Assessing the comparative productivity advantage of bioenergy feedstocks at different latitudes

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Abstract
We evaluate the comparative productivity of maize and sugarcane biofuel feedstocks as a function of latitude. Solar radiation for photosynthesis varies by latitude and contributes to differential productivity of tropical and temperate zones. We calculate comparative productivity in two ways—the amount of net sugar energy produced per unit area, and the amount produced per unit of net primary productivity (NPP). NPP measures the accumulation of energy in an ecosystem and can be used as a proxy for the capacity of an ecosystem to support biodiversity and a broader array of ecosystem services. On average sugarcane produces three times more energy per unit area than does maize. The comparative productivity advantage of sugarcane decreases with increases in latitude. Latitudes closer to the equator have higher NPP, so there is a greater trade-off between biofuel production and ecosystem productivity in the equatorial zones. The comparative productivity of sugarcane relative to maize is reduced when comparing biofuel energy per unit of NPP. Sugarcane is still twice as productive on average compared to maize in the amount of biofuel energy produced per unit of NPP. Regions near the equator have lower biofuel energy per unit NPP, making them less attractive for biofuels production.

Keywords: biofuels, ecosystem services, maize, sugarcane, net primary productivity, net energy, comparative productivity, latitude

1. Introduction

Though the production of biofuels has the potential to reduce the dependence on fossil-fuels, biofuel production is land intensive. Land use impacts are of central importance in the debate over the sustainability of biofuels. A consistent theme throughout the history of biofuels is the ‘food versus fuel’ dilemma (US DOE 1980, Runge and Senauer 2007). While that debate continues and has been made more salient by current drought-related shortfalls and the expansion of mandates for biofuels in the US and the European Union, land impacts also raise issues about climate change and biodiversity. Expansion of agriculture onto forests and grasslands can release carbon, generating a carbon debt that can take years, decades or centuries to repay through concomitant reductions in fossil CO\textsubscript{2} emissions (Fargione et al 2008, Searchinger et al 2008). Conversion of natural
habitats to biofuel production can also have negative impacts on biodiversity and ecosystem services (Fargione et al. 2010).

We frame land use decisions for biofuels based on the idea of comparative productivity. Comparative productivity is a way of explaining why individuals, countries or regions of the world would do better if they produced goods where their productivity is higher.

The specific contributions of this approach are to show the relationship between the comparative productivity of bioenergy feedstocks and where they are grown at a global scale. We present these results as a function of latitude, gaining insight into the relative efficiency with which plants convert solar energy on the surface of the earth. We believe next generation biofuels will tend to use by-products from current generation technologies, and we explicitly account for these by-products in our analysis. Finally, we show the trade-offs of growing feedstocks for biofuels versus the ecosystem services of unmanaged land producing biomass.

In a simple model where labor is the only factor of production, comparative productivity is measured by how much output is gained per unit of labor applied. The more labor required for output the lower is the comparative productivity. Here we express comparative productivity that reflects trade-offs involving land (rather than labor) in the production of biofuels. We do so in two ways. The first and simplest is a measure of the net amount of bioenergy measured in gigajoules (GJ) produced per hectare. The second is a measure of the net amount of bioenergy produced per unit of NPP in unmanaged ecosystems. This second measure attempts to capture the lost opportunity for use of solar energy to support natural (undisturbed) ecosystems that deliver a variety of environmental and ecological benefits, or ‘ecosystem services’ (Daily 1997, Kareiva et al. 2011).

In this analysis, we focus on the two dominant sources of bioenergy for current biofuels production—maize and sugarcane. First generation biofuels technology relies on the well-established conversion of starch-derived sugars in maize and sucrose in sugarcane into biofuels. While expectations are that expansion of the biofuels industry will have to rely on new, more sustainable, cellulosic feedstocks (especially with regard to maize), these new technologies and feedstocks will likely first develop around the current infrastructure for biofuels production, making it important to understand the comparative productivity of maize and sugarcane grown at different latitudes.

This incremental evolution and continued reliance on maize and sugarcane is driven by economies of scale and space. For example, a large maize-based biorefinery in Iowa will be optimally located close to its feedstock—that gives it access to supplies around the clock. Because of the large volume to energy ratio, a biorefinery using a cellulosic crop feedstock (such as switchgrass) would need to draw its supply from nearby. Getting Iowa farmers to switch from maize to switchgrass would be unlikely under any circumstances, but especially in today’s market with high prices for maize. By contrast, if farmers supplying maize can sell corn stover (stalks, cobs and residue) for advanced biofuels, these feedstocks will be available in the same area. In Brazil—the second largest fuel ethanol producer in the world—this will involve further utilization of sugarcane bagasse (the cane after the juice is squeezed out), which today is already used to produce heat and power.

We therefore chose to focus on a more narrowly defined comparison of maize and sugarcane as primary sources of fermentable sugars readily convertible using today’s technology, while accounting for the energy value of their residual components, which could be used in second generation processes. The notion that these new technologies will first find their home near to—or as add-ons to—existing first generation plants has been well analyzed from an economic and engineering perspective (Wallace et al. 2005, EfE et al. 2005). These residues have also shown promise from a life cycle perspective (Contreras et al. 2009, Sheehan et al. 2003).

Our analysis compares alternative feedstocks to a biorefinery and assesses the relative land and ecosystem costs of these two sugar sources for bioenergy. We compare fermentable sugar derived from maize and from sugarcane in terms of the amount of energy produced per unit land area and per unit of NPP. The last measure based on NPP is a way of assessing the comparative productivity of maize and sugarcane crops as biomass feedstocks in terms of the likely impact on a broader array of ecosystem services and biodiversity. We propose these measures not as substitutes for the already heavily debated impacts of bioenergy related to food supply and climate change but rather as additional measures for evaluating land use choices related to bioenergy production.

Finally, we stress (and illustrate) the geospatially explicit nature of such comparisons (see Krugman 1997). Our analysis aligns well with three commonly recognized latitudinal belts around the globe. In the equatorial zone, approximately 15° north and south of the equator, the natural ecosystems exemplified by the Amazon rainforest are highly productive sources of biodiversity and other important ecosystem services, although they also function as lower productivity sources of local food, feed and fuel. High productivity sugarcane production exists in belts located at 15°–30° latitude on either side of the equator. To the north, production occurs in South Asia and the Caribbean. To the south, the largest production occurs in Brazil, southern Africa and northwestern Australia. Maize has its highest productivity in two belts at 35°–50° on either side of the equator. This includes the US Corn Belt in the north and the Argentinian Pampas in the south.

2. Latitude, solar energy and biofuels

At a fundamental level, the reason that the comparative productivity of growing plants differs at different latitudes is explained by solar radiation levels and variations in these levels over the course of a yearly cycle. The quantitative relationship between solar energy intercepted per square meter and the amount of dry biomass produced was first expressed as ‘radiation use efficiency’ (RUE) by Monteith (1977) as dry matter per megajoule (MJ) of intercepted solar
radiation (g MJ$^{-1}$). RUE is known to vary across crops and other plants. C4 species such as sugarcane, maize and sorghum have significantly higher RUE maximums than C3 species such as wheat, sunflower, rice and soybeans.

In a study of wine grape production, Ashenfelter and Storchmann (2010) show how RUE varies across latitude and months of the year. At the equator, plants receive maximal solar energy of about 35 MJ per square meter per day, or 13 GJ per square meter per annum, which varies by only 3–5 MJ per square meter per day over the 12 calendar months. But as one moves into the more northerly latitudes, the energy flux over the course of the calendar year becomes concentrated at a maximum on 21 June, which is above 40 MJ per square meter per day, and then declines on either side of this maximum as one moves toward December. The pattern is the same in the southern hemisphere, but the seasons are reversed, with maximum temperatures reached in temperate zones in December rather than June. At 40° north, minimum energy levels in December are about 9 MJ per day with an average of 10.4 GJ per annum. The farther from the equator in latitude one goes, the greater the fall off from peak summer energy to winter energy levels from the sun. This has agronomic implications as well: at the equator, the annual energy available for plant growth is highest, but the lack of a winter season means that fungal, bacterial and viral diseases and plant pests are not arrested by winter freezes, making cropping more problematic.

3. Measuring comparative productivity

3.1. Data

Our analysis is based on the M3 geospatial dataset for global agricultural land (Monfreda et al 2008, Ramankutty et al 2008, www.earthstat.org). This dataset combines satellite-based land cover data with detailed (subnational) level agricultural census data. Reconciling these different sources of information produces a more accurate picture of global agricultural land supply than can be found from any data set based on one of these sources alone. The data provides a snapshot of agricultural land use and productivity for 175 crops on a 5 arc-min × 5 arc-min resolution based on the year 2000. We considered more recent trends in yield for maize and sugarcane, and find that each crop has seen essentially equal rates of improvement (see supplemental material, available at stacks.iop.org/ERL/7/045906/mmedia, FAO 2012). This suggests that the comparative productivity of the two crops based on year 2000 data is similar to comparative productivity at present.

3.2. Best attainable yield versus actual yield

The M3 dataset includes geospatially explicit information on actual yields and crop management practices. The recent addition of crop management information allows us to distinguish the influence of both climate and management practices on yield (Mueller et al 2012). For a given climate, actual yields can vary as a result of differences in these management practices. A comparative analysis based on actual yields would thus be confounded by a variety of factors beyond those specific to the crop itself.

To correct for this, we estimate yields at each location on the basis of the best attainable yields for a given climate condition. The attainable yield for each crop was calculated using an empirical method initially described in Licker et al (2010) and later refined as described in Mueller et al (2012). In this approach, all cultivated land on the globe is divided into 100 discrete climate bins defined by characteristics such as rainfall, temperature and growing-degree days. For a given crop in a given climate bin, all yields are ranked from lowest to highest. The best attainable yield at a given location is then calculated from the 95th percentile yield achieved for the climate bin associated with that location.

### 3.3. Estimating the comparative productivity of maize and sugarcane

The amount of land needed to produce biofuels from sugar can be estimated from information about crop yield per hectare and amount of fermentable sugar per unit of crop. We used the M3 dataset to calculate an area-weighted best attainable yield for maize and sugarcane over increments of latitude. Average yield by latitude is based on areas of land where each crop is actually grown. We did not extrapolate yield performance for land not currently in production for each crop. We also limited our comparison of natural ecosystems and managed systems for each crop to values estimated on land producing the specific crop (maize or sugarcane). Thus, our estimate of land productivity at each latitude relates to land actually managed for that crop.

To put each crop on an equal basis, we convert the yields in the M3 data set into an equivalent net energy of delivered fermentable sugars per unit of land. We can then evaluate the amount of fermentable sugars per hectare or per unit of NPP.

#### 3.3.1. Maize.

The annual harvested energy in the fermentable sugars in maize is calculated as a product of yield per hectare and energy per unit of yield:

\[
E_{fs} = Y_{maize}x_{starch}H_{starch}
\]

where \(E_{fs}\) is the energy delivered as fermentable sugars per hectare; \(Y_{maize}\) is the dry yield of grain harvested in tons per hectare; \(x_{starch}\) is the dry weight fraction of yield that is starch; \(H_{starch}\) is the heating value of starch in units of GJ per ton of starch.

We adjust this gross energy in the fermentable sugars produced per hectare by subtracting out the energy required to grow and harvest the grain, \(E_{farm}\), based on life cycle estimates from the literature (Shapouri et al 2002). To allow for the utilization of maize stover as a source of heat and power and/or a source of fermentable sugars in second generation technology, we add the heat value of stover collected at a rate of 30% of the total available stover, a nominally acceptable level of sustainable stover removal (Sheehan et al 2003):

\[
E_{net} = E_{fs} - E_{farm} + E_{stover}
\]

\[
E_{stover} = x_{stover}Y_{grain}H_{stover}
\]

\[
E_{farm} = e_{grain}Y_{grain}
\]
where $E_{net}$ is energy in fermentable sugars delivered to a biorefinery corrected for farm inputs and stover energy value per hectare; $E_{farm}$ is the energy required to produce and harvest grain per hectare; $E_{stover}$ is the energy value of delivered stover per hectare; $x_{stover}$ is the fraction of stover that can be sustainably removed (assumed to be 30%); $H_{stover}$ is the heating value of the cobs, leaves and stalks of the corn plant (from Domalski et al. 1986); $e_{grain}$ is the farm energy input per unit of grain (from Shapouri et al. 2002).

Note that, in calculating $E_{stover}$, we are assuming a harvest index of 1 ($Y_{grain} = Y_{stover}$). In the case of maize, there is one more complication in the analysis of its comparative productivity. Maize contains protein, fats and other materials that are not converted to biofuels, but that have a value as animal feed (known as distillers’ dry grains and solubles or DDGS). There is no simple way to add in a credit for this co-product. So, instead, we apply a land credit based on the weight fraction of this feed co-product. In other words, we increase the effective productivity by a factor of (1.0/0.72) to allow for the assumption that 28% of the product harvested would have displaced an equivalent amount of maize cropland dedicated to animal feed production (Wallace et al. 2005, Arora et al. 2010).

3.3.2. Sugarcane. The calculation for sugarcane is much the same, and is, in fact, simpler. In this case, the net energy delivered to the biorefinery is:

$$E_{net} = Y_{cane}[H_{sucrose} + 0.5H_{bagasse} - e_{plantation}].$$

Sugar content and energy inputs for sugarcane production, as well as the amount and energy value of bagasse are based on Seabra et al. (2011).

Details of our methodology are available in the supplemental material (available at stacks.iop.org/ERL/7/045906/mmedia) for this paper.

3.4. The comparative productivity of sustaining natural ecosystems

Measuring the comparative productivity of land as a resource for supporting biodiversity and ecosystem services is somewhat less straightforward. Not all hectares are equally productive in terms of the services or biodiversity they support. The difficulty in obtaining such measures has limited much of the analysis of bioenergy’s impact on biodiversity, carbon sequestration and other natural ecosystem-derived services to either a qualitative approach at the regional, national and global scales or a quantitative and highly site specific approach at a very local scale (Daily 1997, Clark et al. 2001, Kareiva et al. 2011).

In order to arrive at a consistent and quantifiable measure at the global scale, we start with the concept of net primary productivity (NPP) as a general measure of the ability of a given piece of land to support a natural ecosystem (Clark et al. 2001). Net primary productivity is defined as the net rate at which plants assimilate carbon, accounting for photosynthetic uptake as well as releases due to autotrophic respiration. In our analysis, it is calculated in units of metric tons of carbon per hectare per year on a section of unmanaged land. NPP thus serves as an indicator of net energy flow through an ecosystem by measuring its accumulation and the ecosystem’s capacity to support biodiversity and ecosystem services (Roxburgh et al. 2004).

We use a simple statistical model with temperature and precipitation as parameters to predict NPP. Originally developed in the 1970s based on a very limited set of data, the model has been updated to reflect data from field studies conducted around the globe (Zaks et al. 2007). For each hectare of land in the dataset on which maize and sugarcane are grown, we use climate data for that location to estimate NPP using the updated NPP model (see supplemental material available at stacks.iop.org/ERL/7/045906/mmedia).

3.5. The ecosystem capacity costs of maize and sugarcane

For the last set of comparisons between maize and sugarcane, we make use of the NPP calculations for each piece of land on which these crops are grown to calculate lost capacity to support a natural ecosystem. We capture this trade-off as the ratio of net energy per hectare of each crop to the potential NPP of each hectare of land where the crops are grown.

$$E_{net} \text{ per ecosystem potential} = \frac{E_{net}}{\text{NPP}}$$

where $E_{net}$ is the same net energy in GJ ha$^{-1}$ calculated previously for sugarcane and maize, divided by the capacity of the land to capture carbon (NPP). NPP is in units of metric tons of carbon per hectare per year, giving this ratio units of GJ per metric ton of carbon.

4. Comparative productivity of maize and sugarcane bioenergy feedstock production

Figure 1 compares the productivity of sugarcane and maize per hectare as biofuel feedstocks, as described in...
sections 3.3.1 and 3.3.2. The comparison is in terms of gigajoules of energy deliverable to a biorefinery in relation to latitude. The size of the circles reflects the area of land planted in each crop at specific latitudes. The dashed lines represent curves that were fitted to the data points utilizing a cubic function with the $R^2$-squares (explained variation) given.

Sugarcane is more productive than maize at every latitude at which the former is grown (from approximately $-30\degree$ to $+30\degree$). Sugarcane produces three times more energy per hectare on average than does maize. On average (area-weighted across the globe), the current mix of land used for sugarcane production produces 392 GJ of energy per hectare, whereas for maize the figure is only 124 GJ. Maize productivity is higher in the temperate zones and declines as one moves toward the equator. The latitudes from $35\degree$–$50\degree$ north, which includes the US Corn Belt, stands out in terms of both its higher yields and its large production, as reflected in the size of the circles. The concentration of sugarcane production in Sao Paulo state in Brazil can be seen from $20\degree$–$25\degree$ south. Latitude explains far more of the variation in maize productivity than for sugarcane, as shown by relevant $R^2$-squares. The very wide range in the productivity of sugarcane around $30\degree$ north is likely a reflection of the very high yields achieved in the southern United States and the low yields in locations such as northern India.

Figure 2 shows the comparative productivity of sugarcane and maize in terms of the natural ecosystem services foregone by their production. The comparative productivity of sugarcane in relation to maize is less when comparing biofuel feedstock energy per unit of NPP (measured as per metric ton of carbon), than per hectare in figure 1. However, sugarcane is still twice as productive on average in terms of biofuel feedstock energy per unit of NPP in figure 2. Again larger circles reflect higher planted area for each crop and the dashed curves are cubic functions fitted to the data. The amount of variation in sugarcane productivity explained by latitude is substantially higher in this case than previously. The productivity of both sugarcane and maize in relation to the value of natural ecosystems declines around the equator. In fact, there is very little sugarcane production near the equator, since a cooler season is needed to pull the sugar up from the roots into the cane. Most of the maize production in the equatorial zone occurs at elevation in countries such as Columbia and Kenya (FAO 2012). Between $35\degree$ and $50\degree$ north, which encompasses the US Midwest, maize productivity in relation to the NPP forgone is high enough that it approximately matches that of sugarcane.

5. Conclusions

Land use choices, as they pertain to questions of supplying food and fuel and ensuring an adequate flow of natural ecosystem services such as biodiversity and carbon capture, are always complicated by national interests and local demands. This analysis offers insight into land use choices for biofuels by considering the comparative productivity of sugarcane and maize at different latitudes. We have explored the comparative energy yields of maize and sugarcane based feedstocks for biofuels (including the value of their residues) per hectare and per unit of NPP, as a proxy for the natural ecosystem services foregone. The limitation of energy (NPP) as a proxy of ecosystem services needs to be acknowledged, and in particular the importance of different types of biodiversity. We also want to emphasize that this comparative analysis is silent with regard to the many other ways in which land use decisions might be measured. Questions of food security and economic development are other important considerations and warrant an analysis of comparative productivity in their own right. In particular, the US has elected to direct some 40% of its maize crop to biofuels, which has an effect on global stocks and prices of grains. If the most productive producer of maize in the world uses so much of it to produce biofuels, that leaves less efficient producers to fill the gap for feed and food.

References

Arora S, Wu M and Wang M 2010 Estimated displaced products and ratios of distillers’ co-products from corn ethanol plants and the implications of life-cycle analysis Biofuels 1 1–13
Ashenfelter O and Storchmann K 2010 Using hedonic models of solar radiation and weather to assess the economic effect of climate change: the case of Mosel Valley vineyards Rev. Econ. Stat. 92 333–49
Clark D A, Brown S, Kicklighter D W, Chambers J Q, Thomlinson J R and Ni J 2001 Measuring net primary production in forests: concepts and field methods Ecol. Appl. 11 356–70
Contreras A M, Rosa E, Pérez M, Van Langenhove H and Dewulf J 2009 Comparative life cycle assessment of four alternatives for using by-products of cane sugar production J. Cleaner Prod. 17 772–9
Daily G (ed) 1997 Nature’s Services: Societal Dependence on Natural Ecosystems (Washington, DC: Island)
Domalski E S, Jabe T L Jr and Milne T A 1986 Thermodynamic Data for Biomass Conversion and Waste Incineration (Golden, CO: Solar Energy Research Institute)
Efe C, Straathof A and van der Wielen L 2005 Technical and Economical Feasibility of Production of Ethanol from Sugarcane and Sugarcane Bagasse (Delft: Delft University of Technology)

FAO 2012 FAOSTAT (Rome: UN Food and Agriculture Organization) (available at www.faostat.org)

Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P 2008 Land clearing and the biofuel carbon debt Science 319 1235–8

Fargione J, Plevin R and Hill J 2010 The ecological impact of biofuels Annu. Rev. Ecol. Evol. Syst. 41 351–77

Kareiva P, Tallis H, Ricketts T H, Daily G C and Polasky S (ed) 2011 Natural Capital: Theory and Practice of Mapping Ecosystem Services (Oxford: Oxford University Press)

Krugman P 1997 Development, Geography and Economic Theory (Cambridge, MA: MIT Press)

Licker R, Johnston M, Foley J A, Barford C, Kucharik C, Monfreda C and Ramankutty N 2010 Mind the gap: how do climate and agricultural management explain the ‘yield gap’ of croplands around the world? Glob. Ecol. Biogeogr. 19 769–82

Monfreda C, Ramankutty N and Foley J A 2008 Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000 Glob. Biogeochem. Cycles 22 GB1022

Monteith J L 1977 Climate and the efficiency of crop production in Britain Phil. Trans. R. Soc. B 281 277–97

Mueller N D, Gerber J S, Johnston M, Dufour D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management Nature 490 254–7

Ramankutty N, Evan A T, Monfreda C and Foley J A 2008 Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000 Glob. Biogeochem. Cycles 22 GB1003

Roxburgh S H et al 2004 A critical overview of model estimates of net primary productivity for the Australian continent Funct. Plant Biol. 31 1043–59

Runge C F and Senauer B 2007 How biofuels could starve the poor Foreign Affairs 86 41–53

Seabra J E A, Macedo I C, Chum H L, Faroni C E and Sarto C A 2011 Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use Biofuels, Bioprod. Biorefin. 5 519–32

Searchinger T, Heimlich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Yu T H 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change Science 319 1238–40

Shapouri H, Duffield J A and Wang M Q 2002 The energy balance of corn ethanol: an update Agricultural Economic Report No 814 (Washington, DC: Office of Energy and New Uses, US Department of Agriculture)

Sheehan J, Aden A, Paustian K, Klocke K, Brenner J, Walsh M and Nelson R 2003 Energy and environmental aspects of using corn stover for fuel ethanol J. Industr. Ecol. 7 117–46

US DOE 1980 Gasohol: A Report of the Energy Advisory Board (Washington, DC: US Department of Energy)

Wallace R, Ibsen K, McAloon A and Yee W 2005 Feasibility Study for Co-Locating and Integrating Ethanol Production Plants from Corn Starch and Lignocellulosic Feedstocks (Revised) (Golden, CO: National Renewable Energy Laboratory)

Zaks D P M, Ramankutty N, Barford C C and Foley J A 2007 From Miami to Madison: investigating the relationship between climate and terrestrial net primary production Glob. Biogeochem. Cycles 21 GB3004