173	0.785	1.671	-4.039	-0.622	2.745	3.042	22.764	4.675
NONIRR/LAND	1.290	2.871	1.181	2.253	-13.856	-0.697	2.532	1.947	92.424	4.821
LAND	0.668	8.218	0.753	12.129	0.327	3.565	0.319	2.566	0.926	8.386
LABOR	-0.068	-1.094	0.065	1.252	0.140	1.428	0.083	0.782	-0.377	-4.469
FERTILIZER	0.398	6.734	0.118	2.870	0.326	3.531	0.464	4.469	0.316	3.616
MECHANIZ	0.021	0.509	0.050	1.316	0.185	3.042	0.194	2.900	0.213	3.521
TMEAN	-2.042	-2.329	-1.659	-2.334	-2.639	-1.130	0.761	1.463	4.431	1.709
TMIN	0.844	1.539	1.039	2.360	1.710	1.052	-0.012	-0.126	-0.901	-0.745
EPCP	0.016	0.581	0.060	3.165	0.039	1.234	0.058	2.391	0.034	1.751
APET	0.113	1.533	-0.049	-0.556	-0.242	-1.068	-0.151	-1.159	0.078	0.354
AMINRH	-0.328	-1.229	-0.434	-1.562	-0.236	-0.438	-0.089	-0.539	0.461	0.994
IGDD	0.152	1.065	0.021	0.657	-0.289	-0.836	-0.499	-1.501	-1.297	-2.009
CONSTANT	7.595	4.277	6.823	4.420	-2.180	-0.143	8.017	3.514	-38.581	-4.951

4. CONCLUSIONS

The research reported here was undertaken as a test of whether NPP, net primary productivity, could be used as an index of the effect of climate and other natural local conditions on net carbon embodied in natural vegetation in estimating agricultural production functions. If successful, that could lead to the use of the index in projecting the impact of climate change. The results, however, discourage this application.

Regressions were estimated first in which land area and NPP were combined into an, “effective land,” variable and used as an input in agricultural production functions together with other farm input and weather variables. The use of effective land variables is analogous to the estimation of the dual of agricultural production functions using farm land values that cannot and do not distinguish between the price for land area and the price for land quality. The regressions give plausible results with the coefficients on the effective land variable being positive and generally significant. Coefficients on the other inputs were, for the most part, also plausible, although the labor and weather variables were, for the most part, not significant.

Regressions were then estimated in which land area and NPP appear separately, in attempt to isolate the effect of NPP. These regressions assigned a negative value to the coefficient on NPP. There are several possible explanations for the results. The first is that the data are unreliable, although it is not clear as to why they should be unreliable in just the manner in which they appear. A particular reason for this unreliability is that, to some extent, the distribution of farm inputs still reflects the pre-reform policies of regional agricultural self-sufficiency. If the application of these policies offset the effects of natural land fertility and climate, that would explain why the coefficient on the NPP variable was variable. In addition, either through the operation of markets, before the Revolution, by some trial and error process, or by conscious decision-making since the Revolution, in many prefectures more irrigation has been provided where the land needed more water than was supplied by rainfall and fields terraced where the slope of the land reduced its yield, and so on. All this may have been done to equalize the returns to capital and labor. While the processes are quite plausible, it is not obvious whether they worked on the average or marginal returns. In any case, the negative relation between NPP and other inputs that have positive effects on output could manifest itself as a negative sign on NPP in the estimation of the agricultural production functions.

Two strong conclusions follow from the analysis. The first is methodological: since smart farmers will chose the combinations of resource inputs that are optimal for each NPP and farm input and crop prices, estimates of NNP, which reflect only natural growing conditions, are, by themselves, not reliable gauges of the impact of climate on agriculture. Biological modeling alone will not indicate the effects of any particular climate or climate change and must be combined with economic modeling of farm decisions to produce useful indicators of the effects of climate change. The second and related conclusion has to do with policy. While climate change will, undoubtedly affect growing conditions, the effectiveness of human adjustments to natural conditions is so strong that, to a considerable extent, the limitations of those conditions can often be largely offset. Swamps can be drained. The deserts can be made to bloom with irrigation and fertilizer and, with terracing, the hills and mountains can be made to produce abundantly. These adjustments take time and resources, of course. To ignore their potential, however, would be another version of the “dumb farmer” view of the impact of climate change on agriculture, that producers’ would not make adjustments.

The results are also relevant to the debate as to the future impact of China’s economic growth on world food markets. There is an argument is that, in the not so distant future, China will become heavily dependent on food imports, since it will not be able to increase its own food production at the rate necessary to keep up with its growing population and income. Because of China’s size, its growing demand will result in major increases in world food prices. The results presented here, however, suggest that there is substantial scope for increasing food production in China by increasing its irrigation of farm land and the use of farm inputs of fertilizer and mechanical power.

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