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AGRICULTURAL EMISSIONS AND THE ENVIRONMENTAL KUZNETS CURVE

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Using country-level panel data obtained from the Emissions Database for Global Atmospheric Research (EDGAR), this paper examines whether or not agricultural emissions, including methane, nitrous oxide, carbon dioxide, and ammonia, exhibit the inverted-U relationship of the Environmental Kuznets Curve (EKC). The traditional cubic functional model of GDP per capita is expanded to include agricultural share of GDP, agricultural land, and agricultural machinery, and subsequently determines whether or not these added variables provide a better fit to the data.

I find that one of ten emissions variables exhibits a strict inverted-U relationship with GDP per capita, while an additional five variables portray the inverted-U shape but show signs of an upward turn towards the end, indicating that the curve may be more N-shaped. The downward turning points are found to fall between 10 and 20 thousand 2000 U.S. dollars, while the upward turning points occur between 30 and 40 thousand 2000 U.S. dollars.

JEL Classifications: Q10, Q18, Q53, Q54, Q56

Key words: agriculture, emissions, environmental kuznets curve (EKC), climate change, environment and development

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I. Foundations of Emissions and the Environmental Kuznets Curve

Environmental economics is a growing field as scientists and economists have developed a concern for the preservation of natural resources and the state of the environment. One major topic of interest in this field of study is global warming, or climate change, characterized by changes in weather patterns and more specifically, an increase in Earth's average temperature. Despite the increasing concern in this area, the effects of climate change continue to be observed. In the last 100 years, Earth's average temperature has increased by 1.4°F, while one degree of this observed change has occurred in the last 30 years (Committee on America's Climate Choices, 2011). Much of this temperature increase is attributed to the greenhouse effect, the trapping of heat in Earth's atmosphere by greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). One of the leading producers of GHGs is the agricultural industry, including both crop and meat production. It is estimated that agriculture is responsible for 15 to 35 percent of global anthropogenic GHG emissions, depending on whether or not deforestation is accounted for (World Bank, 2012).

With these adverse effects of agricultural emissions, there comes the potential for mitigation. Many United States emissions reduction policies are directed towards motor vehicles and industrial processes, while the possibilities in the agricultural industry remain unconsidered. Studies have estimated that anywhere from 9 to 20 million tons of carbon equivalent can be abated annually in the United States through implementation of a carbon tax (Hertel et al., 2008; Murray et al., 2005). Potential for mitigation and implementation of policies could be examined in the relationship that exists between pollution and economic development. This relationship is depicted by the Environmental Kuznets Curve (EKC), which shows an inverted-U relationship, or bow curve, existing between environmental degradation and GDP or income per capita.

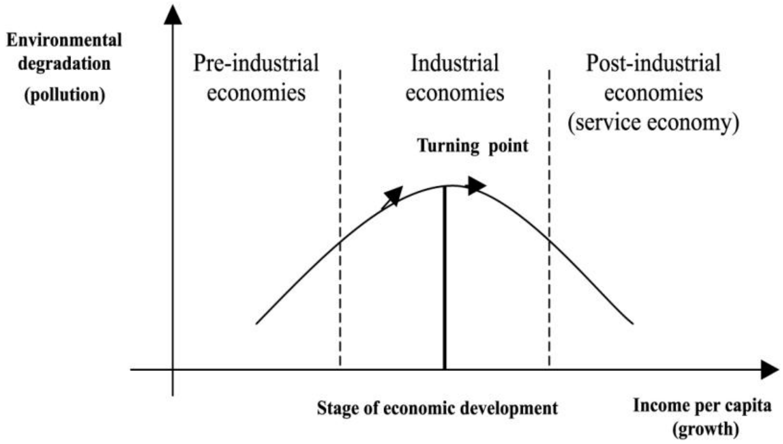

Figure 1. Environmental Kuznets Curve. Source: Panayotou (1993).

The shape of the curve indicates that at low levels of development, when income per capita is low, environmental degradation is also at a low level. However, an increase in income per capita is paralleled by increasing environmental degradation until a certain turning point is reached. Beyond this point, as development and income per capita increase, environmental degradation decreases and environmental quality actually increases. By observing this relationship, countries could determine the stages of development at which policies are needed. For example, a developing country could use the information from the EKC to determine when to implement and end a GHG mitigation policy; the policy would be useful at the income per capita levels where environmental degradation is still rising, but would be unnecessary at points past the turning point on the curve, where environmental degradation decreases as a function of income per capita.

As the existence of the EKC is still under debate, this research aims to determine whether or not EKCs exist among agricultural emissions, including carbon dioxide, methane, nitrous oxide, and ammonia. This analysis utilizes global panel data and explores different functional forms to define the relationship between pollution and GDP per capita. The subsequent sections of the paper examine previous literature, describe the data and model, display the results, and conclude the research.

II. Literature Review

There are many theoretical explanations for the EKC. One such explanation is based upon the income elasticity on environmental quality demand. Under this theory, people in low income economies do not have much demand for good environmental quality. The focus of these economies is more job and output oriented. As an economy develops, however, people with higher incomes have increased concern for the environment. Their higher income levels allow for increased spending on environmentally-friendly products, as well as increased demand for environmental regulations (Selden and Song, 1994). The environmental regulation theory then asserts that economic growth strengthens institutions, which are then more capable of implementing and enforcing emissions reduction policies (Dasgupta, 2001).

Another existing theory is based on scale, technological, and composition effects. The scale effect says that economic growth coincides with increased output, which requires more inputs and produces more waste and emissions. On the other hand, the technological effect hinges on the idea that increased research and development leads to the invention of cleaner technology, therefore reducing emissions. The composition effect refers to changes in economic structure as a response to changes in income. Higher income levels aid in an economy’s transition from an agricultural economy to an industrial economy, causing increased emissions. At even higher income levels, an economy transitions from industrial production to service production, which reduces emissions. Together, these effects could explain the EKC. The inverted-U relationship would be present if the scale effect dominated at early stages of economic development, representing the upward slope of the curve. At later stages, the composition and technological effects outweigh the scale effect, thus creating the downturn of the curve (Grossman and Krueger, 1991).

Many other theories that aim to explain the EKC are interrelated. The Displacement Hypothesis proposes that free trade causes pollution intensive industries to move to lesser developed countries. This causes poor countries to focus on “dirty” material products, while rich countries are more concerned with cleaner production of services (Cole et al., 2001). Similarly, the “race to the bottom”, triggered by globalization, causes pollution intensive industries to relocate to lesser developed countries in order to avoid the more strict environmental regulations that exist in higher developed countries. This shifts production, causing lesser developed countries to emit more. Eventually, however, the developed countries’ governments are forced to lower environmental standards due to increased capital outflows, and there is a continuous race to the bottom that causes emissions to increase (Jaffe et al., 1995).

The aforementioned theories are not very relevant without confirmation of the existence of the EKC. Much empirical research has been conducted to test the existence of the inverted-U relationship between environmental degradation and income per capita. A study by Holtz-Eakin and Seldon (1992) explores a quadratic economic model with global panel data on carbon dioxide emissions. The study finds that as development increases, countries experience a decreasing marginal propensity to emit carbon dioxide. Despite this finding, Holtz-Eakin and Seldon predict that global carbon dioxide emissions will still increase at 1.8 percent each year because economic and population growth, and therefore development, will be highest in countries with low incomes, where the marginal propensity to emit is high compared to countries with higher incomes.

This study led to further consideration of the relationship between environmental degradation and economic development. Grossman and Krueger (1991, 1993, 1995) were among the first to investigate the existence of an EKC. They develop a reduced form model to run multiple regressions containing dependent variables indicative of air and water quality. Air quality is quantified by sulfur dioxide (SO_2) and suspended particulate matter (SPM) emissions, while water quality is measured by dissolved oxygen, pathogen contamination, and heavy metal concentrations. They use the following cubic model that is built upon in later studies:

$$Y_{it} = \beta_1 G_{it} + \beta_2 G_{it}^2 + \beta_3 G_{it}^3 + \beta_4 \overline{G}_{it} + \beta_5 \overline{G}_{it}^2 + \beta_6 \overline{G}_{it}^3 + \beta_7 X_{it} + \varepsilon_{it}$$

In this model, *Y* is the measure of environmental degradation, *G* represents GDP per capita, $\overline{G}$ is the average GDP per capita over the past 3 years, X is a vector of other factors affecting pollution, and ε is the error term. The study finds that although individual coefficients cannot be interpreted due to issues with multicollinearity, the collection of terms is found to be highly significant in most cases, indicating that national income is a significant factor in determining air and water pollution. Further, two out of three air quality indicators and six out of nine water quality indicators exhibit the inverted-U shape that is characteristic of an EKC when graphed against GDP per capita. On average, the pollutants that demonstrated an EKC had turning points in the range of four to eight thousand dollars, measured in 1985 U.S. dollars.

Another study conducted by Selden and Song (1994) expands on the findings of Grossman and Kruger (1995), examining global data for sulfur dioxide, particulate matter, nitrogen oxides, and carbon monoxide. They transform the model slightly, including exponential functions of GDP per capita and a variable for population density. The results show that cubed and higher functions of GDP per capita are insignificant in the model, and that emissions do not monotonically increase with GDP, but rather follow the inverted-U shape of the EKC. Further, population density is found to be indirectly related to emissions, and the coefficient is significant in some, but not all models. The turning points calculated by Selden and Song for aggregated emissions fall mostly between eight and twelve thousand 1985 U.S. dollars. These income values at the turning points are higher than those calculated by Grossman and Krueger (1995), who use measures of urban pollution. This difference is attributed to the fact that urban emissions pose a more direct threat to human health and the environment than do aggregated emissions, and people therefore become more concerned at lower stages of economic development.

More recent literature focuses on proper construction of the model depicting the relationship between environmental degradation and economic development. Millimet et al. (2003) examine multiple modeling strategies and specifications to illustrate the differences in estimation created by varying models. They use U.S. state-level emissions of nitrogen oxide and sulfur dioxide emissions as reported by the Environmental Protection Agency (EPA) to observe the difference in estimates between a parametric cubic specification model and a semiparametric partially linear regression (PLR) model. The results show that the regressions produce statistically different results, some of which portray the inverted-U relationship of an EKC while others do not. This demonstrates that the type of model used in EKC estimation can drastically affect the results, which can subsequently affect the conclusions drawn, as well as the formulation of optimal regulatory policies.

Rather than examining the form of the model, Maddison (2006) considers other variables that should be included in the parametric models. The main variable of interest to him is the spatial relationship between countries. The distance between countries can affect emissions depending on whether a particular country is close to other low emitting or high emitting countries. This effect can be a result of many factors including pollution displacement, the idea that high income countries push pollution-intensive processes to low income countries, or technology diffusion and policy spillover, causing one country's emissions to indirectly affect a neighboring country's emissions. The study finds that emissions for two of four pollutants are a function of the spatially weighted average of neighbors' emissions, indicating that changes in emission levels are transmitted to neighboring countries.

Additional literature continues to alter models when estimating an EKC for a single country. Egli (2002) conducts a time series analysis for sulfur dioxide, nitrogen oxides, carbon monoxide, carbon dioxide, ammonia, methane, particulate matter, and non-methane volatile organic compounds emissions in Germany from 1966 to 1988. He incorporates different variables into the model, such as the industry share of GDP, and imports and exports of goods from pollution-intensive production. He also develops a growth rate model where he regresses the growth rates of lagged pollution, GDP per capita, and imports and exports on the growth rate of pollution. Eliminating gases that exhibit serial correlation leaves only NH_3 and NO_x (Nitrogen oxides including NO, NO_2, and NO_3) estimates to be examined. Regression results show that the growth rate model is not significant, nor is the variable for imports and exports of pollution-intensive goods. However, the variable for industry share of GDP did prove to be significant, and the model including the cubic function of GDP per capita showed evidence of an EKC, with the relationship between pollution and GDP per capita taking the form of an inverted-U. Other model forms did not show evidence of an EKC.

Similarly, Coderoni and Esposti (2009) alter variables for a cubic specification model in a panel analysis of methane and nitrous oxide emissions within Italian regions. The researchers use panel data over a long time period rather than only cross-sectional or only time series data in order to increase the robustness of their findings, and they conduct a sector-level analysis rather than an aggregate emissions analysis in order to consider cross-sectional heterogeneity in environmental performance. The study disaggregates Italian GHG inventory from the following five sources: enteric fermentation, manure management, rice cultivation, agricultural soils, and field burning of agricultural residues. Rather than using per capita emissions as a dependent variable like previous research, this study uses emission level per agricultural working unit. The independent variables are then cubic functions of agricultural value added per agricultural working unit. This study also explores the inclusion of a variable accounting for an autoregressive, AR(1), process. The results show that the AR(1) term is significant in all models, making it the prevailing explanatory variable. With respect to an EKC, the researchers conclude that evidence is not consistent across different model specifications, time periods, or pollution indicators, indicating that the inverted-U relationship between pollution and income per capita is very specific to certain gases and data.

This paper is different from previous research in that it specifically examines agricultural emissions, including methane, nitrous oxide, carbon dioxide, and ammonia, across countries in a panel format. The estimated model is expanded to include agricultural machinery, agricultural value added, and agricultural land, in addition to the cubic function of GDP per capita.

III. Data

The data used in this analysis comes from the Emissions Database for Global Atmospheric Research (EDGAR), which is a project of the European Commission Joint Research Centre (JRC) and the Netherland’s Environmental Assessment Agency (PBL), as well as from The World Bank database.

EDGAR contains figures for direct GHGs, ozone precursor gases, acidifying gases, primary particulates, and stratospheric ozone depleting gases. Of these, this paper considers carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), all of which are greenhouse gases, as well as ammonia (NH_3), an acidifying gas. These gases are studied because they are the most prominent emissions produced by the agricultural industry. The data is reported per source category at a country level from 1970 to 2008.

For this study, the source categories pertaining to agriculture are aggregated to obtain total agricultural emission levels for each gas in each country. Although slightly different between gases, the sources include the following: enteric fermentation, manure management, rice cultivation, direct soil emissions, manure in pasture/range/paddock, indirect nitrous oxide from leaching or runoff, other direct soil emissions, and agricultural waste burning. Enteric fermentation is the release of methane gas as a byproduct of the digestion process of ruminant livestock, such as cattle, sheep, goats, donkeys, and horses. The next category, manure management, refers to the way that farmers handle and dispose of animal waste, while manure in pastures and paddocks includes emissions from animal waste that is left to decompose on its own. Rice cultivation simply includes the emissions released during facilitation of rice growth. Direct and other direct soil emissions encompass the gases released by the soil itself, as well as gases produced from processes involving soil, such as tilling the land and adding materials to soil in order to benefit plant growth. Indirect nitrous oxide emissions are produced by the conversion of nitrogen from soil and animal waste to nitrous oxide, a process that is often facilitated by small organisms known as microbes. Lastly, emissions from agricultural waste burning are produced from the burning of vegetation that is not useful or no longer productive to agricultural processes.

The remaining variables are generated using data from The World Bank. These include GDP per capita, agricultural value added, agricultural land, agricultural machinery, and population. Like the others, these variables also span from 1970-2008. Summary statistics for all data can be found in Table 1.

Table 1. Summary statistics, including mean, standard deviation, and number of observations, for all variables used in the model.

Variable	Mean	Standard Deviation	Number of Observations
Methane (metric tonnes)	2,122,764	3,919,061	975
Nitrous Oxide (metric tonnes)	74,302.6	128,982.7	975
Carbon Dioxide (metric tonnes)	1.36×10^7	2.93×10^7	975
Ammonia (metric tonnes)	450,662.4	786,874.3	975
Total Agricultural Emissions (metric tonnes)	1.62×10^7	3.38×10^7	975
GDP per capita (constant 2000 U.S dollars)	9,152.41	10,304.95	975
Methane per Capita (kg/person)	40.73	26.40	975
Nitrous Oxide per Capita (kg/person)	1.77	1.12	975
Carbon Dioxide per Capita (kg/person)	186.88	245.95	975
Ammonia per Capita Emissions (kg/person)	9.95	6.48	975
Total Agricultural Emissions per Capita (kg/person)	239.34	255.62	975
Agricultural Value Added (percentage of GDP)	12.53	11.97	966
Agricultural Land (percentage of arable land area)	40.25	21.94	975
Agricultural Machinery (tractors per 100 sq. km)	1,022.14	3,223.74	908
Population (people)	3.38×10^7	1.75×10^8	975

IV. Model

As most studies utilize a model including some measure of environmental degradation and a cubical function of income per capita, that is what this research builds upon. The dependent variable will be a measure of air pollution, more specifically, agricultural emissions of CH_4, N_2O, CO_2, NH_3, and total agricultural emissions which includes all four gases. The model is estimated separately for each gas, once using aggregate emissions for the gas, and again using emissions per capita for each gas. The independent variables will include a cubic function of GDP per capita, similar to studies conducted by Grossman and Krueger (1991, 1993, 1995), Millimet et al. (2003), Maddison (2006), and Egli (2002). In addition, I include a variable for agricultural value added as a percentage of GDP, rather than industry share of GDP, which was included by Egli (2002). Similarly, I incorporate a variable for agricultural land into the model, as it likely affects the amount of emissions a country produces.

Another factor influencing the amount of emissions produced by a country is technology. Technological changes often alter the environmental impact of machines used in the agricultural process. To account for this change, an agricultural machinery variable is included, accounting for the amount of tractors used in the industry. Additionally, emissions regulations and the strictness at which they are enforced also play a role in emission levels. Because this is a hard effect to measure, some studies choose to include a proxy variable such as abatement costs for firms or industries. However, even the proxy variables are largely unavailable for agricultural emissions. Therefore, I include a time dummy variable that is representative of exogenous factors, including emissions reductions policies. With these variables, the model looks as follows, with the variables defined in Table 2:

$$E_{it} = \alpha + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \beta_4 A_{it} + \beta_5 L_{it} + \beta_6 M_{it} + \beta_7 T + \varepsilon_{it} \qquad (1)$$

Table 2. Definitions of variables in Equation (1)

E_{it}	Emissions for country *i* at time *t*, measured in metric tons or kg/person: Methane, Nitrous Oxide. Carbon Dioxide, Ammonia, Total Emissions
Y_{it}	GDP per capita for country *i* at time *t*, measured in constant 2000 US dollars
A_{it}	Agricultural value for country *i* at time *t*, measured as percentage of GDP
M_{it}	Agricultural machinery in country *i* at time *t*, measured as number of tractors per 100 sq. km
L_{it}	Agricultural land in country *i* at time *t*, measured as percentage of total land area.
T	Matrix of time dummy variables, 1970 used as a base.

V. Results

The data is first tested for panel autocorrelation, and the null hypothesis of no first order autocorrelation is rejected in each case. To correct for the autocorrelation, models are estimated using a linear regression with AR(1) disturbances, where the autocorrelation is computed based on the panel Durbin-Watson statistic. Because this study uses panel data, the Hausman test is conducted to determine whether the model should be estimated with fixed or random effects linear regression. The results of the Hausman test are presented in Table 3.

Table 3. Hausman test results from estimating the fixed and random effects models.

Dependent Variable	$\chi 2$ Statistic	P-values
Methane	2.70	0.6098
Nitrous Oxide	4.95	0.2927
Carbon Dioxide	10.83	0.0286
Ammonia	4.72	0.3177
Total Emissions	9.36	0.0526
Methane per capita	25.02	0.0000
Nitrous Oxide per capita	37.14	0.0000
Carbon Dioxide per capita	5.51	0.1380
Ammonia per capita	19.68	0.0000
Total Emissions per capita	4.98	0.1731

Failing to reject the null hypothesis means that random effects estimation should be used, while rejecting the null hypothesis means that the model should be estimated with fixed effects. The results in Table 3 indicate that the null hypothesis is not rejected at the 1% significance level for methane, nitrous oxide, carbon dioxide, ammonia, total emissions, carbon dioxide per capita, and total emissions per capita. Therefore, I use random effects linear estimation for the aforementioned variables. Conversely, the null hypothesis is rejected at the 1% significance level for methane per capita, nitrous oxide per capita, and ammonia per capita; These three emissions are therefore estimated using fixed effects linear regression. The results of estimating Equation (1) with aggregate (not per capita) emissions as the dependent variable appear in Table 4. Table 5 shows the results of estimating Equation (1) using per capita emissions. The agricultural value added variable is dropped in the emissions per capita regressions because it was found to be highly correlated with the dependent variable.

Table 4. Results of estimating Equation (1) with random effects linear regression.

Dependent Regressors	**Methane**	**Nitrous Oxide**	**Carbon Dioxide**	**Ammonia**	**Total Agricultural Emissions**
GDP per capita	88.249** (40.83)	1.972 (2.26)	1,365.362* (721.81)	23.943* (13.94)	1,526.208** (764.33)
GDP per capita^2	-0.005*** (0.002)	-9.86×10^{-5} (1.04×10^{-4})	-0.077** (0.03)	-0.0013** (0.001)	-0.085** (0.03)
GDP per capita^3	7.38×10^{-8}*** (2.8×10^{-8})	1.38×10^{-9} (1.56×10^{-9})	1.07×10^{-6}** (5.07×10^{-7})	2.04×10^{-8}** (9.65×10^{-9})	1.18×10^{-6}** (5.33×10^{-7})
Ag Value	3,292.563 (2,143.34)	99.164 (121.79)	126,707.5*** (40,787)	177.171 (749.21)	130,268.6*** (42,548)
Ag Land	8,827.979* (5,318.47)	211.898 (294.01)	79,302.57 (93,871.2)	296.411 (1,812.93)	88,020.38 (99,472.91)
Machine	-12.914 (15.67)	-0.336 (0.89)	-107.595 (296.33)	-1.821 (5.46)	-121.822 (309.60)
Constant	1,143,035 (806,633)	32,894.84 (28,096.3)	-90,922.44 (7,194,671)	200,011.3 (169,554)	1,117,451 (8,053,264)
Model Significance (Wald $\chi 2$)	97.40***	89.58***	76.50***	101.33***	78.93***
R^2 (overall) **(within)**	0.0057 0.1511	0.0198 0.1920	0.0046 0.1309	0.0142 0.1749	0.0034 0.1351

***=Significant at 1%, **=Significant at 5%. *=Significant at 10%, standard errors in parentheses. Time controls are used with 1970 as the base year. Estimates are corrected for AR(1) autocorrelation.

Table 5. Results of estimating Equation (1) with random effects linear regression for carbon dioxide per capita and total emissions per capita, and fixed effects for methane per capita, nitrous oxide per capita, and ammonia per capita.

Dependent Regressors	**Methane per capita**	**Nitrous Oxide per capita**	**Carbon Dioxide per capita**	**Ammonia per capita**	**Total Agricultural Emissions per capita**
GDP per capita	9.53x10^{-4} (0.001)	1.01x10^{-4}** (4.1x10^{-5})	0.018 (0.01)	0.001*** (0.0002)	0.019* (0.01)
GDP per capita^2	-2.80x10^{-8} (4.6x10^{-8})	-3.19x10^{-9}* (1.9x10^{-9})	-9.00x10^{-7} (5.7x10^{-7})	-3.87x10^{-8}*** (9.5x10^{-9})	-9.38x10^{-7} (5.81x10^{-7})
GDP per capita^3	2.32x10^{-13} (6.8x10^{-13})	2.79x10^{-14} (2.77x10^{-14})	1.33x10^{-11} (8.93x10^{-12})	4.27x10^{-13}*** (1.4x10^{-13})	1.35x10^{-11} (9.12x10^{-12})
Ag Land	0.059 (0.135)	0.002 (0.005)	-2.114 (1.42)	0.009 (0.03)	-1.991 (1.47)
Machine	-1.92x10^{-4} (0.0004)	-2.23x10^{-5} (1.4x10^{-5})	-0.003 (0.006)	-0.0002 (7.3x10^{-5})	-0.003 (0.006)
Constant	22.611 (0.33)	0.898*** (0.012)	232.362 (83.43)	3.812 (0.07)	279.972 (86.21)
Model Significance$^{\#}$	1.63***	1.83***	43.59	2.18***	45.29
R^2 (overall) **(within)**	0.0018 0.0776	0.0863 0.0861	0.0073 0.0535	0.4374 0.1007	0.0076 0.0644

***=Significant at 1%, **=Significant at 5%. *=Significant at 10%, standard errors in parentheses. $^{\#}$ = Carbon dioxide per capita and total emissions per capita Wald $\chi 2$ statistics are reported since they are estimated with random effects. The others are estimated with fixed effects, therefore the F statistic is reported. Estimates are corrected for AR(1) autocorrelation.

The models using methane, methane per capita, nitrous oxide per capita, carbon dioxide, ammonia per capita, and total agricultural emissions are significant at one percent, while the nitrous oxide and ammonia models are significant at five percent. Conversely, the models using carbon dioxide per capita and total emissions per capita are entirely insignificant. Despite the significance of the overall model, the GDP per capita variables are individually insignificant in both the nitrous oxide and methane per capita models. With the exception of the constant, the signs of the coefficients for all independent variables are the same across all dependent variables, excluding the insignificant models. I find a positive relationship between agricultural emissions and both agricultural value added and agricultural land, as expected. Regarding the former, it is rational that as agriculture makes up a larger share of a country's GDP, the country's emissions increase as a result of more agricultural processes taking place. Similarly, as more land is being used for agricultural purposes, there are more activities occurring on the land that contribute to agricultural emissions, causing emission levels to rise. On the other hand, results show that there is a negative relationship between agricultural machinery and agricultural emissions. Since this variable is measured by tractors per 100 square km, I expected a positive relationship demonstrating the idea that a higher concentration of tractors would contribute to higher emission levels. It is possible, however, that the negative relationship is representative of technological increases that make farm machinery less polluting.

Initial investigations into the existence of the EKC used models that contained only the GDP per capita variables. Some researchers, however, were concerned with omitted variable bias, leading them to add in the additional variables that may affect emissions levels. As I have expanded the cubic functional model to include additional variables, I conduct a test of restrictions using the F statistic to find whether or not the agricultural value, agricultural land, and agricultural machinery variables increase the fit of the model compared to a model including just the cubic function of GDP and a time dummy. Specifically, I test if $\beta_4=\beta_5=\beta_6=0$ in the model presented in Equation (1). The null hypothesis of the restrictions test is that the restrictions are valid, such that the smaller model is a better fit, while the alternative hypothesis is that the restrictions are invalid, meaning that the larger model is better. The restricted model appears as follows:

$$E_{it} = \alpha + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \beta_7 T + \varepsilon_{it} \tag{2}$$

The F statistics, calculated using Equation (3), are shown in Table 7 and are only calculated for significant models. The variables in the equation are defined in Table 6. The critical F statistics at 10% significance level are 2.084 and 2.303 for the aggregate and per capita emissions models, respectively. As the calculated F statistics are less than the critical F statistic, the null hypothesis is not rejected, meaning that the restrictions are valid. For this reason, the rest of the analysis focuses on the results obtained from estimating the restricted models, which appear in Tables 8 and 9.

$$F = \frac{(R_{UR}^2 - R_R^2)/m}{(1 - R_{UR}^2)/(n * T - k)} \tag{3}$$

Table 6. Definitions of Variables in Equation (3) for calculating the F statistic for the restrictions test.

R_{UR}^2	R^2 value for unrestricted model, Equation (1)
R_R^2	R^2 value for restricted model, Equation (2)
m	Number of restrictions
n	Number of cross sections (countries) in data set
T	Number of time observations in data set
k	Number of parameters estimated, including the constant

Table 7. Results of restricted F test that β_4=β_5=β_6=0 in Equation (1).

Dependent Variable	F Statistic
Methane	1.58
Nitrous Oxide	2.07
Carbon Dioxide	1.12
Ammonia	0.37
Total	0.58
Methane per capita	0.82
Nitrous Oxide per capita	0.00[#]
Ammonia per capita	0.10[##]

The test statistic is calculated using the overall R^2 value from the models, except as noted. The degrees of freedom are (3,908) for aggregate emissions and (2,908) for per capita emissions.[#] =R^2 from restricted model is slightly larger than R^2 from unrestricted model, making the statistic close to zero, but negative. [##]=Calculated using within R^2 because of fixed effects regression.

Table 8. Results of estimating the restricted model in Equation (2) for aggregate emissions.

Dependent Regressors	**Methane**	**Nitrous Oxide**	**Carbon Dioxide**	**Ammonia**	**Total Agricultural Emissions**
GDP	78.131** (38.21)	2.643 (2.11)	1,446.044* (777.23)	22.664* (13.38)	1,613.60** (819.6)
GDP^2	-0.005*** (.002)	-0.0001 (0.0001)	-0.075** (0.04)	-0.0012** (0.0006)	-0.083** (0.04)
GDP^3	6.66x10^{-8}*** (2.57x10^{-8})	1.49x10^{-9} (1.44x10^{-9})	9.73x10^{-7}* (5.41x10^{-7})	1.80x10^{-8}** (9.13x10^{-9})	1.08x10^{-6}* (5.66x10^{-7})
Constant	1,580,996** (797,790)	40,823.72 (26,190.4)	4,900,944 (6,455,037)	218,716.3 (159,334)	6,482,777 (7,367,766)
Model Significance (Wald χ2)	96.57***	100.87***	85.35***	109.52***	87.06***
R^2 (overall) (within)	0.0005 0.1273	0.0131 0.1886	0.0009 0.1565	0.0130 0.1748	0.0015 0.1571

***=Significant at 1%, **=Significant at 5%. *=Significant at 10%, standard errors in parentheses. Estimated using random effects linear regression with time controls, correcting for AR(1) autocorrelation. Time dummy coefficients not included in table.

Table 9. Results of estimating the restricted model in Equation (2) for per capita emissions.

Dependent Regressors	**Methane per capita**	**Nitrous Oxide per capita**	**Ammonia per capita**
GDP	9.17x10^{-4} (9.1x10^{-4})	1.23x10^{-4}*** (3.7x10^{-5})	0.001*** (1.9x10^{-4})
GDP^2	-2.76x10^{-8} (4.2x10^{-8})	-3.76x10^{-9}** (1.71x10^{-9})	-3.70x10^{-8}*** (8.6x10^{-9})
GDP^3	2.43x10^{-13} (6.23x10^{-13})	3.39x10^{-14} (2.53x10^{-14})	4.03x10^{-13}*** (1.3x10^{-13})
Constant	24.489*** (0.20)	0.787*** (0.01)	3.795*** (0.04)
Model Significance (F statistic)	1.78***	2.13***	2.47***
R^2 (overall) (within)	0.0000 0.0746	0.1375 0.0879	0.4511 0.1005

***=Significant at 1%, **=Significant at 5%. *=Significant at 10%, standard errors in parentheses. Estimated using fixed effects linear regression with time controls, correcting for AR(1) autocorrelation. Time dummy coefficients not included in table. Insignificant models not shown.

Results show that the cubic function of GDP per capita is a significant predictor of emission levels for all gases except nitrous oxide emissions and methane per capita emissions. The chi-squared values for the methane, nitrous oxide per capita, carbon dioxide, ammonia,

ammonia per capita, and total emissions models are high, generating significant models with p-values very close to zero. Signs of the coefficients for GDP per capita, GDP per capita squared, and GDP per capita cubed are found to be positive, negative, and positive respectively. This alternating sign pattern is consistent with the findings of previous literature. Previous studies find that the inverted-U shape of the EKC is created theoretically by the alternating positive and negative signs, along with significant GDP per capita and GDP per capita squared variables and an insignificant GDP per capita cubed variable. This exact relationship is found in the nitrous oxide emissions per capita. The remaining regressions, including methane, carbon dioxide, ammonia, ammonia per capita, and total emissions, demonstrate the alternating sign pattern but not the aforementioned significance pattern. This means that they still display the inverted-U relationship of the EKC, but emissions eventually start to increase again at higher values of income due to the significance of the cubed GDP per capita term.

Moving further, I create graphs showing the predicted dependent variable versus GDP per capita in order to observe the relationship and determine whether an EKC exists. Graphs are constructed for the restricted models only, as they are proven to fit the data better than the full models. Also, graphs are only shown for the restricted models that are collectively significant and where the GDP variables are significant. This selection includes the following: methane, nitrous oxide per capita, carbon dioxide, ammonia, ammonia per capita, and total emissions. The graphs are displayed in Figures 2 through 7, respectively.

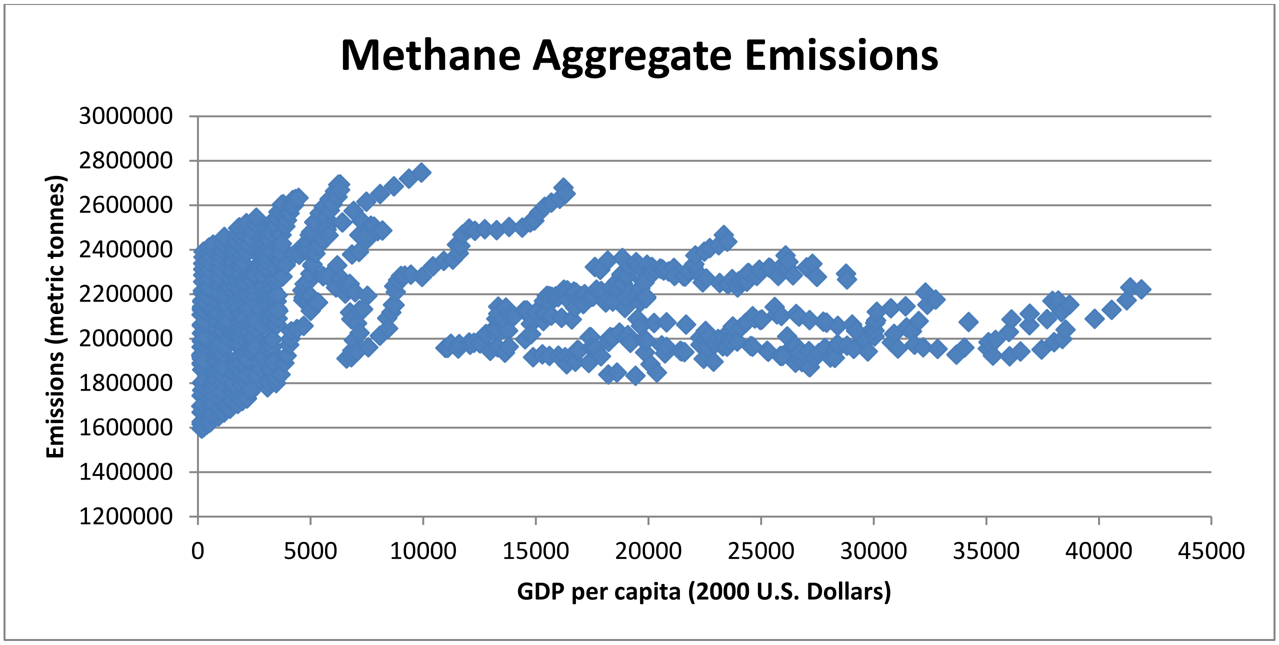

Figure 2. Graph of predicted methane emissions versus GDP per capita. Predicted methane emissions were generated based on the results displayed in Table 8.

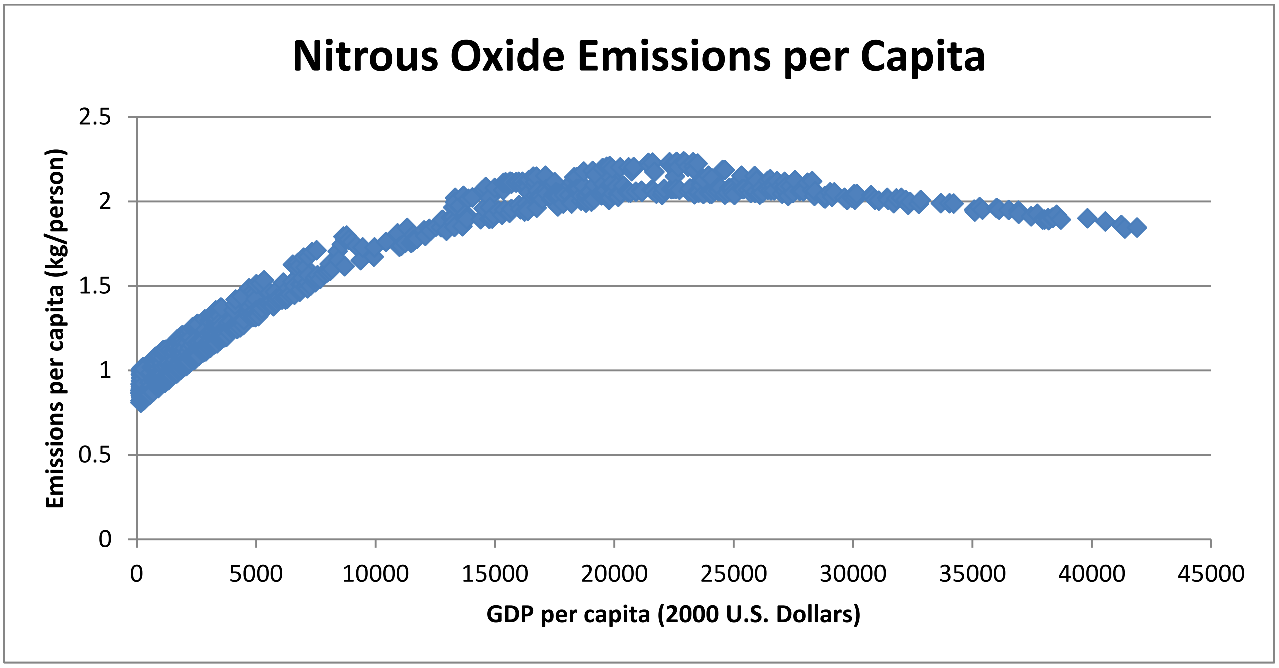

Figure 3. Graph of predicted methane emissions versus GDP per capita. Predicted methane emissions were generated based on the results displayed in Table 9.

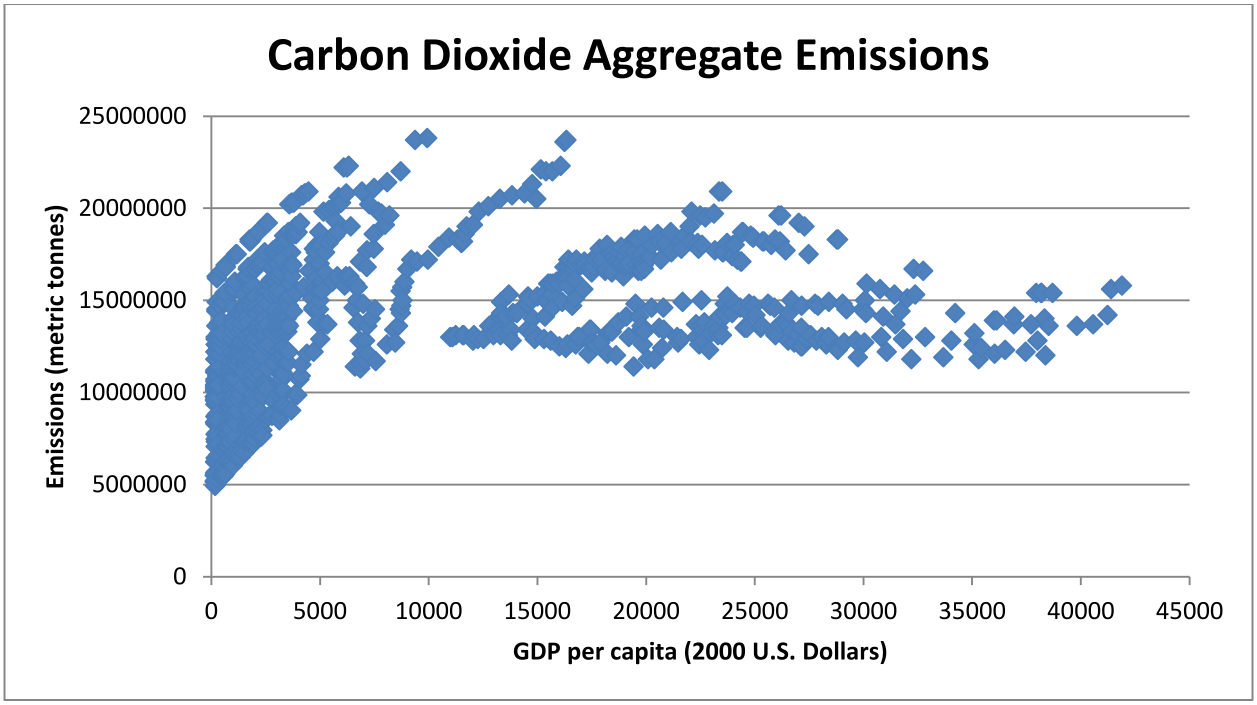

Figure 4. Graph of predicted methane emissions versus GDP per capita. Predicted methane emissions were generated based on the results displayed in Table 8.

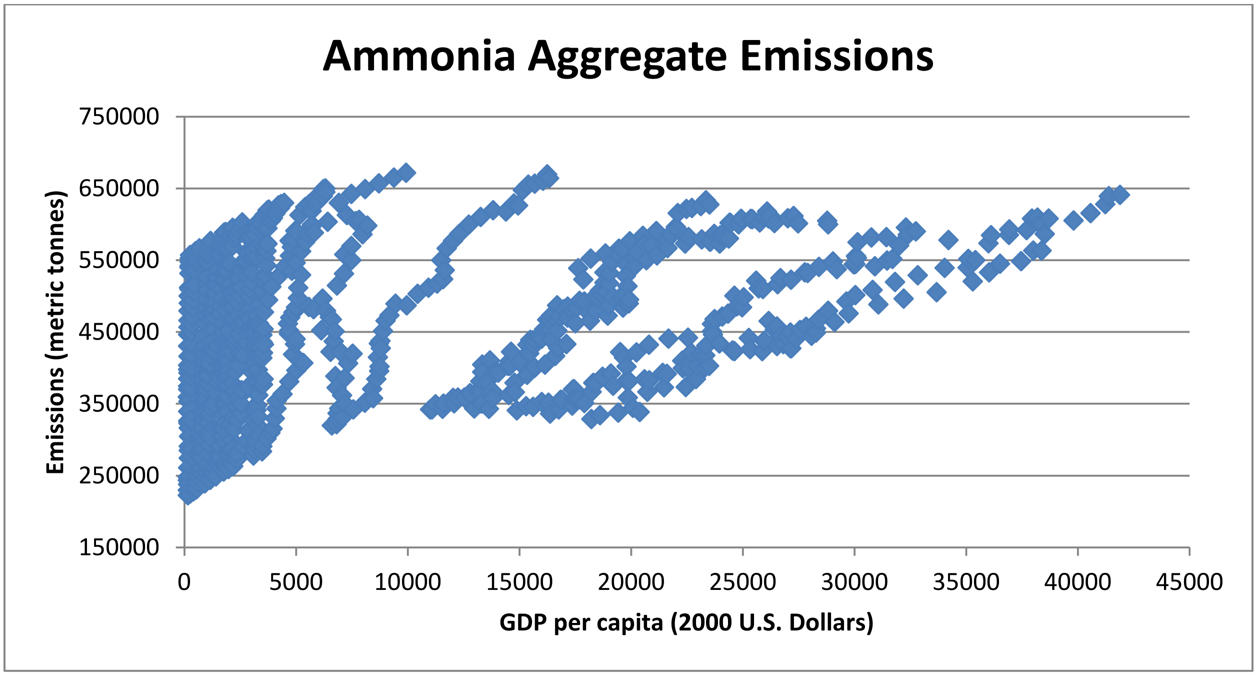

Figure 5. Graph of predicted methane emissions versus GDP per capita. Predicted methane emissions were generated based on the results displayed in Table 8.

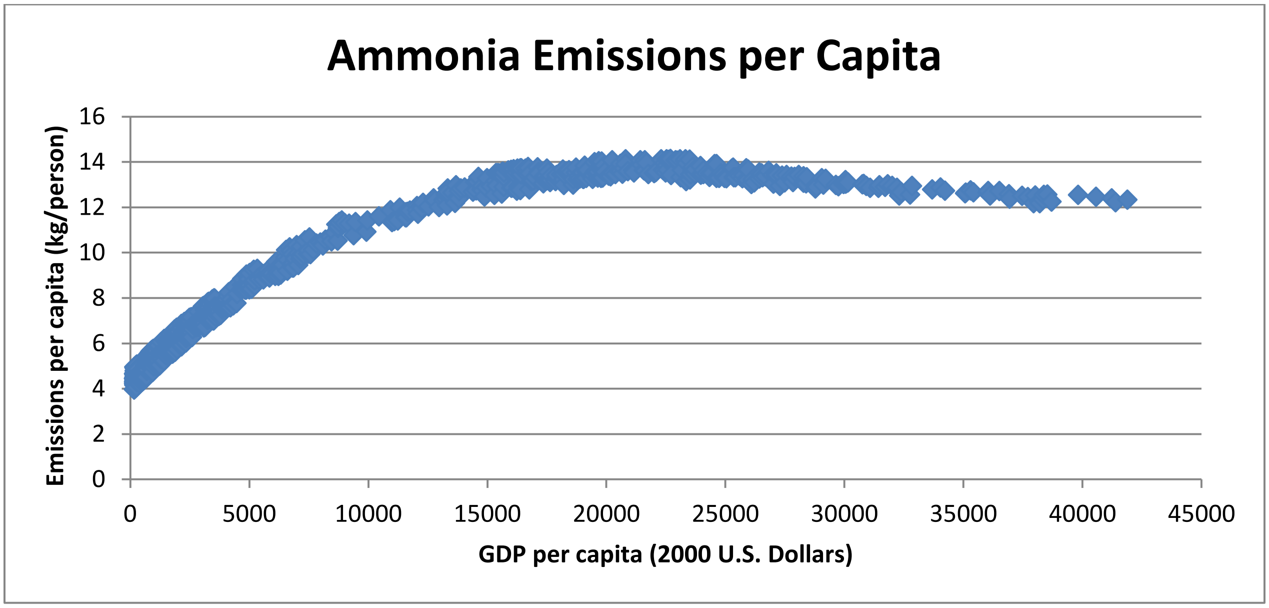

Figure 6. Graph of predicted methane emissions versus GDP per capita. Predicted methane emissions were generated based on the results displayed in Table 9.

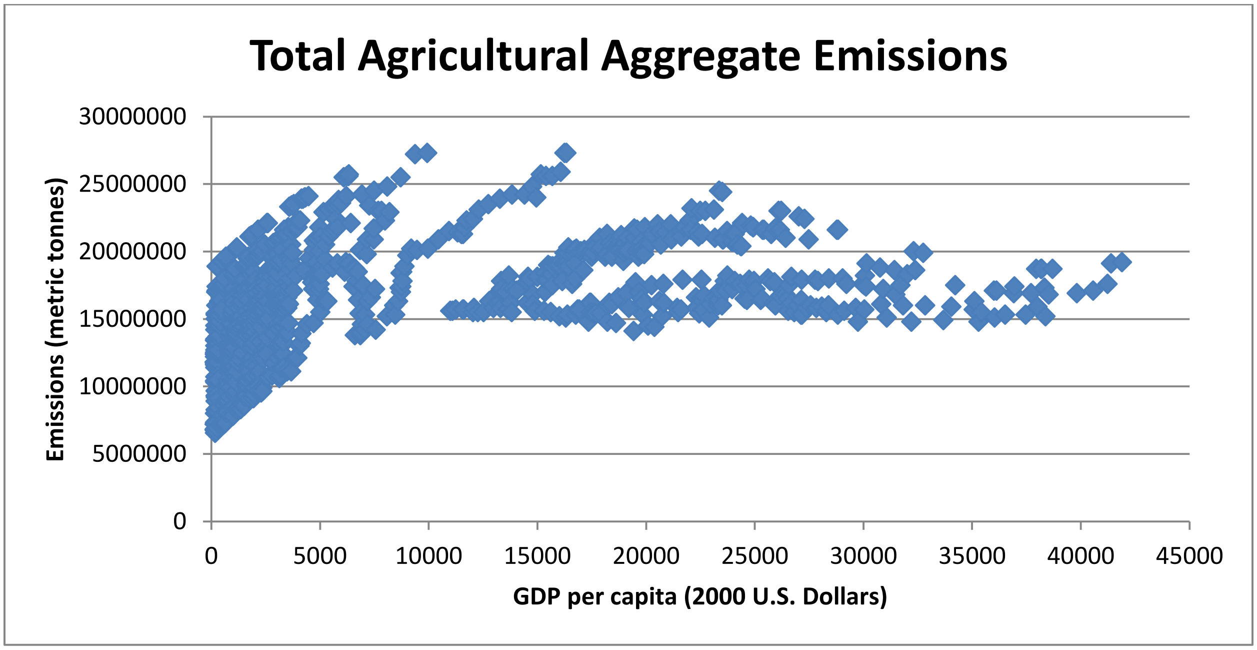

Figure 7. Graph of predicted methane emissions versus GDP per capita. Predicted methane emissions were generated based on the results displayed in Table 8.

The graphs show that the alternating sign pattern for the cubic function of GDP per capita does indeed create the inverted-U shape of the EKC. From the graphs, it is evident that nitrous oxide per capita is the only emissions variable that exhibits a true EKC. The other variables, methane, carbon dioxide, ammonia, ammonia per capita, and total emissions, show the bow curve with a second turning point that causes emissions to begin to increase at the higher income levels.

The final step in EKC estimation is finding the turning point(s) of the curve. The turning point(s) is/are found by taking the partial derivative of the model with respect to GDP per capita, setting it equal to zero, plugging in the estimated parameters, and solving for GDP per capita, represented by Y^*. This process is displayed in detail in Appendix A, using Equations (4) through (7). In this analysis, Equation (6) is used to determine the income at the turning point for the nitrous oxide emissions per capita EKC, while Equation (7) is used to calculate the remaining income levels at the turning points of the EKC. The results of these calculations appear in Table 10. The downward turning points of the curves, which occur at the peak of inverted-U shape of the curve, fall between approximately 10 and 20 thousand 2000 U.S. dollars. When applicable, the upward turning points of the curves, resulting from the significant GDP per capita cubed term and resulting N-shape, are found at higher income levels ranging from 30 to 40 thousand 2000 U.S. dollars.

Table 10. Income levels at the turning points of the EKCs presented in Figures 2 through 7. Income level reported in 2000 US dollars, to the nearest five dollars.

Dependent Variable	Downward Turning Point (2000 US Dollars)	Upward Turning Point (2000 US Dollars)
Methane (Figure 2)	9,690	40,360
Nitrous Oxide per capita (Figure 3)	16,355	N/A
Carbon Dioxide (Figure 4)	12,855	38,530
Ammonia (Figure 5)	13,610	30,830
Ammonia per capita (Figure 6)	20,140	41,065
Total Agricultural Emissions (Figure 7)	13,040	38,195

VI. Conclusions

Previous literature concerning the Environmental Kuznets Curve has experimented with various forms of the parametric cubic functional model originally implemented by Grossman and Krueger (1991). This paper also builds on that model, including variables for agricultural share of GDP, agricultural land, and agricultural machinery. The added variables are mostly found to be insignificant in predicting emission levels, and restricted F tests show that a smaller model, including only the cubic function of GDP, provides a better fit for the agricultural emissions data obtained from EDGAR.

Out of all the regressions run with both aggregate and per capita emissions, the model as a whole proves to be insignificant in only carbon dioxide emissions per capita and total agricultural emissions per capita. However, although the model is significant for nitrous oxide emissions and methane per capita emissions, the GDP per capita variables are found to be insignificant. Thus, six out of ten emissions variables display a semi-inverted-U relationship with GDP per capita. These emissions include the following: methane, nitrous oxide per capita, carbon dioxide, ammonia, ammonia per capita, and total agricultural emissions. Only nitrous oxide per capita showed a strict inverted-U relationship, while the others showed an increase towards the end of the curve, indicating that it might follow more of an N shape if there was more data.

The downward turning points of the curves fall between an income level of 9,500 and 20,000 when measured in 2000 U.S. dollars. When applicable, the subsequent upturn in the curve occurs between 30,000 and 40,000 in 2000 U.S. dollars. Selden and Song (1994) find that the downward turning points fall between an income level of eight and 12 thousand 1985 U.S. dollars, which convert to approximately 11.5 and 17 thousand 2000 U.S. dollars, respectively.

Thus, the turning points calculated in this paper are rather consistent with those found in previous literature.

The N-shaped curve that this paper finds for some emissions has also been found in a few past studies (De Bruyn and Opschoor, 1997; Sengupta, 1997). One explanation for that relationship is that the decreases in environmental degradation are not permanent, but rather temporary, due to an inability to keeping up efficiency increases with output increases (Dinda, 2004). Further research should aim to further investigate the existence of the EKC, using more types of emissions over longer time periods as the data becomes available. The turning point(s) of the EKC can provide knowledge to reduce agricultural emissions, thereby decreasing their contribution to global warming. The shape and position of the curve can help countries determine what stages of development are the most harmful to the environment, allowing them to make decisions on when to implement emissions reduction policies.

VII. References

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APPENDICES

Appendix A: Turning Point Estimation

The turning point(s) of the curve is/are found by taking the derivative of the model with respect to GDP per capita, setting it equal to zero, inserting the estimated parameter values, and solving for GDP per capita. This process is represented by Equations (4) and (5), where the variables correspond to those previously defined in Table 2.

$$\text{Model: } E = \beta_0 + \beta_1 Y + \beta_2 Y^2 + \beta_3 Y^3 \tag{4}$$

$$\text{First Derivative, set equal to zero: } \beta_1 + 2\beta_2 Y + 3\beta_3 Y^2 = 0 \tag{5}$$

In models that have results with alternating coefficient signs for the cubic GDP per capita function, as well as an insignificant GDP per capita cubed, solving for the turning point becomes easy because the $\beta_3 Y^3$ term drops out of Equation (4). The turning point income level, Y*, can then be found using Equation (6).

$$Y^* = -\frac{\beta_1}{2\beta_2} \tag{6}$$

Alternatively, when all of the GDP per capita variables are significant in the model, the quadratic formula, presented in Equation (7), must be used to solve Equation (5), which follows the form $ax^2+bx+c=0$. In this case, $a = 3\beta_3$, $b = 2\beta_2$, and $c = \beta_1$.

$$Y^* = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{7}$$