A Quantitative Assessment of the Determinants of the Net Energy Value for Various Biofuels

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Paper presented for the GTAP Twelfth Annual Conference "Trade Integration and Sustainable Development: Looking for an Inclusive World", June 10-12 2009, Santiago, Chile

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Abstract. Many recent studies have investigated the net energy value (in terms of savings of fossil fuel) of biofuel products and have assessed how much greenhouse gases emissions was curtailed by substituting biofuels for fossil fuel. Many of these studies rely on life cycle analyses, but some of them include also a more systemic modeling approach, while a few include a full blown economic analysis of the changes in agricultural and forestry production at the international level. In this study, we start from a large sample of technico-economic studies, and we attempt to unravel the determinants of the main findings in terms of net energy value. Our approach relies on econometric estimates of the effects of various potential determinants across studies. We use statistical decomposition techniques derived from meta-analysis, on a worldwide sample. The preliminary estimates suggest that the large variability across studies can be explained by determinants such as the type of feedstock, the degree of integration of economic mechanisms (from simple static life cycle analysis to large scale modeling accounting for changes in land use), the number of input nests for which energy consumption is controlled for, and to some extent, the type of organization that has carried out the study (suggesting some mandated science). The study makes it possible to construct an explicit formula that corrects for biases in the overall estimate, using hedonic techniques. This should prove useful for estimating the shadow price of greenhouse gas emission reductions and value the positive externalities of biofuels.

Introduction

Biofuel production has grown rapidly since the early 2000s, both in developed and developing countries. A significant part of US corn production (more than a third), EU rapeseed production (more than half), and Brazilian sugar cane (almost half) is now channeled into the energy market. The rapid growth in US bioethanol and EU biodiesel production has largely been caused by public policies. The European Union and the United States support the development of biofuels through subsidies, tax exemptions or mandatory blending (the Brazilian ethanol production is now more driven by market prices than by subsidies, but early steps were largely government driven and there is still a mandatory blending content). Taking into account the various subsidies at both the Community/federal level and at the Member States/ state levels, Steenblink (2007) found that in 2006, support to biofuels reached USD 4.5 billon in the European Union and USD 6 billion in the United States (preliminary estimates for 2008 suggest that these figures are much larger).

EU, US and Brazilian authorities invoke several motives to justify and legitimate public support to biofuels. Biofuels have been encouraged as promising renewable substitutes to conventional fossil fuels, which could help mitigating climate change and reducing dependency to energy imported from unreliable suppliers. In both the European Union and the United States, however, one cannot ignore that a major driving force for the ambitious policies that encouraged the development of biofuels was to support farm incomes and helping reform agricultural policies, in a context of low agricultural prices and intense pressure for reducing border protection and subsidies due to the combination of budgetary pressures and international trade commitments.

Recently, public support for biofuels has been questioned. Some potentially negative effects of biofuels, i.e. competition with food for land and other resources, have led several developing countries to re-examine their objectives. There is now no longer an apparent consensus in the European Union on whether one should pursue tax exemptions and subsidies to biofuels. In the United States, controversies regarding the costs and benefits of the ethanol program have contributed to the reduction of subsidies to the first generation of biofuels in the 2008 Farm Bill that amended the energy legislation on this issue.

Focusing on the energy balance of biofuels

One major question is whether the benefits of biofuels match the cost of public policies. Biofuel production in the European Union and the United States is highly dependent on public programs, whose legitimacy is questioned.[1] There is a growing need to assess whether non-market benefits are large enough to compensate for

[1] Simulations suggest that EU and US biofuels would be profitable without subsidies only for high prices of oil, and the recent market price developments show that high oil prices tend to generate high prices for feedstocks (because of the demand from the bioenergy sector) so that biofuels rapidly "price themselves out of the market" (Schmidhuber 2007).

both the negative externalities of biofuels such as extra use, of land, fertilizers and water, and the cost for taxpayers and consumers. In the overall benefits of biofuels, the actual reduction in GreenHouse Gases (GHG) emission is the central point. Other non market benefits play a limited role. Even in the most optimistic scenarios, local biofuel production would only slightly dent EU and US oil imports, and dependence from foreign sources would remain high, for example.

The contribution of biofuels to the reduction of GHG has led to many studies, and the overall conclusions are highly controversial. The Life Cycle Assessment (LCA) methodology has been used, and has been progressively refined. Several methods have been proposed, in particular to allocate the use of fossil energy among the different co-products, a classical problem of jointness in inputs (displacement, or "systemic" method, energy content allocation, mass based allocation). The systemic method takes into account local changes in the allocation of land.

In spite of the growing consensus on a standardized LCA methodology, the question of structural modifications of the price system and changes in technology that a much larger biofuel production would generate can hardly be taken into account. In addition, assessing the GHG benefits of biofuels has recently be shown to be much more complex than expected. New sources of controversies have recently made the debate even more confused. First, it has been suggested by Creutzen et al (2007) that the traditional parameters that were used to estimate the N2O emissions in agriculture was underestimated by a factor of 4 to 5. Because of the high global warming power of this GHG (300 times the one of CO2), this would change dramatically the actual impact of agricultural production, and therefore that of biofuels. However, because the complexity in measuring indirect emissions (through atmospheric ammoniac, nitrogen transfers in water, etc) it seems currently impossible to assess the GHG impact through N2O and to go beyond sensitivity analyses to a coefficient that might range from 1 to 5 (Seguin 2009). Another recent development of considerable importance is the illustration of the importance of the indirect GHG consequences of global changes in land use. A large extension of the biofuel production would lead to release carbon when forest and pastures are converted in agricultural land. Because some of these effects are very indirect (for example the US use of corn for ethanol can lead the EU livestock production to buy more feedstock from Latin America), taking them into account would need to supplement LCAs by a full blown economic model and detailed data on land use as well as agro-ecological conditions (Fargione et al 2008). The GHG balance varies greatly with the quantities of biofuels produced, and variations are non linear because of the need to mobilize marginal factors. That is, the validity of LCAs beyond non-marginal increase in production appears limited. The changes involved by large developments of biofuel would require assessing the changes in prices on interrelated markets, the responses of global land use to prices, the impact on livestock and the way they are fed, estimates of CO2 and CH4 release, and a whole reconsideration of the complete chemical cycle of nitrogen in soil, water and atmosphere. Clearly, the many components of such a global assessment is presently beyond scientist's capacity, and the few global assessments studies that have started to appear since 2008 still rely on crude assumptions (Searchinger et al 2008).

In this study, we focus on an important component of the GHG emission balance of biofuels, the energy efficiency. Energy balance, i.e. the degree in which the consumption of fossil fuel is reduced when gasoline and diesel are replaced by biofuel is the main building block of GHG balance assessments. It is also the main determinant of the global CO2 balance, even though taking account of other GHG gases introduces a considerable source of variation in results. Unlike GHG balance, energy balance has also been the subject of a large number of studies, and the analysis of this literature can shed light on the main factors that influence the results, even before extra assumptions on the GHG aspect bring an extra layer of complexity.

The sources of variation in results and the mandated science assumption

Energy balances of biofuels have attracted both academic and media interest as their conclusions give some insight on the suitability of biofuel policies as a credible solution for energy independence and GHG mitigation concerns.

The different studies that have been published (in journal articles, reports, working papers) show extremely different results regarding the energy efficiency, from extremely positive to negative (i.e. biofuels would use more fossil fuel in their production than they would save fossil fuel when used as a substitute for gasoline or diesel). This variability is observed irrespectively of the feedstock, the type of biofuel (ethanol, biodiesel), the country where the study took place.

The great variability observed in their results makes it difficult to conclude unambiguously on the desirability of biofuels as substitutes for fossil fuels on a purely energy basis. A path-breaking study by Farrell et al. (2006) has striven to show that, as far as corn ethanol is concerned, the Net Energy Value (NEV) of biofuels is slightly positive. To reach such a result, Farrell et al. scrutinized the hypotheses underlying six leading studies on corn ethanol and proceeded to a harmonization of these studies, replacing “odd” values found in some studies by seemingly more suitable values found in others. Quite predictably, this harmonization exercise led to much closer NEVs across studies.

While we build on the methodology developed by Farrell et al. (notably for carefully dividing up the various energy expenses all along the biofuel production chain), our standpoint is completely different. Our objective is to uncover the main determinants that fuel the variability across studies. Said differently, the differences observed between studies go beyond simple errors or omissions computed in the filling up of the values of the different energy expenses. The objective is to unravel how the choice of a particular method for controlling the energy content in inputs, to valuate the indirect energy consumption through capital or labor, or to allocate energy consumption across co-products affects results. Different authors have made particular assumptions on parameters that might look harmless at first sight, but which may affect considerably the results.

A close examination of the various LCA studies suggest that when some authors chose rather conservative estimates for a parameter at a given phase of production, he/she often does the same at another phase. The same exists at the other end of the spectrum of the assumptions. That is, there is some correlation between the conventions and parameters regarding energy use during the different stages of biofuel production. This may be the sign of some form of a personal bias of the author. One cannot rule out that the position of the entity conducting the study (whether the entity is an advocate of biofuel development or not) might be a factor explaining the results observed in the level of NEVs, alongside other “physical” determinants.

In the biofuel sector, the interaction between science and economic interests has often been an issue. In the 1990s, scientific controversies surrounded the relative technical advantages of ethanol over MTBE.[2] Both techniques make it possible for transport fuel to meet emission standards, but MTBE was derived from petroleum products while ethanol based ETBE originated from agricultural products. At the time, researchers working on the comparative benefits of the competing additives faced a particular difficulty, that most of the technical information was put together by some of the parties that had particular economic interests in the debate.[3] Typically, a large share of the information on the technical performance of engines with different fuels is developed by motorists, while technical information on the efficiency, costs and possible problems (e.g. corrosion of pipes and storage tanks, ease of blending, safety) is developed by the oil industry, while other information on the agricultural production phase of biofuels relies on information and data that is often provided by the farm sector or by extension services that showed some links with this sector. In such cases, scientific and technical studies are often promoted or selectively used to support a particular point of view

In the current debate on the energy efficiency of biofuels, LCAs are often seen as a way to make the debate more objective. Hence the efforts to harmonized methodologies and to converge towards ISO certified LCAs (International Standardization Office). However, communication on the benefits (or lack of benefits)

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[2] MTBE stands for Methyl Tertiary Butyl Ether which is an additive derived from fossile oil that can be used as an octane improver in gasoline. Among other oxygenates available for use in gasoline, including ethanol and other ethers/alcohols, MTBE was preferred by the oil industry because of its low cost, dilution effects, the ability to blend it without extra costs (ethanol must be transported and stored separately from the base gasoline mixture to which it is added until the last step in the distribution chain) and the ease of blending. Opponents accused MTBE of having "human carcinogenic hazard potential" (defenders of the MTBE argued that the proposed substitute, ethanol is a proven and carcinogen), and that MTBE exacerbated the risk of groundwater contamination, because it particularly soluble in water and capable of travelling through the subsurface at the same speed as groundwater. The US Energy Policy did not ban MTBE outright, it led petroleum companies to it, mostly because of fear of liability exposure.

[3] Faulk and Gray (2006) go back to the ethanol/MTBE controversy, and their document shows the use of many conflicting studies by both the defenders of the MTBE and what these authors call "the ethanol lobby".

of such or such biofuel by processing companies quote selectively particular studies. In some European countries, the difference between the figures released by say, the Ministry of Agriculture and the Finance Ministry is striking. The enthusiasm of farmers' organizations and some ministries of agriculture in promoting biofuels and lobbying for higher incorporation targets suggested that some of the studies might be affected by the proximity to particular actors. One of our objectives is to see whether such an effect can be isolated.

Methodology

In order to unravel the determinants of the troubling variation in results regarding the energy efficiency of biofuels, we use first descriptive statistics and then a meta-analysis. The latter requires an objective sampling procedure of the various studies, in order to ensure that there will be no selection bias. To construct our sample, we implemented a selection protocol in two steps. First, we sent a questionnaire to 8 researchers involved in LCA and biofuel impact assessment in public universities and research centers, asking them what was the bibliographical databases that they used in their work, as well as the most appropriate keywords. There was a remarkable convergence in electronic scientific platforms, i.e. Web of Science, CAB Abstracts, Econlit and the electronic catalog of Blackwell and Elsevier, as well as Google Scholar (some of them also indicated the use of regular Google). We then carried out a search on these electronic platforms using the keywords that have been mentioned, in both English and French. We also checked references mentioned in the selected studies in order to expand our set of studies. Altogether, we ended up with 126 studies that provided an assessment of the energy efficiency of one or several types of biofuels. These studies were indexed in a bibliographical software that made it easy to access the main text and tables (JabRef®), and their content was carefully examined so that information on the methodology and the parameters used was collected.

A half of the studies do not provide enough information to be included in our sample because not enough detail was provided on the methodology, or because the information gathered did not allow to compute a net energy value that could be compared with other studies. These deletions leave us with a total of 59 observations. (In the meta-analysis, we delete two outliers using the Hadi test (one observation comes from the European Commission, 1994 and the second one is from Pimentel, 2005. Eventually, our sample consists of 57 observations).

The statistical analysis also required making variables comparable across studies, given that several conventions exist in terms of measurement units. Here we focus on the Net Energy Value (NEV). Let E_{input} be the total energy expended to produce 1 liter of biofuel, E_{output} the energy contained in 1 liter of biofuel and $E_{coproduct}$ the energy credit attributed to co-products. In order to compare the different studies, the Net Energy Value measure is more suitable than its alternative, namely the energy ratio, since its value does not depend upon the way in which the co-products energy credit is allocated, i.e. this credit can be either added to the energy value of biofuel or substracted from the total energy expense to produce biofuels:

$E_{output}/(E_{input} - E_{coproduct}) \neq (E_{output} + E_{coproduct})/ E_{input}$

On the contrary, the NEV is unaffected by either position taken up by the co-product credit:

$E_{output} - (E_{input} - E_{coproduct}) = (E_{output} + E_{coproduct}) - E_{input}$

The various variables that have been taken into account in order to explain the origin in the variations of the NEV found in different studies include the quantities of the different inputs used in the production of the feedstock, its transportation processing, their energy content (including capital and labor), the feedstock, the country, the year, the energy sources (e.g. coal, electricity or biomass such as bagasse), the allocation method applied to the various co-products, etc.

Heterogeneous results

The observation of statistics for the different variables that make up the energy balance leads to a classification in three categories (Tables 1 to 3):

- Variables with a high degree of variability: NEV and co-product credits. Table 1 summarizes the great variability of the NEV across different crops of course, but also within the same feedstock category. Hence, the coefficient of variation (CV) of NEVs within the corn category (6.23) is greater than the overall CV (2.15). Likewise, the variability of co-products credit is very high within each feedstock category: apart from sugarcane, the CV is always greater than 1. This variability is in each case quite logical, since it represents the very reason why this meta-analysis has been undertaken (for NEV) and one of the main factors explaining this variability (for the co-product credit).

- Variables with a medium degree of variability: this category entails the energy expense of fertilizers in MJ per ha (for nitrogen, potassium and phosphate). The variability hinges upon the intensity of the application rate (in kg/ha) and the energy content of fertilizers (in MJ/kg).

- Variables with a low degree of variability. This category is made up of yield variables (agricultural yield in kg/ha, biorefinery yield in liter/kg of feedstock, volumetric yield in liters/ha, etc.). Such a low variability was quite predictable, as the technologies used to transform feedstock into biofuels are intrinsically limited by the concentration in starch, sugar or oil contained in the agricultural raw material. For all these variables, the CV is very low within a feedstock (lower than one).

- Another category of variables can be singled out: variables with a high degree of variability but with a marginal weight in the total energy outlay. The energy expended for seeds belongs to this category: its variability is very high within a given feedstock (CV greater than one). The energy for lime used on corn is also part of this sub-group. The CV is high (1.39), the mean (333 MJ/ha) is very low compared to the energy represented by nitrogen (8,349 MJ/ha). A puzzling observation is that the correlation coefficient between NEV and lime is very high in absolute value: -0.85.

Table 1: Statistics for Net Energy Value by feedstock

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	7.10	1.94	0.27	4.99	8.81	3
Corn	1.34	8.36	6.23	-24.67	10.09	30
Rapeseed	33.58	27.65	0.82	13.83	86.66	6
Soybean	6.98	22.41	3.21	-8.87	22.82	2
Sugarbeet	11.62	1.15	0.10	10.80	12.43	2
Sugarcane	18.30	3.52	0.19	13.01	22.88	7
Sunflower	-8.33	43.42	-5.21	-39.03	22.37	2
Switchgrass	6.46	23.27	3.61	-10.00	22.91	2
Wheat	5.22	5.60	1.07	-0.84	11.46	5
Total	**7.64**	**16.39**	**2.15**	**-39.03**	**86.66**	**59**

Table 2: Main Variables, moments by type of fuel

Biofuel		NEV (MJ/l)	Nitrogen (MJ/ha)	Potassium (MJ/ha)	Phosphate (MJ/ha)	Seed (MJ/ha)
Biodiesel	Mean	19.90	4982.10	368.30	635.40	503.60
	Std. dev.	32.10	3762.71	401.96	357.85	965.46
	Coeff. var.	1.61	0.76	1.09	0.56	1.92
Ethanol	Mean	5.14	6728.00	615.03	809.22	632.13
	Std. dev.	9.70	3700.52	478.40	1318.60	956.01
	Coeff. var.	1.89	0.55	0.78	1.63	1.51
Total	Mean	7.64	6432.08	573.21	779.76	610.34
	Std. dev.	16.40	3737.14	472.44	1209.60	950.46
	Coeff. var.	2.15	0.58	0.82	1.55	1.56

Table 2bis: Main Variables, moments by type of fuel (continued)

Biofuel		Co-product credit (MJ/l)	Crop yield (kg/ha)	Biorefinery yield (l/kg)	Volumetric yield (l/ha)	Energetic fuel yield (MJ/ha)
Biodiesel	Mean	16.97	2551.10	0.33	1084.65	30775.90
	Std. dev.	22.88	1121.67	0.15	453.99	18006.23
	Coeff. var.	1.35	0.44	0.46	0.42	0.59
Ethanol	Mean	2.75	19994.40	0.33	3783.86	81884.55
	Std. dev.	3.65	24954.23	0.12	1521.99	33754.24
	Coeff. var.	1.32	1.25	0.37	0.40	0.41
Total	Mean	5.16	17037.91	0.33	3326.37	73222.06
	Std. dev.	11.01	23645.57	0.13	1729.83	36976.33
	Coeff. var.	2.13	1.39	0.38	0.52	0.50

Meta-analysis

The meta-analysis is an useful statistical tool for explaining variations in results between studies. Results on a given topic could strongly differ from one study to another. The meta-analysis helps to disentangle the influence of different explanatory variables and approaches used by the authors on the results and thus the sources of variation between studies. In meta-regressions, the variance in the individual estimates is explained by a set of right-hand-side variables that quantify the different attributes of each study.

We estimate the following equation:

$$Yj = \alpha + \beta \, \mathbf{X}j + ej \qquad j = 1, 2, ..., N$$

where Yj is the net energy value reported in study j, $\mathbf{X}j$ is the matrix of the meta-independent variables included to explain the variation of the net energy value between studies and β the vector of meta-regression coefficients.

Concerning the meta-independent variables, we first distinguish between ethanol and biodiesel. The dummy variable ‘ethanol’ equals one if the studies focus on sugarbeet, sugarcane, cassava, corn, switchgrass, and wheat, while biodiesel is set to one for studies based on rapeseed, soy, and sunflower. Our estimations do not include a constant term. Therefore, two different coefficients could be estimated on biodiesel and ethanol variables.

Second, we include a dummy to control for whether the underlying study received funds from an NGO or a government agricultural institution. We expect higher net energy values for studies funded by entities advocating biofuel development.

Third, we control for some important aspects of the agricultural phase that could affect the net energy value. We focus on two elements (nitrogen and farm labor) and code two dummies, respectively equal to one if the underlying study includes each input in the calculation of the net energy value. Furthermore, by coding a categorical variable based on quartiles, we investigate if the value applied for nitrogen in the calculation also affects the results.

We also add a dummy for whether the underlying study incorporates co-products in the evaluation of the net energy value. Finally, we investigate if the approach used for the allocation of co-products influences the net energy value.

Table 3 presents the results. In the first column, we simply regress the net energy value on the two dummies biodiesel and ethanol. Both have a positive and significant ($p<0.01$) influence on the net energy value. Furthermore, the estimated coefficient on biodiesel is more than three times larger than the one on ethanol.

In column (2), we add different control dummy variables. The funding variable takes a value of 1 if the underlying study received funding from an NGO or a government agricultural institution and 0 otherwise; Control dummies for nitrogen, farm labor, and co-products are respectively equal to one if the underlying calculation of the net energy value includes these elements. The source of funding does not influence the net energy value. On the other hand, the net energy value is negatively impacted by nitrogen and farm labor consumption during the agricultural phase, and positively influenced by the control for co-products. The R^2 equals 0.8, which means that controls for biodiesel vs. ethanol, funding, nitrogen, farm labor and co-products explain 80% of the between-study variation in the net energy value.

Column (3) considers a larger definition for chemicals used in the agricultural phase. Instead of focusing only on nitrogen, column (3) considers nitrogen, phosphorus, potassium and lime. However, studies that do not include nitrogen in the calculation of the net energy value, neither include phosphorus, nor potassium, nor lime. Results are therefore similar to column (2).

Columns (4) and (5) deal with the method used for allocating co-products. Since some studies do not include co-products, we restrict our estimations to observations that consider co-products in the net energy value calculation. Various methods can be used: displacement allocation, weight allocation, energy allocation, market value allocation. We investigate whether the use of the displacement allocation method provides similar or different results from those obtained with other methods. Some papers mix different methods (displacement and a second approach) to evaluate co-products: one for the agricultural phase and one for the biorefinery phase (see for example Lorens, 1995). In column (4), the dummy 'displacement allocation method for co-products' is set to zero for these observations, while it is set to one in column (5). Results in both columns suggest that the use of the displacement allocation approach provides a lower net energy value.

Finally, column (6) controls for the value of nitrogen (in MJ/ha) instead of using a simple dummy. We define a categorical variable, which takes the value of 0 if the underlying study does not include nitrogen and values from 1 to 3, depending on the quartile where the observation is placed (1 if the observation is in the first quartile, 2 for the second and third quartiles and 3 above). Due to multicollinearity, the first category is dropped in the estimations. Estimated coefficients on the three remaining categories are negative and significant at the one percent level and the ranking is as expected: the higher is the value used for nitrogen in the calculation of the net energy value, the higher is the negative effect of nitrogen on the net energy value. The results on the other control variables are in line with the ones of column (3), except agricultural funding, which is now significant at the 5% level.

Table 3: Results of meta-regression

Dependent variable	Net Energy Value					
Model	(1)	(2)	(3)	(4)	(5)	(6)
Biodiesel	18.89*** (4.63)	20.33*** (4.23)	20.33*** (4.23)	31.27*** (4.31)	31.00*** (4.46)	20.60*** (4.26)
Ethanol	5.14*** (1.40)	10.69*** (3.16)	10.69*** (3.16)	19.45*** (2.66)	19.52*** (2.70)	11.30*** (2.67)
Control for study funding		3.14 (1.89)	3.14 (1.89)	2.38 (1.86)	2.90* (1.67)	3.75** 1.63)
Control for nitrogen		-11.22*** (3.19)		-9.71** (3.65)	-9.71** (3.69)	
Nitrogen (MJ/ha): no control						-
Nitrogen (MJ/ha): < 1st quartile						-9.17*** (3.29)
Nitrogen (MJ/ha): [1st quart.; 3rd quart.]						-12.23*** (2.75)
Nitrogen (MJ/ha): > 3rd quartile						-15.47*** (2.93)
Control agricultural phase			-11.22*** (3.19)			
Control for farm labor		-7.60*** (1.86)	-7.60*** (1.86)	-2.00 (2.33)	-1.20 (2.49)	-6.56*** (1.89)
Control for co-products		10.35*** (2.03)	10.35*** (2.03)			9.59*** (1.76)
Displacement allocation method for co-products				-3.74* (2.15)	-4.45* (2.53)	
Number observations	57	57	57	38	38	57
R^2	0.415	0.800	0.800	0.874	0.875	0.838

Note: Standard errors in parentheses with ***, ** and * denoting significance at the 1%, 5% and 10% level.

Conclusion

To be done

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Appendix. Descriptive Statistics

Table A1: Statistics for Nitrogen (in MJ per hectare)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	5680.33	5566.71	0.98	0	11126	3
Corn	8349.66	2758.54	0.33	4028.8	14015.22	30
Rapeseed	6586.50	3370.98	0.51	0	9400	6
Soybean	519.00	384.67	0.74	247	791	2
Sugarbeet	5580.00	632.15	0.11	5133	6027	2
Sugarcane	1046.18	1787.22	1.71	0	3737.5	7
Sunflower	4632.00	3863.63	0.83	1900	7364	2
Switchgrass	5538.78	3099.65	0.56	3347	7730.56	2
Wheat	6516.06	2811.62	0.43	2132	9700	5
Total	**6432.08**	**3737.14**	**0.58**	**0**	**14015.22**	**59**

Table A2: Statistics for Phosphorus (in MJ per hectare)

Feedstock	Mean	Standard deviation	Coefficient of variation	Min	Max	Number of Studies
Cassava	3639.33	4844.44	1.33	0.00	9138.00	3
Corn	786.03	464.43	0.59	106.02	1975.13	30
Rapeseed	571.67	388.04	0.68	0.00	840.00	6
Soybean	579.00	104.65	0.18	505.00	653.00	2
Sugarbeet	1024.00	181.02	0.18	896.00	1152.00	2
Sugarcane	102.68	175.39	1.71	0.00	365.56	7
Sunflower	883.00	485.08	0.55	540.00	1226.00	2
Switchgrass	12.02	16.99	1.41	0.00	24.03	2
Wheat	472.36	380.30	0.81	0.00	948.00	5
Total	**779.76**	**1209.60**	**1.55**	**0.00**	**9138.00**	**59**

Table A3: Statistics for Potassium (in MJ per hectare)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	1215.14	1073.62	0.88	0.00	2035.42	3
Corn	646.67	214.72	0.33	170.94	1146.60	30
Rapeseed	262.67	270.19	1.03	0.00	720.00	6
Soybean	250.50	70.00	0.28	201.00	300.00	2
Sugarbeet	1714.50	630.03	0.37	1269.00	2160.00	2
Sugarcane	193.49	330.48	1.71	0.00	685.00	7
Sunflower	803.00	782.06	0.97	250.00	1356.00	2
Switchgrass	8.83	12.48	1.41	0.00	17.65	2
Wheat	457.96	406.39	0.89	0.00	1079.00	5
Total	**573.21**	**472.44**	**0.82**	**0.00**	**2160.00**	**59**

Table A4: Statistics for Seed (in MJ per hectare)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	4.21	7.29	1.73	0.00	12.63	3
Corn	670.88	980.80	1.46	0.00	2193.03	30
Rapeseed	62.50	88.19	1.41	0.00	240.00	6
Soybean	1159.00	1639.07	1.41	0.00	2318.00	2
Sugarbeet	72.00	101.82	1.41	0.00	144.00	2
Sugarcane	676.37	1203.36	1.78	0.00	3354.00	7
Sunflower	1171.50	1656.75	1.41	0.00	2343.00	2
Switchgrass	209.20	295.85	1.41	0.00	418.40	2
Wheat	1107.65	978.37	0.88	0.00	2497.50	5
Total	**610.34**	**950.46**	**1.56**	**0.00**	**3354.00**	**59**

Table A5: Statistics for Co-product credit (in MJ per liter)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	1.01	1.74	1.73	0.00	3.02	3
Corn	2.53	2.65	1.05	0.00	7.68	30
Rapeseed	21.30	27.30	1.28	0.00	71.69	6
Soybean	16.23	22.95	1.41	0.00	32.46	2
Sugarbeet	0.51	0.71	1.41	0.00	1.01	2
Sugarcane	1.72	0.70	0.41	0.81	3.00	7
Sunflower	4.72	6.67	1.41	0.00	9.43	2
Switchgrass	2.40	3.39	1.41	0.00	4.79	2
Wheat	7.64	8.15	1.07	0.00	18.99	5
Total	**5.16**	**11.01**	**2.13**	**0.00**	**71.69**	**59**

Table A6: Statistics for Crop yield (in kg per hectare)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	15444.33	3948.84	0.26	13000	20000	3
Corn	7921.45	646.35	0.08	6330	9296	30
Rapeseed	2747.17	1410.29	0.51	0	4080	6
Soybean	2544.00	175.36	0.07	2420	2668	2
Sugarbeet	65159.47	1528.09	0.02	64079	66240	2
Sugarcane	72092.79	15172.72	0.21	51600	87100	7
Sunflower	1970.00	664.68	0.34	1500	2440	2
Switchgrass	11725.03	2439.56	0.21	10000	13450	2
Wheat	7466.08	2322.48	0.31	3409	9000	5
Total	**17037.91**	**23645.57**	**1.39**	**0**	**87100**	**59**

Table A7. Statistics for Biorefinery yield (in liters per kg of feedstock)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	0.42	0.08	0.19	0.33	0.47	3
Corn	0.38	0.02	0.05	0.32	0.45	30
Rapeseed	0.35	0.18	0.51	0	0.47	6
Soybean	0.21	0.01	0.07	0.2	0.22	2
Sugarbeet	0.11	0.03	0.24	0.09	0.127	2
Sugarcane	0.08	0.01	0.18	0.06	0.09	7
Sunflower	0.36	0.10	0.27	0.29	0.43	2
Switchgrass	0.39	0.01	0.04	0.38	0.4	2
Wheat	0.38	0.04	0.11	0.35	0.45	5
Total	**0.33**	**0.13**	**0.38**	**0**	**0.47**	**59**

Table A8: Statistics for Volumetric yield (in liters per ha)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	6328.23	331.08	0.05	6005.03	6666.67	3
Corn	3029.51	286.43	0.09	2435.00	3675.62	30
Rapeseed	1380.60	247.67	0.18	1022.73	1715.45	6
Soybean	537.22	11.96	0.02	528.76	545.68	2
Sugarbeet	6976.73	2015.09	0.29	5551.84	8401.61	2
Sugarcane	5539.76	1674.31	0.30	3273.00	7516.73	7
Sunflower	744.24	437.56	0.59	434.83	1053.64	2
Switchgrass	4567.33	802.32	0.18	4000.00	5134.65	2
Wheat	2734.59	683.90	0.25	1541.14	3228.00	5
Total	**3326.37**	**1729.83**	**0.52**	**434.83**	**8401.61**	**59**

Table A9: Statistics for Energetic fuel yield (in MJ per ha)

Feedstock	Mean	Standard deviation	Coefficient of Variation	Min	Max	Number of Studies
Cassava	134158.50	7018.97	0.05	127306.50	141333.30	3
Corn	64669.17	6369.55	0.10	51614.00	77923.25	30
Rapeseed	37935.50	20017.58	0.53	0.00	54346.00	6
Soybean	17765.50	447.60	0.03	17449.00	18082.00	2
Sugarbeet	147906.80	42719.78	0.29	117699.30	178114.20	2
Sugarcane	126135.50	36093.06	0.29	77242.80	162041.40	7
Sunflower	22307.47	11170.13	0.50	14409.00	30205.95	2
Switchgrass	96827.30	17009.18	0.18	84800.00	108854.60	2
Wheat	59475.18	15905.97	0.27	32672.15	73875.77	5
Total	**73222.06**	**36976.33**	**0.50**	**0.00**	**178114.20**	**59**