A global supply-demand balance model to assess potential CO\textsubscript{2} emissions and woody biofuel supply from increased crop production

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Abstract

This study proposes a food supply-demand balance model to evaluate the CO\textsubscript{2} emissions and effects on woody biofuel after an increase in crop production and, thus, in cultivated arable land. In addition to these effects, we consider increasing crop prices and population growth in developing countries in our global mid-term market analysis for four major crops. The results show that the demand for all main crops is increasing, especially that of soybeans, the largest increase in demand is occurring in China and South America. The result is that South America needs to increase its production levels and amount of cultivated arable land to fulfill the increasing demand. Therefore, South America can play a dominant role in maintaining the future supply-demand balance of crops.

1. Introduction

Recently, the depletion of crude oil and its subsequent increase in price have led to bioenergy, a non-fossil energy, garnering global attention as an alternative energy source. Bioenergy is expected to be a positive global warming countermeasure, as it is a carbon neutral resource that does not increase the amount of carbon dioxide (CO\textsubscript{2}) absorbed into the atmosphere. However, liquid fuels, such as bioethanol, often use grains and vegetable oils of food sources, as feed stocks. As a result, increasing grain prices due to the increase in demand. Impacts by climate changes, such as droughts, also attract great concern. In addition, with regard to CO\textsubscript{2} emissions arising from changes in land use, it is possible that woody bio-fuel may gradually give way to carbon-neutral resources.

In addition to them, in the mid-term of the next 10 to 20 years, the population in regions such as India and Africa with rapid growth and China with continuing to grow at a slower pace, which still showing a growing demand trend. In order to respond to this demand increase in the short to mid-term, it is necessary to increase yields and expand the areas under cultivation. However, the deforestation by the expansion cause the concern of CO\textsubscript{2} emissions increase.

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This study proposes demand models to evaluate the changes in woody biofuel and CO₂ emissions due to land use change. The model treat major grains in global level, considers price increases in the grain market since 2000, and increases in the population and demand growing to an increase in gross domestic product (GDP). The potential to expand areas under cultivation to meet the estimated demand is calculated by using a global potential cultivation area model designed by Kato et al. (2008) [1] that uses a geographic information system (GIS).

Although it is shortcoming to give grain prices exogenously, our model has a feature to evaluate the effects, including the mid-term demand increase and CO₂ emissions up to 2020, which had not addressed by existing studies.

2. Research method

2.1. The model outlines

In this research, we chose four major grains in our analysis: corn, wheat, rice, and soy whose demand has been observed in an increase trend meat demand has increased. We divided the world into 12 regions, with the majority of data coming from the Food and Agriculture Organization of the United Nations Statistical Database (FAOSTAT) and the World Bank. The regional allocation are referred from the 18 regional divisions from the GISELA model by Kato et al. (2008) [1] with further aggregation, considering the size of both population and the regional GDP to obtain demand functions, which were statistically significant based on the aggregation. More detail allocations, considering soil conditions, climate change, among other factors, are left for future work.

Here, we express the production volume, S, for grain i in term t and in area k as S(i,k,t). Then, the export volume is EX(i,k,t) and the import volume is IM(i,k,t). Next, the producer price, the export price, and the import price are expressed as PS(i,k,t), PX(i,k,t), and PM(i,k,t), respectively. The domestic average price is expressed as PD(i,k,t), and the international market price as PI(i,t). We applied Equations (1) and (2) for the export price and import price, respectively, with adjustment factors of γ(i,k) and λ(i,k), respectively.

\[
PX(i,k,t) = \gamma(i,k) \times PS(i,k,t)
\]

\[
PM(i,k,t) = \lambda(i,k) \times PI(i,t)
\]

The international market price is formulated as the weighted average of the export price divided by the export volume, as in Equation (3). The domestic average price is formulated as in Equation (4).

\[
PI(i,t) = \frac{\sum \left( EX(i,k,t) \times PX(i,k,t) \right)}{\sum EX(i,k,t)}
\]

\[
PD(i,k,t) = \frac{\left( PS(i,k,t) \times (S(i,k,t) - EX(i,k,t)) \right)}{S(i,k,t) + IM(i,k,t) - EX(i,k,t)}
\]

The production volume is formulated as in Equation (5), obtained from the harvest area, CR(i,k,t), and the yield, YL(i,k,t).

\[
S(i,k,t) = CR(i,k,t) \times YL(i,k,t)
\]

2.2. Time series analysis of the grain market

We conduct a time series analysis using domestic average price and GDP data to predict the feed demand and the grain demand in which includes the feed demand. For each grain, we use data from 1991 to 2011 to analyze domestic grain demand and domestic feed demand. The form of each basic function is defined in Equation (6) and Equation (7). These functions are used in the world food demand/supply prediction model by Ohga (1998) [2], which is globally used in the Food and Agriculture Organization of United Nations (FAO), the International Food Policy Research Institute (IFPRI) etc. We adopted these functions, expressed by the domestic GDP, domestic average price (+ 1 previous term), and the domestic demand for the previous term as explanatory variables.

\[
\ln(D(i,k,t)) = \alpha_i + \beta_i \ln(PD(i,k,t)) + \gamma_i \ln(Y(k,t))
+ \mu_i \ln(D(i,k,t-1)) + \delta_i \ln(PD(i,k,t-1)) + \epsilon_i(t)
\]
\[
\ln(FD(i, k, t)) = \alpha + \beta \ln(PD(i, k, t)) + \gamma \ln(Y(k, t)) \\
+ \mu \ln(FD(i, k, t-1)) + \delta \ln(PD(i, k, t-1)) + \varepsilon(t)
\]  

(7)

where \( D(i, k, t) \) is the grain demand volume in term \( t \), \( FD(i, k, t) \) is the feed demand volume in term \( t \), \( Y(k, t) \) is the GDP in term \( t \), and \( PD(i, k, t) \) is the domestic average price in term \( t \), where \( \beta, \gamma, \text{ and } \delta \) are regression coefficients, \( \alpha \) is a constant term, and \( \varepsilon \) is an error term. Table 1.(a),(b) shows the regression analysis results of parameter in AMN(AMN is America and Canada).

Here, if an explanatory variable is an unsteady process, a regression analysis can lead to a “spurious correlation.” Thus, we cannot apply a regression analysis to the data in its current form. As a result, we conduct a unit root test on the regression residuals (the Dickey-Fuller test). When the regression residual term is a steady process, it is called cointegration. In this case, it is known that the statistical confidence level becomes high.

2.3. Evaluation of land use changes

The arable lands should be expanded or the yield of a grain are to be increased to increase production. Here, we chose by cultivating potential arable lands, including the effects of land use changes.

We evaluate arable land cultivation, based on the results by Kato et al. (2008) [1] on potential arable land. In our research, the cultivation area was determined by using a method in which a certain percentage of potentially arable land in each region by the same cultivation rate. However, when the potential arable land in each region is cultivated uniformly, regions like Africa with small crop products in present day will show a sudden increase in their harvested land area. Thus, upper limits were given based on the experienced expansion rate of the harvested areas.

2.4. Constraints on potential arable land cultivation

We gave several constraints on the cultivation of arable lands. The upper limits are given to convertible areas for each grain, and some areas overlap between grains. Therefore, in this research, returns (i.e., selling price less production cost) are calculated for each region, and can be used in the order of grains with highest returns. The returns expressed as \( P(i, k, t) \) can be obtained from the yield and international market prices. The function is shown in Equation (8).

\[
P(i, k, t) = YL(i, k, t) \times PI(i, t)
\]

(8)

In addition, in this research, the lands are developed in the order of forest (where the region of potential arable land is the largest), pasture, and then tropical rain forest (where protection is demanded). To prevent harvest areas from growing too rapidly in one year, the upper limits are given based on the past growth rate of the each region.

2.5. CO₂ emission volume owing to land use changes

The area for sequestration of CO₂ decreases due to deforestation. In this research, we assume that 3.0 t-C and 3.3t-C absorption sources are lost per 1ha of converted area in forests and tropical rain forests, respectively. In addition, when digging the soil, all the carbon in the soil is emitted into the atmosphere. The weight of carbon in the soil are estimated by Equation (9) based on a research by Baba et al. (2009) [3].
The results we obtained show similar to those from the Global Forest Resources Assessment 2010 (FRA 2010) evaluated by the FAO.

2.6. Woody biofuel supply

When the timber produced by the deforestation as fuel, we obtain the supply volume of woody biofuel. Here, we use the forest biomass stock density data from the FAO and the study of Konagai et al. (2004) [4] as references to calculate the available volume of woody biofuel (Equation 10). The cold gas efficiency is 60%, and heat rate is 21,000 MJ/t.

\[
\text{Available supply of woody biofuel (KTOE)} = (\text{deforestation area (kha)}) \times (\text{biomass stock density (t/kha)}) \times (\text{cold gas efficiency}) \times (\text{heat rate (MJ/t)}) \times (\text{conversion factor from Joule to ton of oil equivalent})
\]

3. Results and discussion

The grain and feed demand functions set above set above are applied to simulations. Since we have data for the grain demand in 2012, data for the feed in 2010, and actual harvest area data in 2013 for the arable land cultivation, our simulation starts from 2013. GDP and producer price were given exogenously. We applied the SRES-B2-Scenario of the IPCC for the GDP, and carried out regression analysis based on the producer price trends to obtain results. The three scenarios are as follows:

Scenario 1: constant yield
Scenario 2: yield has variations by using random numbers
Scenario 3: changes in income elasticity

3.1. Scenario 1

Under the given expansion upper limits described in section 2.4, we use average yield from 2010 to 2012. The part of results for grain demand volume and production volume are shown in Figures 1.(a);(b). The grain demand used here includes the feed demand.

According to the grain demand prediction, in 2021, corn and wheat increase by 1.17 times that in 2012, rice by 1.05 times, and soy by 1.91 times (Figures 1.(a);(b)), respectively. The demand for soy will increase significantly,
particularly in two regions: AMS (Central and South America) and CHN (China). This reflects the effects of the recent increase in the demand for meat in CHN, leading to increased demand for feeds and fats. There is no significant structural change related to the production, however, since there is a large amount of potential arable land in AMS for soy grain farming, production volume increases. Next, we evaluate the arable land cultivation associated with the increase in production.

A large amount of potential arable land in AMS. Since it reaches the upper limit of those in forests to use the tropical rain forest. The results for AFC (Africa) also show a large cultivation area; however, since AFC has great potential arable land, this was insignificant of its percentage.

The may be caused by the expansion rate of past harvest areas in AFC is not very large, as well as being constrained by the expansion limit. CO$_2$ emissions due to the land cultivation are about 1.5 Gt-C per year, a large amount of which is emitted from AMS and AFC. The IPCC reported in their fourth report that the annual CO$_2$ emission by land use change was 1.6 Gt-C±0.8, within which our result falls. Our work showed that the available supply of woody biofuel was approximately 10 times of that consumed globally in 2012 (0.06 GTOE of biofuel). If some part of them is used as woody biofuel, the CO$_2$ emissions can be controlled to a certain degree, since the emissions from fossil fuels per 1 kilo TOE was 1.0 kt-C for coking coal, 0.8 kt-C for crude oil, and 0.6 kt-C for liquid natural gas (LNG), sourced from the Institute of Energy Economics, Japan (2013) [5].

3.2. Scenario 2 (Change in yield per unit)

Random numbers are given within the range of one standard deviation for the yield in the past 10 years. Then, we conducted the simulation that changes the yield by 10 times. There is a large variation in AMS and AFC, where the cultivated areas are large. When the yield changes, this affects the arable land area greatly. The decrease in the yield in areas with little potential arable land other than wheat, such as AMN, EUP (Europe), and FSU (Former Soviet Union) has significant effects on other regions.

3.3. Scenario 3 (Changes in income elasticity values)

Here, we observe the effects of changing income elasticity for grain demand in three regions (AFC, CHN, and SAS (India)) in developing nations, where the population growth is significant. The comparison of cultivation areas with those in Scenario 1, after changing the income elasticity by 0.3 in all the regions.

The grain demand for corn, soy, wheat, and rice changed by 2.4 Mt, 2.8 Mt, 1.8 Mt, and 4.8 Mt, respectively by the changes in income elasticity. In particular, soy in CHN and rice in SAS showed a notable increase. Since there is little potential arable land in CHN and SAS, we cultivated other regions so that they might export to CHN and SAS. The grain and feed demand functions set above set above are applied to simulations. Since we have data for the grain demand in 2012, data for the feed in 2010, and actual harvest area data in 2013 for the arable land cultivation, our simulation starts from 2013. GDP and producer price were given exogenously. We applied the SRES-B2-Scenario of the IPCC for the GDP, and carried out regression analysis based on the producer price trends to obtain results. The result when the constant yield show.

4. Conclusions

We examined the price increase in the grain market after 2000, and the increase in the future population and demand due to increases in GDP. By constructing a demand estimation model treating major grains in global level, we quantitatively evaluate the potential impact on woody biofuel and CO$_2$ emissions associated with the land use change. As a result, in the grain market, all grains in most areas showed an increased demand. In particular, the soy demand increased owing to the effect of AMS and CHN. Owing to the expansion of the harvest area, the production led to the cultivation of a large amount of arable land in AMS and AFC, significantly affected by the yield.

As shown here, AMS has a large amount of potential arable land, and handles the soy production. The majority of this production comes from Brazil. Currently, Brazil has 145–170 Mha of uncultivated arable land that can be commercially farmed, as exemplified by the area known as Cerrado. Caveating that the Cerrado is a national conservation areas as well. Based on our results on food demand, we found that AMS is going to play an important role in maintaining the demand balance for grains. The CO$_2$ emissions due to land use changes would increase. Without increases in the use of timber as fuel, the CO$_2$ effects due to land use change will increase further.

In this study, the grain demand for soy showed a rapid increase. If we extend the prediction period to 2030, we need to identify saturation factors for soy. Furthermore, according to Kawashima (2008) [6] and the FAO, there is a large
amount of fallow land in all over the world. Thus, evaluating the usage of this fallow land is another topic for future work.

In addition, existing research points out that even if feedstock crops of woody biofuel do not directly cause deforestation, there is an indirect effect of planting feedstock crops in farmland where edible crops were planted (Searchinger et al., 2008[7]). Though this research is different from our research in many ways, if we carry out more precise analysis in our research, as summing land use change occurs in the order of forest, pasture, then tropical rainforest, the indirect effects mentioned by Searchinger et al. (2008) [7] could happen. These issues of indirect effects, or how to use the findings of this research (i.e., a massive supply of potential woody biofuel) in society are future research topics.

5. Future works

In this research, we constructed a demand estimation model treating major grains in global level, considering by the increase in the future population and demand due to increases in GDP. It is, however, that the demand of bio-ethanol derived from grain have not been taken into account. Therefore, we are planning to construct a demand estimation model for bio-ethanol to consider mutual effects among the models in our research. We also reconstruct the food supply-demand balance model to incorporate impacts by technological change in agriculture and by climate change. In addition, price and demand of fossil fuels are incorporated as explanatory variables of grain demand estimation.

Figure 2 provides schematic view of the bio-ethanol model currently constructing which is referred from Koizumi [8]. Gasoline demand with fraction of bioethanol in gasoline demand as well as bio-ethanol demand are estimated by conducting a time-series analysis. Mutual effects between grain and bio-ethanol demand are planned investigated.

![Bio-ethanol demand estimation model (Region k)](image)

References