ISEIS

Journal of Environmental Informatics 26(2) 121-139 (2015)

Journal of Environmental Informatics

www.iseis.org/jei

Quantification of Agricultural Land Use Changes in Consequential Life Cycle Assessment Using Mathematical Programming Models Following a Partial Equilibrium Approach

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Received 22 July 2013; revised 31 Augut 2014; accepted 5 November 2014; published online 28 December 2015

ABSTRACT. Conventional Life Cycle Inventories (LCIs) are static models not considering any mechanism of revenue maximization and price equilibrium under external constraints. The underlying assumption is that demand of a given commodity, irrespective of the amount, can always be supplied by the average supplier (fully elastic market). This constitutes a recognized limitation for the application of Life Cycle Assessment (LCA) to the evaluation of complex systems, like agro-systems. In the Consequential LCI, the relationships between the activities and processes of a life-cycle are no longer seen as essentially technical connections, based on average data; instead the relevant socio-economic mechanisms are considered via market information and economic models (partial or computable general equilibrium). The paper presents two partial equilibrium (PE) models of the agricultural sector of the Grand Duchy of Luxembourg, to calculate the LCI and the Indirect Land Use Change (ILUC) effects related to the introduction of a given demand for biomass (in particular maize) for biogas generation. The model is market-based and has farmers' revenue maximization as the driver, represents the first step of a Consequential Life Cycle Assessment (CLCA) for biogas production in Luxembourg.

Keywords: biofuels, consequential LCA, crops rotation, land use change, linear programming, Luxembourg, partial equilibrium model, positive mathematical programming

1. State of the Art and Objectives

Many countries, including Luxembourg, motivated by the continuous rise in oil prices (with the geopolitical and energy security problems that come along with it) and the greenhouse gas (GHG) emissions' control policies, are currently promoting the expansion of renewable energy harnessing. The opportuneness of implementing this kind of policy is underpinned by the large number of studies (e.g. Adler et al., 2007; Spatari et al., 2010; Messineo et al., 2012) advocating substitution of fossil fuels by renewable energy production as a favourable option in the context of energy dependence and global warming mitigation. For these reasons, the European Union (EU) has decided to promote electricity generated from renewable sources (European Union, 2001).

In this context, although sometimes questioned (Mathew, 2008; Sheehan, 2009), biofuels and the biofuel industry have started to play an increasingly pivotal role. It is in fact worthy remarking here that, while the evaluation of the direct environmental (mainly reduction of fossil fuels consumption that leads to a decrease in GHG emissions) and economic implications of replacing fossil fuels with biofuels is usually dealt with in scientific publications with a relatively satisfactorily level of detail at the local scale, the situation is different concerning an integrated assessment which looks also at the indirect effects of biofuels production. Conducting this assessment at a global scale presents several difficulties, related to the consideration, amongst other elements, of indirect land use changes caused by increases in biofuel production, carbon transfers between vegetation/soil and air and temporal dynamics of soil organic carbon after land-use. As a result, many studies, even those using Life Cycle Assessment (LCA), an environmental management tool that provides a comprehendsive evaluation of a wide range of environmental impact categories (ISO, 2006), simply do not heed the indirect consequences of biofuels production. This issue is not of secondary importance, especially considering that it has been demonstrated that, in some cases, the indirect consequences of biofuel production can outweigh the environmental benefits attributed to oil substitution (Raghu et al., 2006; Righelato and Spracklen, 2007; Searchinger et al., 2008; Fargione et al., 2008; Plevin et al., 2010). Kløverpris and Mueller (2013) argue that research studies can be biased in their computation of global warming potential based on their initial time frame of refe-

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ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.201500304

rence but Martin (2013) refutes their claim which is also biased due to the arbitrary length of 100 years used for studying the impacts of indirect land use change. Conventional (so-called *attributional*) LCAs are indeed descriptive models that do not consider any mechanism of revenue maximization and price equilibrium under external constraints. The attributional approach works under steady state conditions and its underlying assumption is that any demand of a given commodity, irrespective of the amount, can always be supplied by the average supplier (fully elastic market). However, in the *consequential* LCA (CLCA), the relationships between the activeties and processes of a life-cycle are no longer seen as essentially technical connections, based on average data. Instead, relevant socio-economic mechanisms can be considered, for example via market information and possibly economic models (partial or general equilibrium). Finkbeiner (2013) is a comprehensive survey of indirect land uses changes in the context of LCA and analyses the scientific robustness and consistency of various approaches prevailing in literature.

The first efforts to account for indirect environmental impacts in LCA made resort to simple market-based approaches (Ekvall, 2000) and heuristic methods for identifying affected technologies (Weidema et al., 1999). Over the past decade, however, more complex and comprehensive (partial and computable general equilibrium) economic models have been developed (e.g. Earles and Halog, 2011). Many of the partial equilibrium models (PEMs) applied, use reduced-form supply equations, or have yield and area response equations without an explicit land market. Thus, they do not have any constraint on aggregate land use and competition between alternative uses is weak and often non-existent. In some cases it is implicitly captured only in the cross-price elasticity of the area response equations. Since the competition for land with other uses is at the heart of biofuel analysis, this is a significant limitation of the modelling approaches. Nevertheless detailed modelling of the agricultural sector is not easy to incurporate into traditional PEM and different models use different approaches to tackle the prices. Another important point of discussion concerns the step from the aggregate scale of the results of economic equilibrium models and the higher resolution spatial scale needed for environmental assessment.

An extensive critical discussion of the modelling approaches that can be used for consequential LCA (CLCA) and a description of the main research questions that have to be answered by the modellers is provided in Marvuglia et al. (20 13). An analysis of the similarities and differences between LCA and PEMs was carried out by Bouman et al. (2000). Focusing on the specific case of biomethane production from maize in a small country like Luxembourg (extensively described in Vázquez-Rowe et al., 2013), the use of economic modelling to address CLCA has to consider two main arguments: 1) the unusual nature of Luxembourgish farms (i.e. small-holding integrated farms, practicing both husbandry and animals breeding); 2) existing PEMs and CGE models do not have the appropriate granularity of spatial detail for a Luxembourg-specific case study (in these models Luxembourg is, in the best case, aggregated with Belgium). Therefore, according to Occam's razor (A maxim attributed to the scholastic philosopher William of Ockham (c.1288-c.1348) and reading as follows: entia non sunt multiplicanda praeter necessitatem (entities must not be multiplied beyond necessity)) approach, we developed a new PEM, specific for the Luxembourgish agriculture and farming sector, which appropriately considers all the requirements and specificities related to CLCA.

Two alternative PEM approaches (non-linear programming-NLP and Positive Mathematical programming-PMP) are applied and discussed with respect to the aims of CLCA. A very comprehensive agriculture model (CAPRI, see Britz and Witzke, 2012) already exists, but it could not have been used in our case study, for the following reasons. CAPRI is applied at the European NUTS 2 level for assessing the regional impacts of the common agricultural policy. The model is a virtual tour-de-force with market clearing and supply working in a loop. The market module provides prices for the supply module which computes the supplies. These supplies lead to market clearance and these updated prices are then used in the next period based on weights given to previous prices. The supply module is a hybrid input-output system based on Leontief technology with a non-linear cost function computing the prices of primary factors, labour and capital. This formulation ensures that no activity is making losses. However, in CAPRI, Luxembourg is coupled with Belgium thus making it impossible to analyse policy impacts at a local (beyond NUTS 2) level. Also in the case of Luxembourg, the year 2009 (for which we had data available and that was used for the model calibration) has been exceptional in that crops exhibited financial losses. The possibility of financial losses does not exist under a Leontief fixed coefficient technology, where constant returns to scale imply price equals marginal cost. This has implications for calibration and further results. Other models, like GLOBIOM (Havlík, 2011), analyse the impacts of second-generation biofuels at the global scale, which is also way beyond the scales that are being targeted in this paper. For these reasons it was deemed necessary to build a specific model for Luxembourg, which is presented in detail in the following sections. The main contribution of the paper lies in comparison of two different methodologies for computing CLCA of increased maize production for biofuels by incorporating as many technical conditions as possible that also permit financial losses.

2. Problem Description, Data and Models

This section outlines the problem, data requirements, availability and manipulation and model description.

2.1. Problem Description

The Grand Duchy of Luxembourg totals an area of 258600 hectares, of which 130762 hectares are devoted to agriculture (Table 1). The agriculture activities are integrated with crops and animal rearing for meat and milk. Financially the operations are either fully owned by the farmers or rented. The model described in this paper aims in particular to simulate the situation that would result from increased production of maize using maize dry matter for biogas (crop name: maize_dry_matter_BG), to generate biogas. The biogas production process has not been accounted for in this paper, instead it focuses exclusively on the farming operations. This implies a shift from existing crops to grow maize, that would also have ramifications for animal feed due to the integrated chain of operations. The possibility of importing cheaper animal feed exists but is not encouraged. From a pure profit maximization perspective, the farmers would increase allocation of land to crops that give the maximum returns per hectare. To a certain extent this effect would be mitigated depending on the metabolic content (dry matter, proteins, metabolic energy and net lacto energy) of feed generated from the various crops harvested. For rearing animals for meat and milk, the feed should fulfill the minimum requirements for animals. Since the prices of animal products and crops are market determined, minimizing costs would imply maximizing profits. So it may not be in the best interest to grow only those crops that give the maximum benefit per hectare, but also those crops that meet the feed requirements, so as to maximize the total profit from crops and animal products. Farmers also indulge in crop rotation in order to preserve soil characterristics and would plant a variety of crops in order to ensure that. Also climate plays a major role in the suitability of crops in particular regions of the country. Environmental regulations pertaining to fertilizer application, irrigation, also play a role in yields and crop rotation. The problem then is to build a model that would encompass all financial operations of the farms, including crops and animals and simultaneously generate a realistic picture of the cropping patterns.

Table 1. Luxembourg Total Land Area (ha) and Type in 2009

Land Type	Area (ha)	%
Agriculture and Wooded Area	222137	85.90
Of which utilized Agriculture Area	130762	50.57
Built-up Area	23791	9.20
Road-net Railways etc.	11120	4.30
Water Courses, sheets of water	1552	0.60
TOTAL AREA Luxembourg	258600	100.00

2.2. Data Set

Table 1 shows the basic land composition of Luxembourg. Agricultural land occupies a modest 50.6% of the total land mass of the country. Studies in land use change would ideally deal with changes to the total land including forest and fallow land and development of urban sprawl (Gawel and Ludwig, 2011). However, in light of the restrictions imposed in Luxembourg on conversion of forests, meadows and pastures for uses other than the existing ones (SER, 2012), different model approaches that are generic in nature are evaluated.

The relevant data needed for building the model are listed in Table 2. There are 21 crops of which dried pulses, beans, potatoes, other_crops and crops Not Elsewhere Specified (NES), belonging to set SC (subset of the set of crops C that does not undergo cropping change), have been excluded from undergoing cropping area changes on account of their small size and specific locations within the country. Since the time period for the model is one year, all yields, outputs are on a yearly basis while prices and subsidies are valid for the year (yr) 2009. Vineyards, also belonging to set SC, (output in liters/yr and price in €/liter) have also been excluded due to the substantial time and monetary resources to use that land for cultivating other crops. The financial information, including price (€/t) and subsidies (€/ha/yr), and the output (expressed in metric tons per year, where a metric ton is equal to 1000 kilograms and is denoted by t) were obtained from national statistics and from the Luxembourgish *Service d'Economie Rurale* (SER, http://ser.etat.lu), while the annual subsidy turns out to be €330/ha/yr (Annual Subsidy/Compensatory allowance: *Ausgleichszulage* = €170/ha/yr; annual landscape conservation subsidy for pastures and meadows: *Landschaftspflegeprämie* = €87/ha/yr and annual subsidy for cropland = €73/ha/yr). Since this subsidy is per hectare per year, it has no relevance on the farmers' decision to plant crops. Finally, Table 3 shows the distribution by size of the 2242 farms existing in Luxembourg.

Regarding livestock in Luxembourg, the number of animals of each major type along with the metabolic requirements per day of dry matter (DM), metabolic energy (ME), net energy lactation (NEL) and proteins (XP) are listed in Table 4. These numbers are obtained mainly from the available literature (KTBL, 2006). The computation of demand, supply and excess demand for metabolic requirements for animals is tabulated in Table 5.

The prices of animal products (meat and milk) are averaged over the year 2009. Despite the fact that these prices fluctuate on a weekly basis, average values were used to harmonize the prices to the time scale of the model (i.e. one year of assessment). Crops have definite cropping seasons and it is possible that the same field can sustain two or three crops per year. However in the case of Luxembourg, such a case does not occur. This is an important aspect when it comes to rotation schemes as the same field would grow different crops over time. However the seasons are such that each field grows only one crop per year.

In reality crop yields are a function of soil characteristics, fertilizer input, irrigation, climatic conditions and weather patterns. From a modeling perspective, climatic conditions and weather patterns are assumed to affect the whole region in a uniform manner and thus the stochastic component of yield dependent on this aspect is ignored. Since we model the whole region as one, the soil characteristics and the suitability for crops to each soil type are out of the scope of the study. Moreover at a microscopic level of the field where one may have information on the soil characteristics and the suitability to crop, the individual farmer practices would further exacerbate the uncertainty with respect to yields. Additionally, crop yields are a function of fertilizer use and are subject to diminishing returns as is the case with all inputs. In order to endogenise the intensity decision as a function of crop prices and net benefits, we postulated a non-linear expression as in Equation (8), for crop yield (t/ha) as a function of the kilograms of combined application of Nitrogen (N), Phosphorous

Table 2. Price, Benefit, Area, Yield and Output by Crop in 2009 in Luxembourg

	N°	Price	Benefit (€/ha)		Area	Area	Yield	Output
Crop Name		€/t	without subsidy	with subsidy	ha	% of total	t/ha	t
Wheat for Humans	Cr1	145.74	449.87	779.87	6575	5.03	6.66	43761
Wheat for Animals	Cr2	105.76	219.86	549.86	6866	5.25	6.62	45444
Spelt	Cr3	208.94	449.87	779.87	400	0.31	4.64	1857
Rye	Cr4	80.30	126.80	456.80	1101	0.84	6.29	6924
Barley Winter	Cr5	87.02	123.24	453.24	5863	4.48	6.15	36044
Barley Spring	Cr6	90.76	103.26	433.26	3507	2.68	5.23	18354
Oats	Cr7	87.68	-625.57	-295.57	1384	1.06	5.20	7197
Mixed_Grain	Cr8	87.68	-620.65	-290.65	242	0.19	5.26	1272
Grain_Maize	Cr9	134.12	-615.78	-285.78	409	0.31	6.00	2453
Triticale	Cr10	86.16	196.83	526.83	4055	3.10	6.27	25415
Other_Forage_Crops	Cr11	98.57	-212.12	117.88	7981	6.10	13.67	109135
Maize_Dry_Matter_BG	Cr12	98.57	-274.46	55.54	16079	12.29	13.67	219869
Dried Pulses	Cr13	25.29	-207.62	122.38	305	0.23	3.95	1206
Beans	Cr14	125.00	-396.40	-66.40	77	0.06	3.52	271
Potatoes	Cr15	179.14	3403.96	3733.96	604	0.46	33.19	20044
Rapeseed	Cr16	259.84	573.08	903.08	4629	3.54	3.92	18132
Other_Crops	Cr17	29.26	701.50	1031.50	1708	1.31	53.13	90752
Meadows	Cr18	163.53	1014.20	1344.20	9023	6.90	8.22	74212
Pastures	Cr19	222.87	519.19	849.19	58320	44.60	8.23	479688
Vineyards*	Cr20	1.97	20497.81	20827.81	1242	0.95	10851.37	13477407
Crops_NES	Cr21	330.04	1167.61	1497.61	392	0.30	6.20	2431
TOTAL					130762	100.00		

* price €/litre; Output: litre.

Table 3. Distribution of Farms by Size (ha) in Luxembourg in 2009

	TOTAL	< 2	2 - 4.9	5 - 9.9	10 - 19.9	20 - 29.9	30 - 49.9	50 - 60.9	70 - 99.9	100+
Number	2242	230	165	217	186	116	246	263	398	421
Area (ha)	130762	131	598	1533	2667	2890	9956	15743	33583	63661
Average size	58.32	0.57	3.62	7.06	14.34	24.91	40.47	59.86	84.38	151.21

Table 4. Metabolic Requirements by Type and Age of Animal and Price of Animal Product in Luxembourg

		DM	ME	NEL	XP	Meat Price	Milk Price	Animals	Weight
	Animal	kg/day	MJ/day	MJ/day	g/day	€/kg	€/litre	number	kg
1	Bovine: Male < 1 year	4.8	77.44	0	866	5.77	0	20005	327
2	Bovine: Female < 1 year	4.6	70	0	790	5.77	0	32406	294
3	Bovine: Male 1 - 2 years	8.84	111.71	0	1237	5.41	0	47710	540
4	Bovine: Female 1-2 years	8.71	91.07	0	984	5.58	0	19257	739
5	Bovine: Suckler cow	8.71	88.58	0	951	0	0	32783	700
6	Bovine: Dairy Cow	15.17	0	101.55	2281	0	0.31	44310	700
7	Piglet	0.37	6.82	0	40	2.09	0	7395	50
8	Fattening pig	2.5	29	0	220	1.58	0	65448	120
9	Sow	2.5	29	0	600	0	0	7374	120

(P) and Potassium (K) (henceforth we denote this combination by NPK). We assume that the farmer is in a position to obtain the different fertilizers and mix them in the necessary proportion before applying the same on the land. The objecttive is then to obtain the values of the parameters for the expression in Equation (8). Based on the actual yield by crop (Table 2) and the benchmark values regarding the use of N, P and K for different crops (Figure 1), the range of inputs of fertilizer (N, P, K) was split by iterating till the yield input relationship approximates the actual yield levels in 2009 (see Table 2). Table 6 shows the parameters for yield of the selected crops that undergo cropping change due to changes in fertilizer input. Since the actual expenditure on fertilizers is unknown (only the total expenditure by type is available), the input price of fertilizers (N, P, K) by kg was iterated to approximate those for 2009. These assumptions, however, do not have a serious repercussion on the model behavior since it is dealing on an aggregate national level over the time span of

Table 5. Demand, Supply and Excess Demand for Metabolic Requirements for Animals

Variable	DM	ME	NEL	XP
Demand	721638	5828034	1642383	99374
Supply	594780	5286300	3089036	60669
Excess Demand	126858	541734	-1446653	38705

Table 6. Parameters for Yield Response to Fertilizer (N + P + K) Input in Kilograms

Crop Name	No	a	b	c	d
Wheat Humans	Cr1	2	3.306	0.01000	41.300
Wheat Animals	Cr2	2	2.950	0.00781	42.005
Spelt	Cr3	2	3.000	0.01099	41.750
Rye	Cr4	2	3.330	0.01000	41.300
Barley Winter	Cr5	2	3.200	0.01000	41.950
Barley Spring	Cr6	2	2.950	0.01000	41.830
Oats	Cr7	2	2.950	0.00965	42.000
Mixed_Grain	Cr8	2	3.000	0.01000	41.710
Grain_Maize	Cr9	2	3.150	0.01000	41.700
Triticale	Cr10	2	3.000	0.01000	34.985
Other_Forage_Crops	Cr11	2	8.500	0.02703	42.000
Maize_Dry_Matter_BG	Cr12	2	8.346	0.03000	42.000
Rapeseed	Cr16	2	3.200	0.01364	41.950
Meadows	Cr18	2	6.056	0.02500	43.000
Pastures	Cr19	2	5.766	0.02200	43.000

one year.

The costs for seeds, fertilizers, protection, other miscellaneous crop costs, farm and/or house rent, variable machine costs, labor costs or building/barn costs are obtained from (SER, 2009a, 2009b).

2.3. Model Description

The choice of model mainly depends on the service that will be finally delivered to the users and the data available to estimate parameters or calibrate the model. In the current case, the impetus to boost output of maize for biogas, apart from farmers or their cooperative, would also be of crucial importance to policy makers. However, issues such as the information asymmetry between the farmers and the policy makers, the lack of data availability or the scale and the scope of research questions besides the differing nature of relevant aspects to take into account, lead to divergence in the choice and implementation of models. Despite these discrepancies, what is common to both farmers and policy makers is the optimization approach, since in principle both interest groups seek a maximization of profits subject to various constraints. In addition, it is important to highlight that farmers at different scales are also subject to different constraints, making some specificities farm-size dependent. The other aspect of impact of individual decisions such as intensity of fertilizers, amount of nitrogen in the soil and the regulations relating to the maximum permissible limits of nitrogen and rotation schemes for crops to preserve soil characteristics is infeasible in an aggregate model. It is assumed that the presence of minor

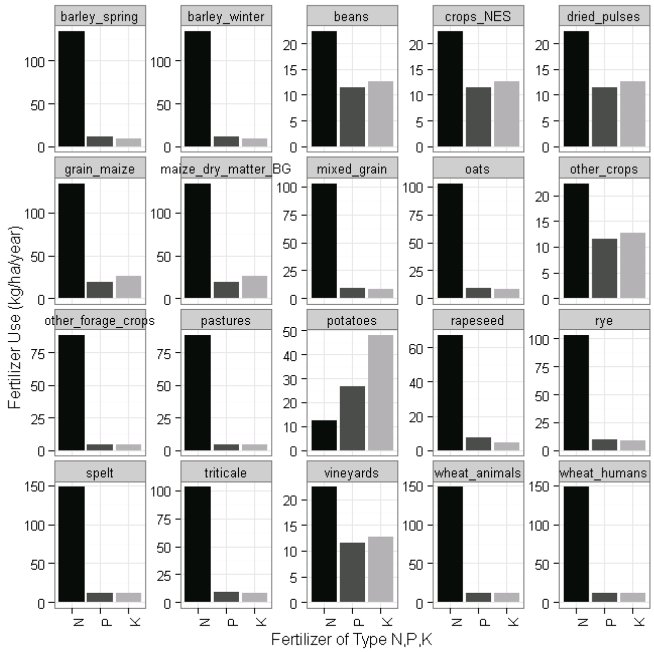

Figure 1. Fertilizer Use by Type (N, P, K) in kg/ha/year in 2009.

crops is a deliberate decision on part of the farmers to ensure soil characteristics and to adhere to regulations stipulating the chemical content of soils. To deal with this discontinuous behaviour of farmers, disaggregation between farms was not considered, assuming a single farm system while maintaining the core set of constraints. Hence, the specific decision context for farmers was formulated as a classical non-linear programming (NLP) problem. In Luxembourg farming operations exist under share cropping, rental and owner farming. It might be in the interest of certain farmers to indulge in intensive farming wherein the amount of fertilizers on the soil is increased to increase yield. As with all inputs, yield demonstrates diminishing returns to scale with increasing amount of fertilizers. A detailed description of optimization problems at the farm level is available in Kaiser and Messer (2011).

Regarding the policy maker perspective, it should be remarked that they may not have access to data at the farm or regional level. Consequently, policy makers may not be in a position to conduct statistical estimates of relevant parameters like demand-supply elasticity. Since policy makers deal with issues at the national level, this leads to difficulties in adopting the standard NLP model wherein additional constraints are needed to calibrate the model to the base case. The NLP model would offer corner solutions and would normally have only a few crops in the basis set or in the decision making set, but hardly all crops. There is no problem in corner solutions per se but it does not reflect the ground reality and in the extreme case could lead to just the presence of only one or two crops out of the entire list of crops which are actually observed in reality and lead to fallacious conclusions. In order for the NLP model to reproduce the base year data, one needs

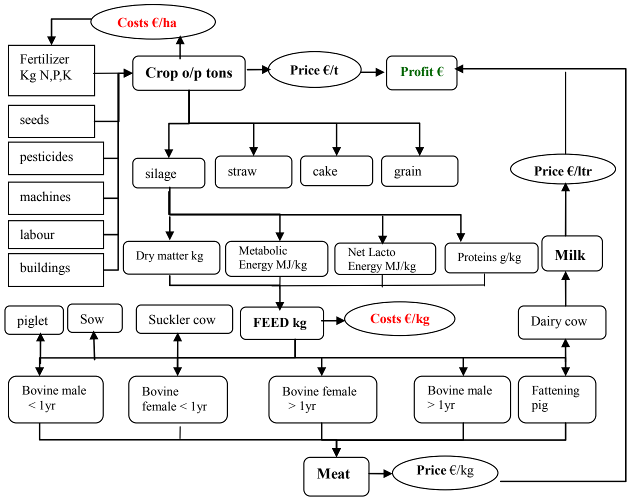

Figure 2. Schema of the NLP model.

to introduce additional constraints. These additional constraints despite replicating the base year also make the model results susceptible due the fact that these constraints are mainly the driving force behind the models. Therefore, in order to circumvent the calibration problem by adding additional constraints in the NLP problem, Howitt (1995) proposed the Positive Mathematical Programming (PMP) model.

2.4. Non-Linear Programming (NLP) Approach

The model formulation is split into two parts. The first part deals with the revenues and costs for crops, while the second part deals with the feed and revenue from animal products. From Figure 2 we observe that inputs such as fertilizers, seeds, pesticides, labour, machines, buildings are used to produce crops. The cost of inputs is in €/ha and only fertilizer costs in €/kg which varies with the yield and hence output. The crops generate grains, straw, cake and silage (only rapeseed produces cake after oil extraction). Each has a dry matter (DM) content (measured in % of the total weight) and intrinsic energy content (mega Joules MJ/kg of DM) and proteins (g/kg of DM). There is a conversion cost associated in converting the crop to grains, straw, cake and silage. Animal feed is comprised of these elements. There are six bovine animals and three swine classes. Animals produce meat and milk in addition to giving birth to young. The price of meat and milk minus the feed costs gives the profits from animal operations. The total profit comprises of animal and crop output.

2.5. Modelling Crop Output

The set C of 21 crops was split into those that are legally permitted to undergo land use changes (NS) and those for which any land use change is forbidden (SC) by the regulations in force (SER, 2012). One would have fixed and variable costs associated with each farm based on the size and the famer should be in a position to cover the average costs so as to make money. The fixed costs are incurred on machinery bought or rented, buildings (barns, stables), permanent labour, while variable costs would relate to seeds, fertilizers, pesticides, temporary labour, fuel, animal related costs such as feed. Since the whole country is treated as a farm without any distinction between owner-occupied, rented or share cropped, the rental price of land does not enter the optimization and plays no role in the planting of crops. Since the national data sources aggregate costs across farmers, the costs are given on a per hectare basis for each crop, eliminating variations across farmer and farm sizes. The basic data structure and crop costs incurred under various heads are summarised from the KTBL (2006): "*Betriebswirtschaftliche Planung*"; *Pflanzenproduktion*, for conventional and organic system with separate cultivation steps of ploughing, seed bed preparation with pulled equipment, sowing. In addition we obtain the various costs from SER (2009a, b) which includes permanent and temporary labour costs. In the model permanent labour costs are aggregated under fixed costs while temporary labour costs are attributed to variable costs. In the NLP formulation of the optimization problem, these costs are fixed per hectare per year for each crop. The direct costs (*cost_direct*) include the sum of cost of seeds (*dc_seed*), plant protection, i.e., pesticides (*dc_prot*) and other miscellaneous costs (this nomenclature is from SER (2009a, 2009b) and KTBL (2006) and covers all costs not mentioned in other direct costs) (*dc_other*). They are expressed in Equation (1):

$$cost\_direct(C) = dc\_seed(C) + dc\_prot(C) + dc\_other(C) \tag{1}$$

Variable costs (*cost_variable*) are defined (Equation 2) as the sum of rental (*c_rent*) and variable machine costs (*c_vcmc*):

$$cost\_variable(C) = c\_rent(C) + c\_vcmc(C) \tag{2}$$

Fixed costs (*cost_fixed*), defined in Equation (3), are constituted by the sum of labour costs (*c_plab*) and costs incurred on maintenance of farmland (*c_area*) and buildings (*c_bldg*):

$$cost\_fixed(C) = c\_plab(C) + c\_area(C) + c\_bldg(C) \tag{3}$$

Finally, fertilizer costs, (*cost_fert*), defined in Equation (4), are those incurred on the use of fertilizers. The model treats fertilizer costs separately from other variable costs, primarily due to the response of crop yield to fertilizer use. The logic followed in the model was to make the decision making of fertilizer use endogenous, based on yield and cost. Higher use of fertilizers leads to higher yield, albeit with diminishing returns despite the increased cost. The set of crops (C) is subdivided further into those crops that can undergo change (NS) and those that cannot (SC). The decision whether to intensify the fertilizer use for the crop belonging to set NS is based on the yield possible. There is an optimal use of fertilizers that trades-off the use with the return from incremental crop yield and revenue. In addition, the fertilizer use by each

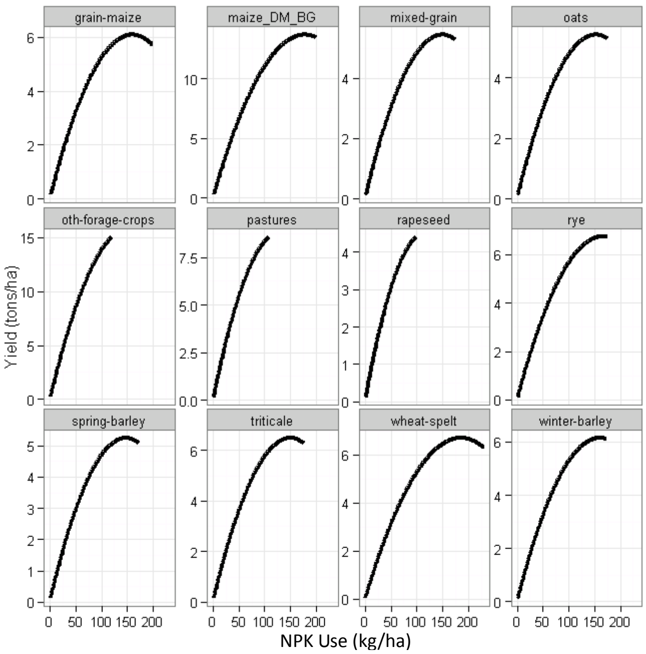

Figure 3. Derived functional relationship between NPK quantity and expected yield for selected crops.

type (NPK) is within a lower bound (*lb=0.8*) and an upper bound (*ub=1.8*) (Equations 5-7). For crops that do not undergo land use change, set SC, there is no change in the intensity of fertilizer use and hence the variable cost of fertilizer $cost\_fert(SC)$ equals the direct cost $dc\_fert(SC)$ of fertilizer in the base case:

$$cost\_fert(SC) = dc\_fert(SC) \tag{4}$$

$$lb \times kg\_N_{in}(NS) \le kg\_N(NS) \le ub \times kg\_N_{in}(NS) \tag{5}$$

$$lb \times kg\_P_{in}(NS) \le kg\_P(NS) \le ub \times kg\_P_{in}(NS) \tag{6}$$

$$lb \times kg\_K_{in}(NS) \le kg\_K(NS) \le ub \times kg\_K_{in}(NS) \tag{7}$$

where parameters kg_N_{in}, kg_P_{in}, and kg_K_{in} represent the base case application levels in kilograms of N, P and K fertilezers, respectively. Since there are limits on the maximum amount of fertilizer that can be applied, we permit the amount of fertilizer, $kg\_N(NS)$, a variable that will denote the extent of intensity of fertilizer use, to lie between a lower and upper bound. These bounds are based on the initial application of fertilizers. Yield is dependent on soil quality, irrigation, weather, technology shocks and fertilizer inputs. Weather affects the entire region due to its small size and is out of control of the farmers. As to irrigation, there are restrictions to use of artificial means for irrigating fields. Soil quality does differ and has an impact on the yields, but in the model we are dealing with an average yield for a crop that may be increased due to use of fertilizers. We posit a non-linear relationship between yield and the physical quantities in kilograms of N, P and K. The assumption is that a famer can commercially avail a sack of fertilizers of N, P and K and mix them to obtain the necessary proportions. The functional relationship between the quantity *of NPK* (*kg_NPK*) and the expected yield (*yield_NPK*) is thus expressed as in Equation (8):

$$\begin{aligned} &yield\_NPK(NS) \\ &= \frac{1}{Y_d(NS)}\{Y_a(NS) + Y_b(NS) \times kg\_NPK(NS) \\ &\quad - Y_c(NS) \times kg\_NPK(NS)^2\} \end{aligned} \tag{8}$$

which is graphically depicted for each crop in Figure 3.

The benefit per hectare of crop (*benefit*), described in Equation (9), is given by the difference between the revenue per hectare and the costs:

$$\begin{aligned} benefit(C) = {} & rev\_Ha(C) - cost\_variable(C) \\ & - cost\_fixed(C) - cost\_fert(C) \end{aligned} \tag{9}$$

Revenue per hectare (*rev_Ha*) is obtained from the price per ton of crop (*prc_ton*) times the yield (*yield*) in t/ha for crops without land use change and *yield_NPK* for crops with yield and land use change:

$$rev\_Ha(SC) = prc\_ton(SC) \times yield(SC) \tag{10}$$

$$rev\_Ha(NS) = prc\_ton(NS) \times yield\_NPK(NS) \tag{11}$$

The gain (*net_gain*), for each crop, expressed in Equation (12), is the benefit per hectare of crop multiplied by the area under cultivation under the crop (*new_area*), while the total gain (Equation 13-*total_gain*) from the system is the sum of the gains from all crops.

$$rev\_gain(C) = benefit(C) \times new\_area(C) \tag{12}$$

$$total\_gain = \sum\nolimits_C net\_gain(C) \tag{13}$$

The new area under crop allocation after the farmers undertake an optimization action is then calculated and the constraint that the summation of the new area cannot exceed the total agriculture area of Luxembourg (*total_area*) is imposed (Equations 14-15). The area under each crop in the base case is denoted by *acreage(C)*:

$$total\_area = \sum\nolimits_C new\_area(C) \tag{14}$$

$$total\_area = \sum\nolimits_C acreage(C) \tag{15}$$

The output of crops, (*output_crop*), expressed in Equations (16) and (17), depends on the *yield* (t/ha) (Equation 18) and the area under cultivation (ha). The output is computed in tons for the two sets of crops: those that undergo land use change (*NS*) and those that do not (*SC*):

$$output\_crop(SC) = yield(SC) \times new\_area(SC) \quad (16)$$

$$output\_crop(NS) = yield\_NPK(NS) \times new\_area(NS) \quad (17)$$

In order to compute the land use changes, the model requires a shock implying an additional demand for maize for biofuel (Cr12). This additional demand is named *toncorn*, and is set exogenously to 0 in the base case and 80000 t in the counter factual:

$$yield('Cr12') \times acreage('Cr12') + toncorn = yield\_NPK('Cr12') \times new\_area('Cr12') \quad (18)$$

The change in output (*output_change*), for each crop, described by Equation (20), is the difference in production in the base case (*output_base*) (see Equations 19-20) and in the counter factual (*output_crop*):

$$output\_base(SC) = yield(SC) \times acreage(SC) \quad (19)$$

$$output\_base(NS) = yield(NC) \times acreage(NS) \quad (20)$$

$$output\_change(C) = output\_crop(C) - output\_base(C) \quad (21)$$

The land use change (*change_landuse*) by crop, expressed in Equation (22), is the difference in the land use before and after the shock:

$$change\_landuse(C) = new\_area(C) - acreage(C) \quad (22)$$

2.6. Modelling Livestock

The feed for animals (*SS_GS*), given by Equation (23), consists of grain, straw, silage and cake (*feed*), and is a fixed proportion *POP*(*C, feed*) of the output of the crop:

$$SS\_GS(C, feed) = output\_crop(C) \times POP(C, feed) \quad (23)$$

Normally by weight the straw equals the grain, however only 20% of it is used for feeding purposes. Feed from each crop has a certain percentage of dry matter (*DM*) and this dry matter has proteins (*XP*) [g/kg of dry matter], metabolic energy (*ME*) [MJ/kg of dry matter] and net energy lactation (*NEL*) [MJ/kg of dry matter]. Animal growth is largely a function of the amount of these inputs. The supply of dry matter (Equation 24) $SS\_DM(C, feed)$, protein $SS\_XP(C, feed)$ (Equation 25), metabolic energy $SS\_ME(C, feed)$ (Equation 26) and net lacto energy $SS\_NEL(C, feed)$ (Equation 27) by feed for each crop are given by:

$$SS\_DM(C, feed) = SS\_GS(C, feed) \times PDM(C, feed) \quad (24)$$

$$SS\_XP(C, feed) = SS\_DM(C, feed) \times PXP(C, feed) \quad (25)$$

$$SS\_ME(C, feed) = SS\_DM(C, feed) \times PME(C, feed) \quad (26)$$

$$SS\_NEL(C, feed) = SS\_DM(C, feed) \times PNEL(C, feed) \quad (27)$$

where *PDM*, *PXP*, *PME* and *PNEL* are respectively: proportion of dry matter, proteins, metabolic energy and net energy lactation in feed of crop C.

The total supply of dry matter (*TS_DM*) (Equation 28), protein (*TS_XP*) (Equation 29), metabolic energy (*TS_ME*) (Equation 30) and net lacto energy (*TS_NLE*) (Equation 31) by crop is the sum over all feeds for each crop:

$$TS\_DM(C) = \sum_{feed} SS\_DM(C, feed) \quad (28)$$

$$TS\_XP(C) = \sum_{feed} SS\_XP(C, feed) \quad (29)$$

$$TS\_ME(C) = \sum_{feed} SS\_ME(C, feed) \quad (30)$$

$$TS\_NEL(C) = \sum_{feed} SS\_NEL(C, feed) \quad (31)$$

Normally there is some additional effort in producing the different feed from the crops and the final cost of feed by crop, $Cost\_C\_Feed(C, feed)$, is computed (Equation 32) as a function of cost escalation $Cost\_escalation(feed)$ of producing feed over the normal cost $C\_Prc\_Ton(C)$ of producing the crop:

$$Cost\_C\_Feed(C, feed) = cost\_escalation(feed) \times C\_prc\_Ton(C) \quad (32)$$

The farm operations aim to maximize the profits from milk and meat production. The meat and milk production are a function of the metabolic inputs given via feed of different crops. The feed eventually determine the cost of production of each animal in addition to other miscellaneous costs like veterinary, housing, etc.

Our objective is to determine *Q_AFCM(anml, c, feed, MB)* (see Equations 33-36), where $MB \equiv \{DM, XP, ME, NEL\}$ is the least cost of feed (*feed)* from crop (*C)* with metabolic requirement (*MB)* for each type of animal (*anml*) such that it fulfils the minimum metabolic requirements of the animals. If *ton_C_feed*(*anml, C, feed*) is the animal feed in tons per year of feed from crop *C*, the dry matter content of this diet and the metabolic contents are given by the following equations:

$$Q\_AFCM(anml,C,feed,'DM') \\ = ton\_C\_feed(anml,C,feed) \times PDM(C,feed) \quad (33)$$

$$Q\_AFCM(anml,C,feed,'XP') \\ = Q\_AFCM(anml,C,feed,'DM') \times PXP(C,feed) \quad (34)$$

$$Q\_AFCM(anml,C,feed,'ME') \\ = Q\_AFCM(anml,C,feed,'DM') \times PME(C,feed) \quad (35)$$

$$Q\_AFCM(anml,C,feed,'NEL') \\ = Q\_AFCM(anml,C,feed,'DM') \times PNEL(C,feed) \quad (36)$$

The metabolic content of each crop *Qty_AC_MB*(*anml, C, MB*) (Equation 37) fed to each type of animal is computed as in Equation (37):

$$Qty\_AC\_MB(anml,C,MB) \\ = \sum_{feed} Q\_AFCM(anml,C,feed,MB) \quad (37)$$

The total metabolic content of each crop *Qty_C_MB*(*C, MB*) is given by Equation (38):

$$Qty\_C\_MB(C,MB) \\ = \sum_{anml} Qty\_AC\_MB(anml,C,MB) \quad (38)$$

The total metabolic input *MB_anml*(*anml, MB*) (Equation 39) to each animal is given by the sum across all feed types and crops of the individual feed in tons per year of various crops *Q_AFCM*(*anml, C, feed, MB*). The total metabolic inputs of $MB \equiv \{DM, XP, ME, NEL\}$ per animal type in a year are given by Equation (39):

$$MB\_anml(anml,MB) \\ \geq \sum_{C,feed} Q\_AFCM(anml,C,feed,MB) \quad (39)$$

The total demand by crop for metabolic inputs (*DD_MR ≡DD_DM, DD_XP, DD_ME, DD_NEL*) (Equation 40) is the metabolic input (*DM, XP, ME, NEL*) per animal multiplied by the number of animals present in the base case *BASE_anml (anml)*:

$$DD\_MR(C) = \sum_{feed,ANML} [Q\_AFCM(anml,C,feed,MR) \\ \times BASE\_anml(anml)] \quad (40)$$

In equilibrium the demand should be less than or equal to the total supply of metabolic input $TS\_MR \equiv (TS\_DM, TS\_XP, TS\_ME, TS\_NEL)$ by crop. These conditions are satisfied in the Equation (41):

$$DD\_MR(C) \leq TS\_MR(C) \quad (41)$$

We impose the condition that each animal gets the exogenously specified minimum metabolic requirement *Min_Req* (*anml, MB*) (Equation 42):

$$MB\_anml(anml,MB) \geq Min\_Req(anml,MB) \quad (42)$$

This ensures that each animal gets the stipulated metabolic inputs obtained by different feeds from crops that maximise the gains from animal operations.

We impose that the total demand *Feed_C_Lim*(*C, feed*) (Equations 43-44) equals the total supply *SS_GS*(*C, feed*) of feed by crops:

$$Feed\_C\_Lim(C,feed) \\ = \sum_{anml} [ton\_C\_Feed(anml,C,feed) \\ \times BASE\_anml(anml)] \quad (43)$$

$$Feed\_C\_Lim(C,feed) = SS\_GS(C,feed) \quad (44)$$

In order to ascertain the costs and benefits of the animal operations, we need information on the number of animals that are in the system. Besides this information on their weight, meat and milk production capacity and the prices of meat and milk are also needed. Although these prices fluctuate on a weekly basis and slaughtering and milking is not an annual phenomenon, it is assumed that this is an annual phenomenon and takes the average annual prices for the products.

The cost of feed per type of animal *Cost_Feed_Anml* (*anml*) (Equation 45) is the sum of the costs of various feed of different crops:

$$Cost\_Feed\_Anml(anml) = \\ \sum_{C,feed} [ton\_C\_Feed(anml,C,feed) \\ \times Cost\_Feed\_C(C,feed)] \quad (45)$$

To compute the benefits from the animal operations we need to compute the related gains. Farmers gain from milk and meat and incur an expense on feed costs (which are indirectly lined to crop costs). Value of milk *Value_Milk*(*anml*), given by Equation (46), is the value of milk per animal (*ValPAnml*) multiplied by the number of animals producing milk (*BASE_ANML*):

$$Value\_Milk(anml) \\ = ValPAnml(anml,'milk') \times BASE\_anml(anml) \quad (46)$$

We also compute a maximum value of meat *Value_Meat* (*anml*) (Equation 47), which is the value of the livestock if all were to be slaughtered or sold and the operations wound-up:

$$Value\_Meat(anml) \\ = ValPAnml(anml,'meat') \times BASE\_anml(anml) \quad (47)$$

Similarly the cost of all animals *Cost_All_Anml*(*anml*) (Equation 48), is the feed cost per animal multiplied by the number of animals of each type:

$$Cost\_All\_Anml(anml) = Cost\_Feed\_Anml(anml) \times BASE\_anml(anml) \quad (48)$$

The net benefit per type of animal *Net_Benefit*(*anml*) (Equation 49), from animal operations include the benefits from milk and meat minus the cost of feed:

$$Net\_Benefit(anml) = ValPAnml(anml,'milk') - Cost\_Feed\_Anml(anml) \quad (49)$$

We assume that only a proportion [*N_slaughter(anml)*] of animals are slaughtered (within lower (*lb=0*) and upper (*ub* = 0.7) bounds Equation 52) and the value of meat [*V_slaughter*)] (Equation 50), is based on this number according to Equation (51):

$$V\_slaughter(anml) = ValPAnml(anml,'meat') \times N\_slaughter(anml) \quad (50)$$

$$lb \times BASE\_anml(anml) \leq N\_slaughter(anml) \leq ub \times BASE\_anml(anml) \quad (51)$$

The total benefit *Tot_Net_benefit*(*anml*) (Equation 52) is the net benefit from all animals by selling milk and meat and incurring the feed costs:

$$Tot\_Net\_benefit(anml) = V\_slaughter(anml) + Value\_Milk(anml) - Cost\_All\_Anml(anml) \quad (52)$$

The total gain is the sum of gains from crops and animals (Equations 53-54). Equation (55) maximises the total gain (*Total_Gain*) subject to the various constraints outlined above:

$$Anml\_Gain = \sum_{anml} Tot\_Net\_Benefit(anml) \quad (53)$$

$$Crop\_Gain = \sum_{C} Net\_Gain(C) \quad (54)$$

$$Total\_Gain = Crop\_Gain + Anml\_Gain \quad (55)$$

The model has 9 types of animals, of which six are bovine and three are swine. The bovine animals are split according to sex and age: males younger than 1 year (M1), females younger than 1 year (F1), males between 1 and 2 years (M2), females between 1 and 2 years (F2), suckler cows (SCow) and dairy cows (DCow). The categories of pigs are: piglets (PLet), fattening pigs (PFat) and sows (PSow). An average body weight per animal was assumed to calculate the carcass weight as 60% of the body weight. The meat realized is assumed to be 60% of the carcass weight or 36% of the body weight of the animal. Suckler cows and dairy cows are not slaughtered for meat. The prices of meat and milk are average prices as observed in 2009. Table 4 shows the minimum metabolic requirements by each type of animal along with the price of meat and milk in 2009.

Livestock plays an important role in the entire farming system. Hence, their existence in the model impacts the nature of the results. From Table 5 one can observe that, except for NEL, all other metabolic requirements like DM, ME and XP are in short supply. This means that Luxembourg is falling short of animal feed and is dependent on imports for its animal feed. Since we do not consider import of animal feed in the model, we assume that any shortfall in feed for any animal is made from import of feed by the farmers. So in fact the farmers are optimizing the total gains from animals and crops and any shortfall is covered by animal feed imports. In the absence of this assumption, we would have needed to incorporate the imports of feed by crop and type for each animal and still would not have achieved endogeneity of the animal feed decision making. In the model an integrated decision (which crops to sow) is taken based on the expected price of the crops and the metabolic characteristics (DM, ME, NEL, XP) of these crops for feed for animals. The variables, parameters and the sets in the NLP model are tabulated in tables 10-12, respectively.

2.7. Positive Mathematical Programming Approach

This approach for modelling change in cropping patterns follows a three step process. The first step is to compute the marginal value for additional area of land for each crop. The farmer will substitute one unit of land from crop1 to crop 2 as long as the marginal return from crop 2 is greater than crop 1. In equilibrium the marginal return (difference between revenue and average costs) from all crops has to be the same, or there is an incentive to substitute one crop for the other. The second step is to calibrate parameters of a non-linear total cost (*TC*) function $TC = \alpha x + 1/2(\gamma x^2)$, with constants α and γ, leading to an average cost $AC = \alpha + 1/2(\gamma x)$ and marginal cost, $MC = \alpha + \gamma x$. Since price equals *MR*, which equals *MC*, we compute:

$$MC - AC = \alpha + \gamma x - \alpha - \frac{1}{2}\gamma x \Rightarrow \frac{1}{2}\gamma x = \lambda \Rightarrow \gamma = 2\frac{\lambda}{x}; \alpha = AC - 2\lambda \quad (56)$$

where λ is the marginal value associated with the land constraint for each crop with area x under cropping. Having obtained γ, we obtain α from the value of the average cost. The last step is to modify the optimization problem (Equation 57):

$$Max \sum_i \left[p_i y_i x_i - \left(\alpha_i - \frac{1}{2}\gamma_i x_i \right) x_i \right] \text{ subject to } Ax \leq b; x \geq 0 \quad (57)$$

to obtain the area x_i allocated to crop i. γ represents the change in marginal cost to change in one unit of area x. With more

Table 7. Calibration Using PMP Approach

No	Crop Name	Base Area	New Area	λ	α	γ	adj	VMP
		ha	ha					€/ha
Cr1	Wheat Humans	6575	6611	813.20	-594.01	0.24	323.33	-4.27
Cr2	Wheat Animals	6866	6919	583.20	-404.00	0.16	233.33	-4.27
Cr3	Spelt	400	402	813.21	-594.01	3.90	323.33	-4.27
Cr4	Rye	1101	1111	490.13	-412.88	0.83	168.33	-4.27
Cr5	Barley Winter	5863	5918	486.58	-375.78	0.15	178.32	-4.27
Cr6	Barley Spring	3507	3542	466.60	-395.80	0.25	158.33	-4.27
Cr7	Oats	1384	0	33.33	751.51	0	151.98	-295.57
Cr8	Mixed_ Grain	242	0	33.33	751.51	0	153.62	-290.65
Cr9	Grain_Maize	409	0	33.33	1090.18	0	268.13	-285.78
Cr10	Triticale	4055	4088	560.16	-517.90	0.26	180.01	-4.27
Cr11	Other Forage Crops	7981	8270	151.21	1107.86	0.03	449.29	-4.27
Cr12	Maize_Dry_Matter_BG	16079	17314	88.87	1232.54	0.01	449.29	-4.27
Cr13	Dried Pulses	305	316	155.71	-149.03	0.80	33.33	-4.27
Cr14	Beans	77	0	33.33	506.34	0	146.65	-66.4
Cr15	Potatoes	604	605	3767.30	-1527.36	12.36	1981.61	-4.27
Cr16	Rapeseed	4629	4651	936.42	-792.64	0.39	339.26	-4.27
Cr17	Other_Crops	1708	1715	1064.84	-512.58	1.21	518.23	-4.27
Cr18	Meadows	9023	9052	1377.53	-1347.67	0.3	448.33	-4.27
Cr19	Pastures	58320	58613	882.52	130.48	0.03	611.04	-4.27
Cr20	Vineyards	1242	1242	18861.14	-16282.67	30.32	7125.74	-4.27
Cr21	Crops_NES	392	393	1530.94	-952.47	7.64	682.34	-4.27
	TOTAL	130762	130762					

than one crop there would also be cross-effects between activities. Hence the marginal cost γ_1 of crop 1 could respond to output x_2 of crop 2, and vice-versa. In the simple PMP these cross effects are assumed to be absent. In order to include cross effects, the modeler needs additional information to estimate the values of off-diagonal elements. For further details refer Heckelei and Britz (1999). The equations for animals remain the same as specified in section 2.6 dealing with modeling livestock.

Step 1:

The objective function is to maximize profit which is the difference between benefit and total cost

$$profit = benefit - totcost \tag{58}$$

Benefit of cultivating each crop is the price of a crop times its yield times the land under cultivation x_i:

$$benefit_i = price_i \times yield_i \times x_i \tag{59}$$

Total benefit is the sum of individual benefits

$$benefit = \sum benefit_i \tag{60}$$

Total cost (*totcost*) equals the sum of variable costs over all crops, where the variable costs (*varcost*) equals the variable cost as given in the variable cost data (*data_varcost*) minus the subsidy per hectare per crop. Thus we have:

$$totcost = \sum_i varcost_i; \quad varcost_i = data\_varcost_i - subsidy_i \tag{61}$$

To ensure proper calibration the area under crop cultivation (x_i) obtained from the maximization problem should equal the original area under each crop (*basearea*$_i$). We have as many equations as the number of crops. Thus:

$$x_i = basearea_i + 0.001 \tag{62}$$

Where 0.001 is a small amount known as the perturbation constant to ensure that the solution equals the original area under cultivation and also that the constraint is non-binding.

The total land under cultivation has to equal the original land under cultivation (*basearea*). We have:

$$basearea = \sum_i x_i \tag{63}$$

From the profit maximization problem we obtain the land allocated to each crop (x_i). Zero marginal value implies that there is no scope for additional increase in profits by changing any crop from its existing cultivated size. If we call equation 62 *eqnlandcrop*, then the marginal of this equation *eqnlandcrop M* gives the dual of the area under cultivation x_i. We denote the dual of *eqnlandcrop* by λ_i.

Step 2:

Given λ_i and the area under each crop in the base case

Table 8. Comparison of Base Case between NLP and PMP Approaches

No	Crop Name		NLP			PMP		
		Base Area	New Area	Δ Area	Area.M	New Area	Δ Area	Area.M
		ha	ha	ha		ha	ha	
Cr1	Wheat Humans	6575	7890	1315	874.87	6602	27	0
Cr2	Wheat Animals	6866	5493	-1373	-27.49	6907	41	0
Cr3	Spelt	400	320	-80	-75.13	402	2	0
Cr4	Rye	1101	1321	220	67.16	1109	8	0
Cr5	Barley Winter	5863	7036	1173	40.12	5905	42	0
Cr6	Barley Spring	3507	4208	701	81.00	3533	26	0
Cr7	Oats	1384	1107	-277	-635.42	1107	-277	-293.34
Cr8	Mixed Grain	242	194	-48	-627.19	194	-48	-288.42
Cr9	Grain Maize	409	327	-82	-952.51	327	-82	-283.56
Cr10	Triticale	4055	4866	811	101.34	4080	25	0
Cr11	Other Forage Crops	7981	6385	-1596	-1134.45	8201	220	0
Cr12	Maize Dry Matter BG	16079	16198	119	0.00	16079	0	0
Cr13	Dried Pulses	305	305	0	217.00	305	0	6.49
Cr14	Beans	77	77	0	-410.00	77	0	-64.18
Cr15	Potatoes	604	604	0	3831.00	604	0	6.49
Cr16	Rapeseed	4629	3746	-883	0.00	4646	17	0
Cr17	Other Crops	1708	1708	0	1128.00	1708	0	6.49
Cr18	Meadows	9023	9023	0	96.00	9023	0	6.49
Cr19	Pastures	58320	58320	0	-887.00	58320	0	6.49
Cr20	Vineyards	1242	1242	0	20924.00	1242	0	6.49
Cr21	Crops NES	392	392	0	1594.00	392	0	6.49
	TOTAL	130762	130762			130762		

Table 9. Fertilizer Intensity in the NLP Model

No	Crop Name	Yield	Original Yield	Δ Yield	Fertilizer Cost	Original Fertilizer Cost	Δ Cost
		t/ha	t/ha	t/ha	€/ha	€/ha	€/ha
Cr1	Wheat Humans	6.60	6.66	-0.06	168.86	195.13	-26.27
Cr2	Wheat Animals	6.17	6.62	-0.45	156.10	195.13	-39.03
Cr3	Spelt	4.95	4.64	0.31	156.10	195.13	-39.03
Cr4	Rye	5.59	6.29	-0.70	110.53	138.19	-27.66
Cr5	Barley Winter	5.84	6.15	-0.31	141.38	176.73	-35.35
Cr6	Barley Spring	5.12	5.23	-0.11	141.38	176.73	-35.35
Cr7	Oats	4.70	5.20	-0.50	110.53	138.19	-27.66
Cr8	Mixed Grain	4.77	5.26	-0.49	110.53	138.19	-27.66
Cr9	Grain Maize	6.02	6.00	0.02	163.91	204.91	-41.00
Cr10	Triticale	5.68	6.27	-0.59	110.53	138.19	-27.66
Cr11	Other Forage Crops	11.85	13.67	-1.82	88.54	110.8	-22.26
Cr12	Maize Dry Matter BG	13.57	13.67	-0.10	184.58	204.91	-20.33
Cr13	Dried Pulses	3.95	3.95	0	52.62	52.62	-52.62
Cr14	Beans	3.52	3.52	0	52.62	52.62	-52.62
Cr15	Potatoes	33.19	33.19	0	230.87	230.87	-230.87
Cr16	Rapeseed	3.57	3.92	-0.35	71.66	89.71	-18.05
Cr17	Other Crops	53.13	53.13	0	52.62	52.62	-52.62
Cr18	Meadows	8.22	8.22	0	110.8	110.8	-110.80
Cr19	Pastures	8.23	8.23	0	110.8	110.8	-110.80
Cr20	Vineyards	10851.37	10851.37	0	52.62	52.62	-52.62
Cr21	Crops NES	6.20	6.20	0	52.62	52.62	-52.62

($basearea_i$), we obtain the non linear cost function parameters γ_i and α_i:

$$\gamma_i = \frac{2 \times \lambda_i}{basearea_i} \tag{64}$$

Table 10. Variables in the NLP Model (in alphabetic order)

No	Variable Name	Variable Meaning	Set	Units	in Equations
1	Anml_gain	total gain from all animals		€	53
2	benefit	benefit per hectare for crop C	C	€/ha	9
3	c_rent	variable cost: rental (farm)	C	€/ha	2
4	c_vcmc	variable cost: machine cost	C	€/ha	2
5	change_landuse	change in land use for crop after shock	C	ha	22
6	cost_All_Anml	cost of maintaining each animal	anml	€	48
7	cost_C_Feed	cost of feed from crop C	C, feed	€	32
8	cost_direct	direct costs: total	C	€/ha	1
9	cost_Feed_Anml	cost of feed per animal	anml	€	45
10	cost_fert	fertilizer cost	C	€/ha	4
11	cost_fixed	fixed costs: total	C	€/ha	3
12	cost_variable	variable costs: total	C	€/ha	2
13	crop_gain	total gain from all crops		€	54
14	dc_other	direct cost: other not mentioned above	C	€/ha	1
15	dc_prot	direct cost: plant protection (pesticides)	C	€/ha	1
16	dc_seed	direct cost: seeds	C	€/ha	1
17	DD_MR	total demand for metabolic inputs by crop	C		40
18	c_area	fixed costs: maintenance of farmland	C	€/ha	3
19	c_bldg	fixed cost: maintenance of barn, buildings	C	€/ha	3
20	c_plab	fixed costs: labour	C	€/ha	3
21	Feed_C_Lim	total demand of feed from crop C	C, feed	t	43
22	kg_NPK	kg of mixed NPK fertilizer	NS	kg/ha	8
23	MB_anml	total metabolic input by animal from all feed sources of all crops	anml,MB	various MB per year	39
24	Min_Req	minimum requirement of metabolic input per animal per day	anml, MB	MB per day	42
25	N_slaughter	number of animals of each type slaughtered	anml	number	50
26	Net_Benefit	net benefit from each animal	anml, AP	€	49
27	net_gain	net gain for crop C	C	€	12
28	new_area	new area after land use change	NS	ha	12
29	output_base	base output of crop before shock	C	t	19
30	output_change	change in output of crop after shock	C	t	21
31	output_crop	output of crop after shock	C	t	16, 17
32	Q_AFCM	quantity of MB	anml, c, feed, MB	per anml	33, 34, 35, 36
33	Qty_AC_MB	metabolic content of each crop fed to each animal	anml, C, MB		37
34	Qty_C_MB	metabolic content of each crop	C, MB		38
35	rev_Ha	revenue per hectare for crop C	C	€/ha	10, 11
36	SS_DM	supply of dry matter from feed of crop	C, feed	kg	24
37	SS_GS	supply of straw and grain from crop C	C, feed	t	23
38	SS_ME	supply of metabolic energy from feed of crop	C, feed	MJ	26
39	SS_NEL	supply of net energy lactation from feed of crop	C, feed	MJ	27
40	SS_XP	supply of proteins from feed of crop	C, feed	gm	25
41	ton_C_Feed	feed of Crop C in for each type of animal	anml, C, Feed	t	33
42	Tot_Net_benefit	total net benefit per animal	anml	€	52
43	Total_Gain	total gain from all operations		€	55
44	TS_DM	total supply of dry matter from crop	C	kg	28
45	TS_ME	total supply of metabolic energy from crop	C	MJ	30
46	TS_MR	total supply of metabolic inputs by crop	C		41
47	TS_NEL	supply of net energy lactation from crop	C	MJ	31
48	TS_XP	total supply of proteins from crop	C	gm	29
49	V_slaughter	value of meat per animal	anml	€	50
50	Value_Meat	value of meat per animal	anml	€	47
51	Value_Milk	value of milk per animal	anml	€	46
52	yield_NPK	yield as a function of NPK use	NS	t/ha	8

Table 11. Parameters in the NLP Model

No	Parameter	Parameter Meaning	Set	Units	in Equations
1	acreage	base acreage in ha under each crop	C	ha	15
2	BASE_anml	number of animals in the base case	anml		40
3	cost_escalation	cost escalation (markup) in making feed from crop	feed		32
4	dc_fert	fertilizer cost in base case	C	€/ha	4
5	kg_K_{in}	amount of potassium (K) fertilizer in kg/ha in base case	NS	kg/ha	5, 6, 7
6	kg_N_{in}	amount of nitrogenous (N) fertilizer in kg/ha in base case	NS	kg/ha	5, 6, 7
7	kg_P_{in}	amount of phosporus (P) fertilizer in kg/ha in base case	NS	kg/ha	5, 6, 7
8	lb	lower bound	C	0.8	5, 6, 7
9	Min_Req	minimum requirement of metabolic input per animal per day	anml,MB	MB per day	42
10	PDM	proportion of Dry Matter in feed from crop	C, feed	%	24
11	PME	proportion of Metabolic energy in feed from crop	C, feed	%	26
12	PNEL	proportion of net energy lactation in feed from crop	C, feed	%	27
13	POP	fixed proportion of feed generated from crop C	C, feed	%	23
14	prc_ton	price per tonne of crop	C	€/t	11
15	PXP	proportion of Proteins in feed from crop	C, feed	%	25
16	toncorn	exogenous amount of maize needed for biofuel (set at 80000 t)		t	18
17	total_area	total area under agriculture in 2009		ha	14, 15
18	ub	upper bound	C	1.8	5, 6, 7
19	ValPAnml	value of product by animal	anml,AP	€	46
20	Y_a	parameter in yield function	NS		8
21	Y_b	parameter in yield function	NS		8
22	Y_c	parameter in yield function	NS		8
23	Y_d	parameter in yield function	NS		8
24	yield	yield in t/ha of crops not undergoing land use change	SC	t/ha	10

Table 12. Sets in the NLP Model

No	Sets	Composed of	Properties
1	C	Cr1:Cr21	All Crops
2	NS	Cr1 to Cr12, Cr16,	Crops that CAN undergo land use change
3	SC	Cr13 to Cr15, Cr17 to Cr21	Crops that CANNOT undergo land use change (regulations or too small or specific due to terrain like vineyards)
4	feed	grain, straw, silage, cake	Types of animal feed
5	anml	bovines, pigs	Bovines (Males, females < 1yr, > 1yr), suckler cow, dairy cow, fattening pigs, sow and piglets
6	MB	DM, XP, ME, NEL	Dry Matter (DM), Proteins (XP), Metabolic energy (ME), net energy lactation (NEL)
7	AP	animal products	Meat, milk

$$\alpha_i = data\_varcost_i - \frac{1}{2} \times \gamma \times basearea_i \tag{65}$$

Step 3:

In the final step we set up the new optimization problem with just constraints on the total land size subject to individual crop areas being non-negative. The modified problem is as follows. Maximize profit (*profit_new*):

$$\begin{aligned} profit\_new = \sum_{c_i} \{ & price_{c_i} \times yield_{c_i} \times x\_new_{c_i} \\ & - [\alpha_{c_i} + 1/2 \times \gamma_{c_i} \times x\_new_{c_i}] \times x\_new_{c_i} \} \end{aligned} \tag{66}$$

subject to

$$\begin{aligned} & \sum\nolimits_{c_i} x\_new_{c_i} = basearea; \\ & x\_new_{c_i} \geq 0 \end{aligned} \tag{67}$$

3. Results and Discussion

In this section, results of the PEM are first detailed for the base case, i.e. the calibration year, and then presented for a counterfactual scenario of an additional 80000 t of maize dry matter for bio gas (maize_dry_matter_BG).

3.1. Base Case

Table 2 shows the values for yield, area, benefit, output and price for all crops in the reference year 2009. The benefits include 330 €/ha of subsidy, without which the farmers would have incurred losses on additional crops. Except for vineyards, where the output is in hectolitres of wine and price in euro per litre of wine, all other crops have the output reported in tons and price in €/t. In Luxembourg, pastures (Cr19:

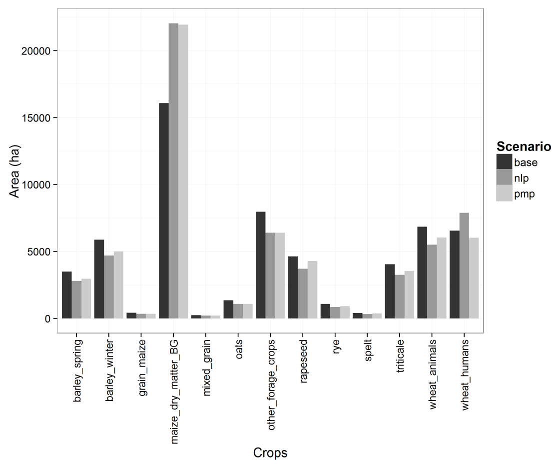

Figure 4. Comparing area (ha) under crops in base case to NLP and PMP models due to a shock of additional 80000 tons of maize.

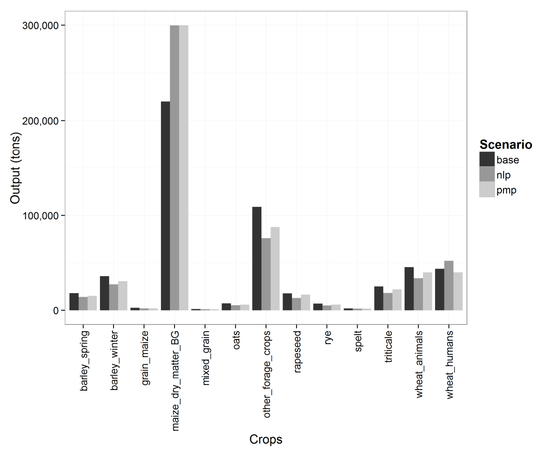

Figure 5. Comparing output (tons) under crops in base case to NLP and PMP models due to a shock of additional 80000 tons of maize.

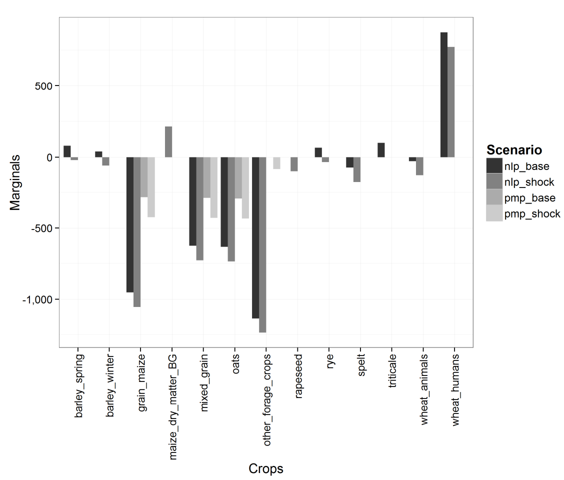

Figure 6. Comparing marginal product of area under crops in base case to NLP and PMP models due to a shock of additional 80000 tons of maize.

44.6%) and meadows (Cr18: 6.9%) account for over 50% of the total land use for agriculture. We notice that maize dry matter for bio gas (maize_dry_matter_BG) is an important crop accounting for 12.3% of the total area under cultivation in 2009.

The results from the calibration of the model using the PMP approach are shown in Table 7. Since one data point (year 2009) is available, a supply elasticity of 1.5 for all crops is used. The adjustment factor for each crop is given by $adj = price * yield / 2 * \eta$, where η is the supply elasticity. We increment λ by the minimum of all the *adj* values to obtain the final values of α and γ. It can be observed that the value of marginal product (VMP) for all crops is not the same, nor is it positive. The reason is that, at the prevailing prices in 2009, farmers had to face losses. The calibration of α and γ are based on those prices that lead to low values of λ. The calibretion in the PMP case works only when all crops show positive returns in the base case. As an experiment, the base price of all crops was uniformly increased until a positive VMP was obtained that was equal for all crops. This price level was 3.1 times the original price prevailing in 2009. The other option was to increase the subsidy per hectare from 330 € to 630 €, which also led to a uniform positive VMP for all crops in the base case, thus confirming the accuracy of the calibration procedure. For simulation purposes, we continue to maintain the original price and subsidy levels.

We run the scenario wherein there is no shock in terms of additional output of maize for biogas but permit changes in cropping area to maximise profit given the prevailing prices and subsidies in 2009. We also maintain the limits on maximum permissible changes to cropping areas to lie between 0.8 and 1.2. Table 8 compares the changes in output in the base case between NLP and PMP approaches for the scenario mentioned above. Changes to cropping area under crops Cr1 to Cr12 and Cr16 (rapeseed) were permitted, whereas no change was allowed for crops Cr13 (dried pulses), Cr14 (beans), Cr15 (potatoes), Cr17 (other crops), Cr18 (meadows), Cr19 (pastures), Cr20 (vineyards) and Cr21 (crops NES). The NLP model behaves as expected with an increase in area of those crops with positive marginal values as indicated by the column *Area.M* and reduction in area of crops with negative marginal values. The NLP model has endogenous fertilizer intensity thus to maximize profits, the yields and cost also change as shown in Table 9.

The NLP model shows that given the level of prices, the farmers would reduce fertilizer use, thus reducing yield and shifting land use for crops with the maximum marginal value. This movement is limited by the lower and upper limits of 20% as imposed by policy (SER, 2012). The PMP model, on the contrary, shows a smoother approach, muting changes in cropping patterns. This is largely on account of the calibration of the model. Had all crops generated profits in the base case, any change in the cropping patterns across crops would have been noticed. The base case prices that lead to losses for certain crops imply negative marginal values for land for those crops. Releasing one hectare of land under cultivation of these crops would lead to a gain in profits equal to the marginal value. As expected, these crops hit a lower bound of 80% of the original area under cropping and would have completely disappeared had not the bounds been in place. The main point of the discussion is that in a generic case for a country with a size much larger than Luxembourg, the average returns to crops would be positive and the PMP approach would work to reproduce the base case. For the case of NLP formulation, one

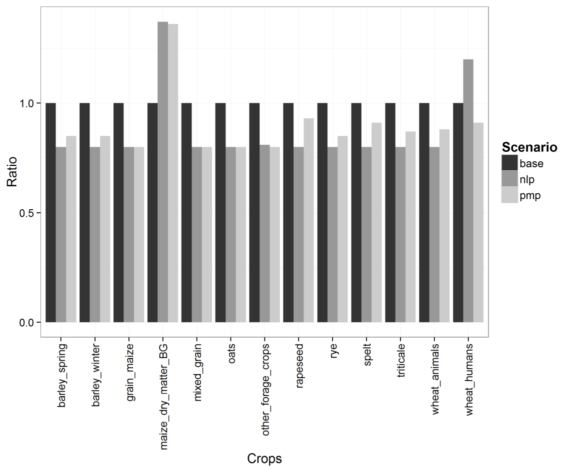

Figure 7. Comparing ratios of area under crops in base case to NLP and PMP models due to a shock of additional 80000 tons of maize.

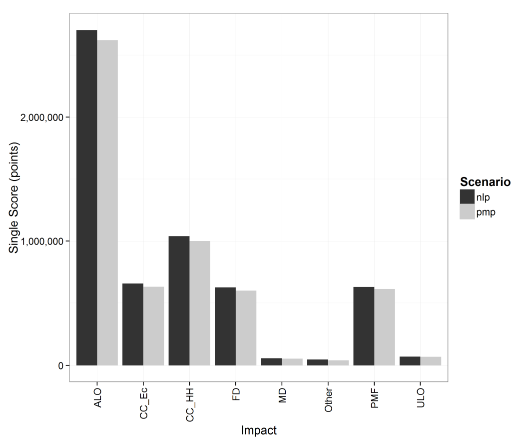

Figure 8. Single Score from CLCA of PMP and NLP models with a shock of additional 80000 tons of maize.

would have to artificially introduce constraints on the potential changes permitted in changes to cropping patterns. One could in principle introduce these constraints based on the cropping pattern changes from past observed data. In case the changes would hit a bound as exhibited by positive marginals, one would need to ascertain the veracity of these bounds.

3.2. Scenario Considering an Additional Demand of 80000 Tons of Maize

We now run a scenario in which the model undergoes a "shock" of an additional demand for maize destined to produce biofuel. The amount of this demand was calculated as 80,000 t of maize dry matter per year based on the 2020 target fixed for biogas production by the Luxembourgish Renewable Energy Action Plan (LUREAP) (Ministère de l'Economie 2010), as explained in Vázquez-Rowe et al., (2013). For both the approaches, the land change restrictions of maximum change of 20% on the upper or lower side are imposed. Figure 4 compares the areas in the base case to the area from NLP and PMP models after a shock of an additional output of 800 00 t of maize dry matter for bio gas (maize_dry_matter_ BG), while Figure 5 compares the output in tons for the same scenario. One finds that the NLP model tends to exhibit higher volatility of cropping areas and corresponding output. The output levels to a certain extent may be mitigated or accentuated with the response of yields to fertilizer inputs based on the expected price of the crop. Figure 6 compares the marginal product of the area under crop cultivation for the two models while Figure 7 shows the ratios of the new area to the base area for the NLP and PMP models. As one can infer the ratios are at the limits of 0.8 or 1.2 for the NLP model as expected, but are between the limits of 0.8 and 1.2 for the PMP model. This implies that the PMP model is more flexible and not prone to corner solutions. The marginal on the crop area also indicate the profitability of the crops due to the prevailing price and the NLP model shows higher extremes, implying a shift away from the existing crops. This extreme behaviour is typical of linear constraints wherein the only solution for profit maximisation is the complete absence of loss making activities. This kind of behaviour is not observed with PMP approach. As mentioned above, both models have restrictions on the maximum permissible land use change per crop to a lower limit of 80% and an upper limit of 120%. The NLP model behaves predictably with crops that exhibit negative marginal values to land show a fall in area. As additional maize is a necessity, the area of maize given the current yield increases by 37%. The PMP model is more muted in response with only a few crops that hit the lower and upper bounds. The main reason is that the cost of production is a function of the area under cultivation and changes in the area imply changes in cost and profits. The PMP model can be calibrated on a single data point, which has its potential limitations. Price shocks that lead to farming losses would lead to calibration of parameters that may not be representative of the agricultural system.

3.3. CLCA

As in Vázquez-Rowe et al. (2013), the ReCiPe endpoint method of Goedkoop et al. (2009) was applied to calculate the environmental impacts due to the variation of crops cultivation in Luxembourg, modeled by NLP and PMP approaches (see Figure 8). The single score impacts (expressed in points) aggregates the 18 impact categories of the LCIA method after normalization and weighting. The results show that the single score of both models is dominated by the effects on climate change (CC), particulate matter formation (PMF), agricultural land occupation (ALO), urban land occupation (ULO), metal depletion (MD) and fossil depletion (FD). All these impacts are mainly influenced by the production of maize for biogas production. Since this latter is higher with the NLP approach than with the PMP approach, better environmental performances are obtained with the PMP model (see Figure 8). Interestingly, the difference between the two scenarios is signifycant for human toxicity (26%) and terrestrial ecotoxicity (16%) even if these categories have a low contribution to the single score. This is mainly explained by the variation of wheat humans which is positive in the case of NLP and negative for PMP. The related impacts on human toxicity due to cadmium emissions to soil and on terrestrial ecotoxicity due to isoproturon emissions to soil have therefore a positive value for the NLP model and a negative value (corresponding to an envirnmental benefit) for the PMP approach. The difference for all other impact categories is comprised between 3% and 7%, which leads to a low overall difference on the single score of 3%.

3.4. Discussion

From the perspective of modelling, the NLP is a non-flexible model that needs constraints to be imposed to reproduce base data. These very constraints also prevent the model from greater deviations from the base case. PMP on the other hand is flexible and the base data (like elasticity) used to calibrate the model would lead to smooth solutions albeit sensitive to the original parameters. However, given the difference in best practices followed by farms and in the case of lack of data, PMP appears to be the most flexible approach to build models to simulate changes in agricultural system. Both models suffer from a supply-only approach to modelling. The lack of any demand system and the price discovery process for crops implies that a change in demand (fall or rise) would translate fully into an equal (increase or decrease) in supply. This however is not true and income and price effects do play a major role on demand. The incremental shock of change in crop output (here the increase in maize_dry_matter_BG and perhaps fall in output of other crops), would lead to price and income effects which would not be fully translated for further demand from neighbouring countries. Also the agriculture system works with a lag wherein farmers, based on expected future prices and profits undertake crop activities. The vagaries of nature and demand play a major role in determining spot prices. The farmers to a certain extent are isolated from the potential price volatilities if they enter into forward contracts regarding their crop output. To incorporate such conditions, the model could be subject to sensitivity analysis on the price to observe the changes in cropping patterns. In case of the NLP model, one would still continue to observe the solution at pre-specified boundaries while with the PMP approach the results would be smoother.

From the perspective of CLCA, the adoption of either model has profound implications for the results, wherein the changes in different outputs and inputs are important to evaluate the life cycle environmental impacts. As one can observe from the Figures 4, 6 and 7, even though the amount of additional maize is the same, the changes to cropping patterns differ substantially between the two approaches. This implies the CLCA results based on the marginal technology to produce one additional unit of demand would vary accordingly. This is however to be ascribed to the different decision contexts that can be tackled by CLCA and to the pertinence of NLP and PMP approaches to these. We can infer that the NLP approach is best suited for CLCA studies adopting a farmer's perspective, i.e. involving individual farms with detailed costs of operations and agents taking decisions based on the future expected price of produce (crop or animal). Conversely, the PMP approach is the fastest approach from a policy perspective and most likely data availability is a problem as we observe in the Luxembourgish case, wherein we have data by type of farm in the best case and at the aggregate national level in the worst case. Furthermore, calibration to the base case ensures that the changes to the system after shock would be reflective of the quality of the data used to calibrate the model in the first place. The NLP model shows larger changes in cropping area for the same change in maize as compared to the PMP model which is also reflected in the higher single scores for every impact category shown in Figure 8. The main contributor to the impact is the additional quantity of maize that is much larger as compared to other crops.

4. Conclusions

Two PEMs were built to analyse the cropping decision behaviour of farmers in Luxembourg, considering the entire farming sector of the country as a single large farm with aggregate farming and animal operations and analysing two different modelling approaches (NLP and PMP). The results of the economic modelling were fed to the LCA software SimaPro and the potential environmental impacts arising from the modelled scenarios have been calculated. For CLCA purposes, our recommendation is to use the LP approach when the decision context is centred on decision(s) involving individual farms, taking decisions based on the future expected price of produce (crop or animal). The PMP approach is recommended for policy-support contexts, involving data at higher level of aggregation (from average farm data to aggregated data at national level) and aimed at supporting stake-holders and policy makers.

Regarding the specificities and scope of the modelling for the Luxembourgish case study, it is worth remarking that inclusion of animals in a farming operation implies that crops with the highest net benefit per hectare are not always the ones to be preferred for growing, but crops that also have a lower market value and can be used as feed are important for the maximization of profits. The agrarian system in Luxembourg is insufficient to meet the demand for animal feed and has to rely on import of crops to meet this demand. The current policy, which prohibits changes to meadows and pastures for conversion into cropland especially for cultivation of maize destined to bioenergy production, is in the right direction. It leads to losses that need to be compensated by distortion mechanisms like subsidies.

The main limitation of the PEMs consists in the lack of a demand system to gauge the impact of changes in crop output due to changes in crop allocations resulting from additional maize for biofuels. We did not model the demand for additional import of feed due to a lack of information on the source, price and quantity of feed. Also from a modelling perspective, if the cost of imported feed is lower than the domestic cost, the whole feed will be imported. In order to ensure that the domestic feed is used first, further research should focus on introducing artificial constraints that would imply that the shortfall is covered by imports which remain undefined due to lack of data, which is the prevailing case.

Acknowledgments. The funding by the Luxembourg National Research Fund (FNR) under the project LUCAS (Indirect land use change effects in Consequential Life Cycle Assessment of bioenergy - C09/SR/11) is gratefully acknowledged.

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