ECONOMIC VIABILITY OF PHYTOREMEDIATION OF AN AGRICULTURAL AREA USING ENERGY MAIZE: PART I

IMPACT ON THE FARMER'S INCOME

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Opmerking [b1]: Deze paper ligt duidelijk in de lijn van onze CLO/MIP samenwerking – dus zou ook Prof. Tack vermelden

Met opmaak: Nederlands (standaard)

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Abstract

This paper deals with the economic viability of phytoremediation in a vast agricultural area moderately contaminated with heavy metals. The acceptance of phytoremediation as a remediation technique is, besides the extraction rate, determined by its profitability, more specifically by the effects it has on the income of the farmer whose land is contaminated. This income can be supported by producing renewable energy through anaerobic digestion of energy maize, a crop that does not only take up metals, but because of its large volume of biomass, is a feedstock to produce a substantial amount of energy. This paper performs an economic analysis concerning the growing of energy maize for phytoremediating purposes. The effect on the income per hectare of growing energy maize instead of fodder maize seems positive, given the most likely values of variables and while keeping stable the basic income, originating from the dairy cattle activities. Choosing energy maize as the phytoremediating plant can therefore be defined as choosing for relative income certainty/stability, and as such is facilitating the reclamation.

Key terms: Heavy metals-Campine-Agriculture-Sensitivity Analysis

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Opmerking [NW2]: Aan te passen

1 Introduction

European policy concerning land contamination converges to an integrated approach considering environmental, health, spatial, and economic aspects. Such an approach requires the design of solutions which take into account all these aspects simultaneously, indicated by the concept of 'Durable land management'. Our paper deals with the economic viability of phytoremediation.

Opmerking [b3]: Sustainable ?

However, the implementation of phytoextraction in the field has been constrained by the expectation that site remediation should be achieved in a time comparable to other more classical civil-engineering clean-up technologies. If phytoextraction could be combined with a revenue earning operation, then this time constraint, often considered as the Achilles heel of phytoextraction, may become less important. Cost recovery, and the appropriateness of including it as a plant selection criterion, is the subject of increasing current research. Especially the valorisation of the biomass has promising avenues a.o. as a 'renewable energy source' (Robinson et al., 2003). One of the key aspects to the acceptance of phytoextraction in agricultural areas pertains to its effects on the income of the farmers involved and the uncertainty this brings with. In this perspective, the economic viability is greatly supported by the valorisation of the resulting biomass (Vassilev et al., 2004).

From the end of the 19th century until mid 1970s, zinc and lead were refined at several locations in the north east of Belgium using a pyrometallurgical process (Vangronsveld et al. 1995; Hogervorst et al., 2007). This refining was done on the sites in Lommel, Overpelt, Hoboken and Olen. Metal fumes were condensed in a condensor, collected and transmitted to moulds. Volatile metal particles and vapour that were not collected in the condensor, condensated on dust particles and were emitted to the air via the smokestack. By consequence a large area is moderately contaminated due to atmospheric deposition of the dust with lead (Pb), zinc (Zn) and cadmium (Cd). These heavy metals can be found in the upper layer of the soil (30-40 cm) and reach a vast area, in the Belgian part of Limburg alone 280 km² (=28,000 ha) (Hogervorst et al., 2007). In our study, we will focus on the areas that are used for farming activities, not on the residential areas. In the area studied there are 233 farmers.

Belgian legislation prescribes that contamination from before 1995 should be remediated from the moment that contamination is serious and until a level where risk is restrained. If this is not possible without unduly high costs, destination has to be changed. The ultimate goal is risk confinement. By consequence, farmers are not obliged to remediate the land. They are however obliged to find safe applications for the contaminated land. In the first place, this is remediation/functional repair of the land at costs that are in proportion to the goal. If not possible, they have to look for an alternative function for their classic agricultural activities (Vlaamse Regering, 2006~~7~~).

The total metal contents found in the Campine region are not very high but nevertheless they impose a risk, mainly due to the sandy and acidic character of the soil (Alkorta et al., 2004). The metals are taken up by the crops cultivated by the farmers and consequently appear in the food chain. This occurs either by direct human consumption of vegetables or indirectly through consumption of fodder (grown on the contaminated soil) by cattle (metals accumulate in liver and kidneys). Maize grown in the region cannot be used as a fodder because the metal content exceeds the legal threshold value for feeding purposes. For fodder maize, norms for Cd and Pb lie respectively at 1 and 10 mg kg^{-1} dry matter (DM) (Demotte, 1999).

At this moment there are not yet legal restrictions or obligations for the farmers in the Campine, but this might change in the future. This uncertainty imposes a serious risk to the profitability of the farming industry (McGrath et al., 2001).

When choosing the remediating plant, one has to keep in mind the social acceptability of phytoremediation by the farmer. In the Campine region, farmers are used to grow maize as fodder for dairy cattle and they may be sceptical about growing willow or rapeseed. Moreover, one has to take into account the drought resistance of the plant, the disease resistance, the ease of harvesting… Factors ~~like~~ such as local soil conditions and climate are important. Maize has optimal growing conditions on the sandy soils in the Campine at a pH between 5.0 and 6.0 (De Boer et al., 2003. ~~).~~ ~~Finally, what metal has to be taken up by the plant? The plant with the highest uptake can be chosen as the remediating plant~~Plant selection also depends on the target metal requiring extraction, and the plants

Opmerking [b4]: Flemish government

Opmerking [b5]: Heeft deze ook op de Kempen gewerkt ?

Opmerking [b6]: Is eigenlijk te sterk – voedermais heeft het risico Europese normen te overschrijden, maar is dus geen verbod op teelt in de regio such as is

Opmerking [b7]: Heeft Demotte een uitspraak gedaan over teelten in de Kempen

Opmerking [b8]: Beetje rare zin om hier tussen te gooien.
Mss. vervangen door:
"Plant species selection also depends on the target metal requiring extraction.

Opmerking [b9]: Uptake is product van concentratie en biomassa. Ik denk dat je hier concentratie bedoelt ?

affinity to take up this metal. Hyperaccumulating species such as, *Thlaspi caerulescens* have been suggested for extraction of Cd and Zn (Chaney et al. 1997).. However, ~~In general,~~ hyperaccumulator plants generally do not produce ~~a lot of~~sufficient biomass to allow rapid and efficient remediation.~~,~~ ~~e.g. *Thlaspi caerulescens* J&C Presl. (Alpine Pennycress), a hyperaccumulator of Cd and Zn (Chaney et al., 1997; Garbisu, Alkorta, 2001).~~ ~~Is it possible to recycle the metals? In that case it might be evident to concentrate the metals and choose for hyperaccumulators (Li et al., 2003).~~

To make phytoextraction of cadmium and or zinc economically feasible, the plants will be used for energy purposes. Possible first generation conversion techniques are anaerobic digestion, combustion, pyrolysis, pressing and gasification. Not every plant is suitable for every technique.

Against this background we opt to investigate the economic viability of energy maize, a crop with low metal uptake capacities, but which has the advantage to produce a high biomass (leading to a moderate absolute extraction/accumulation) and is well known by the local agricultural sector. Energy maize is *Zea mays* used for ~~-~~energy production purposes rather than for conventional applications as food or feed. In Europe, production of energy maize is increasing rapidly, used for conversion into biogas through anaerobic digestion.Specific *Zea mays* cultivars are being selected / bred for optimal biogas production potential, much in the way conventional cultivars were selected for their nutritive characteristics. As such energy maize and biogas production represent a new branch of agriculture, which has emerged at large scale over the last five to ten years.

The 233 farmers involved are mostly dairy cattle farmers who wish to continue their current activities. On average they have an acreage of 40 ha, consisting of 20 ha grass and 20 ha fodder maize to feed their dairy cattle. Their basic income comes mostly from selling milk (Federale Overheidsdienst Economie, 2006). By growing energy maize instead and buying fodder maize outside the contaminated area, the basic income of the farmer will remain and will be supplemented with income from phytoremediating and energy activities (anaerobic digestion). The cost of phytoremediation consists of the necessity to purchase fodder maize, now substituted by energy maize.

Our approach consists of two scenarios. In the first scenario, farmer and digester are separate entities. The cost of phytoremediation for the farmer has to be compensated by revenues coming from

Met opmaak: Lettertype: Cursief

Opmerking [b10]: Ik ben er niet zo zot van om vragen in een manuscript te introduceren.

Opmerking [b11]: Verwarring met first generation biobrandstoffen ? Ik weet niet of deze technieke first generation genoemd worden – je dekt ongeveer volledige lading met deze technieken.

Opmerking [NW12]: Hier verwacht men uitleg wat energiemaïs onderscheidt van voedermaïs

Met opmaak: Lettertype: Cursief

Met opmaak: Lettertype: Cursief

Opmerking [b13]: Er zijn wel beduidend meer dan 233 boeren in de Kempen…

Opmerking [NW14]: Meer info over hun activiteiten, heb ik gedaan in de volgende zin selling energy maize. In the second scenario, farmer and digester are one entity. The cost of phytoremediation now has to be compensated by revenues coming from energy maize sold to the farmer's digester. Extra revenues can then be generated by the digestion activity. This scenario is elaborated in part II of this study.

This paper focuses on the first scenario and calculates the impact on the revenue of the dairy cattle farmer originating from the phytoremediation activities. To take into account the uncertainty involved, sensitivity analyses are performed for several variables.

2 Results and discussion

2.1.1 Maize and heavy metals

Although some authors report that in comparison to other plant species, maize is a rather good accumulator of Pb ((Garbisu et al., 2001; Chrysafopoulou et al., 2005), most authors find that it does not actively take up trace metals (Zhang & Banks, 2006). In a comparison of four agronomic crop species grown on Campine soil (*Zea mays*, *Helianthus annuus*, *Brassica rapa*, *Cannabis sativa*) maize was found to take up the lowest amounts of Cd, Pb and Zn (Meers et al., 2005a). Metal uptake and accumulation in aboveground harvestable plant parts can be significantly enhanced by increasing metal phytoavailability within the rhizosphere, such as by application of mobilising agents to the soil. Increasing metal mobility within the top soil layer can only considered if risks associated with leaching can be sufficiently addressed (Meers et al., 2004). Degradable compounds such as EDDS have been proposed in this regard (Meers et al., 2005b). An overview on chemically enhancing phytoextraction efficiency, ~~Maize does not actively take up certain metals (Zhang, Banks, 2006). Pot experiments in the Campine confirm this for Cd, Pb and Zn (Meers et al., 2005; Garbisu et al., 2001). Compared to other plants, maize is although a rather good accumulator of Pb (Garbisu et al., 2001; Chrysafopoulou et al., 2005). The extraction of metals by maize can be enhanced, more on this~~ can be found in Do Nascimento and Xing (2006), Meers et al. (~~2005~~2008) and McGrath et al. (2001).

Met opmaak: Niet Markeren

Opmerking [b15]: Referentie niet in referentielijst

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Opmerking [NW16]: Hier moest ik voorzichtig zijn: maïs is geen exckuder want there are certainly active uptake mechanisms for essential trace elements as Fe, Zn and Cu. <for non-essential elements such as Cd the lack of an active uptake mechanism does not imply that the plant is an excluder.

Opmerking [NW17]: Please describe briefly how it can be enhanced

Although metal accumulation by maize can be chemically enhanced, phytoextraction as a remediation tool will still take an extensive period of time (years to decades). That is why alternative use and valorisation of the produced biomass, rather than consider it as a waste-product of soil remediation, may become a prerequisite for field-scale application of phytoextraction as a remediation technique (Meers et al., 2005c; 2006; 2007). If produced phytoremediation biomass can be valorised into an alternative farmer income, then the main drawback of phytoextraction, namely the extended remediation period required, may become invalid and slower working phytoremediation schemes based on gradual attenuation of the contaminants rather than short-term forced extraction may be envisaged. In this regard, our group has initiated a number of research projects based on the cultivation of industrial non-food crops on contaminated land, with a distinct focus on renewable energy crops (Meers et al., 2007; Van Ginneken et al. 2007);

The biomass production of energy maize on the trial field in the Campine is 20 ton DM ha^{-1} ~~(table 1)~~, ~~metal concentrations found in the different parts are rather low (table 2), resulting in a moderate extraction rate. In table 3, the remediation duration is given for energy maize, compared to Short Rotation Coppice and rapeseed, two other remediating crops grown on the site in the Campine. Energy maize is the second best extractor.~~. ~~-~~Combined with the acceptance of the farmers (maize being a conventional crop) and the economic opportunities for non-food applications, this offers an incentive to study this crop more in detail.

~~TABLE 1: BIOMASS PRODUCTION FOR THE DIFFERENT PARTS OF ENERGY MAIZE IN T HA^{-1} AND THEIR M%, BOTH MEASURED FOR FRESH MATERIAL (FM) AND DRY MATERIAL (DM), ON THE METAL CONTAMINATED TRIAL FIELD IN THE CAMPINE (HARVEST IN 2007)~~

~~Energy maize~~	~~FM~~		~~DM~~	
	~~m%*~~	~~t ha^{-1}~~	~~m%~~	~~t ha^{-1}~~
~~Grain, rachis and bract~~	~~45~~	~~27~~	~~55,5~~	~~11,1~~
~~Leaves and stem~~	~~55~~	~~33~~	~~44,5~~	~~8,9~~
~~Total plant~~	~~100~~	~~60~~	~~100~~	~~20~~

~~*m%: this percentage indicates the relative contribution of the various plant parts to the total biomass produced~~

~~Source: Van Slycken, 2008~~

Opmerking [NW18]: Dit mag ik enkel zetten indien er een publicatie is of 'in press' is, anders moet ik dit weglaten, idem voor de andere tabellen

Met opmaak: Engels (Groot-Brittannië)

~~TABLE 2: CONCENTRATION RANGES IN MG KG^{-1} DRY MATERIAL BY DIFFERENT PARTS OF MAIZE (BETWEEN BRACKETS THEIR M%) OF CD, ZN AND PB ON A METAL CONTAMINATED FIELD IN THE CAMPINE (HARVEST 2007)~~

~~Energy maize~~	~~Cadmium~~	~~Zinc~~	~~Lead~~
~~Grain~~	~~0,24~~	~~58~~	~~0,13~~
~~Rachis~~	~~0,34~~	~~149~~	~~0,70~~
~~Bract~~	~~0,68~~	~~256~~	~~2,75~~

Stem	1,26	337	2,60
Leaves	3,20	481	12

~~Source: Van Slycken, 2008~~

Opmerking [NW19]: Idem, enkele indien gepubliceerd of in press

Met opmaak: Engels (Groot-Brittannië)

~~TABLE 3: EXTRACTION OF CD TO REDUCE CONCENTRATION IN SOIL FROM 2 TO 1,2 MG KG^{-1} BY THE ENERGY MAIZE, SHORT ROTATION COPPICE AND RAPESEED, AS MEASURED ON THE TRIAL FIELD IN THE CAMPINE~~

Properties soil	Specific weight sandy soil (ton m^{-3})	Depth (m)	Weight of 1 ha sandy soil (ton ha^{-1})		
	1.6 [(1)]	0.3	4,800		
Contamination	Concentration Cd (mg kg^{-1})	Concentration Cd (kg ha^{-1})	Goal Cd (mg kg^{-1})	Goal Cd (kg ha^{-1})	Remediation Cd (kg ha^{-1})
	2 [(2)]	9.6	1.2 [(2)]	5.76	3.84
Remediation	Biomass production (kg DM ha^{-1})	Concentration Cd (mg kg^{-1})	Extraction Cd (kg ha^{-1})		Duration (years)
Energy maize	20,000 [(3)]	0.24-3.2 [(6)]	0.022 [(7)]		176
Short Rotation Coppice	6,000 [(4)]	25 (shoot) 40 (leaves)	0.120 [(4)]		32
Rapeseed	5,200 [(5)]	0.81 (seeds) 5.27 (green parts)	0.014		246 [(8)]

Met opmaak: Engels (Groot-Brittannië)

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Met opmaak: Engels (Groot-Brittannië)

~~(1) Livios (2008)~~

~~(2) Vlaamse regering (20077)~~

~~(3) See table 1~~

~~(4) Only shoots (80 m%= 4,800 kg DM ha^{-1}) are removed~~

~~(5) Based on literature due to low harvest yield: seeds (DM 90%): 3,000 kg DM ha^{-1}; green parts: 2,200 kg DM ha^{-1} (Beleidsdomein LaAndbouw en Visserij, 2005)~~

~~(6) See table 2~~

~~(7) Based on table 1 and 2~~

Met opmaak: Engels (Groot-Brittannië)

(8) ~~Rapeseed is grown in rotation with fodder maize, one year of rapeseed is followed by two years of fodder maize with an extraction of 0.016 kg ha^{-1}~~

Met opmaak: Engels (Groot-Brittannië)

2.2 Economics of energy maize used for phytoremediation

2.2.1 Farmer and digester are separate entities: Effect on the income of the farmer

2.2.1.1 Deterministic approach

The social acceptance of the phytoremediating activity is amongst others determined by its profitability, i.e. the effect it has on the income of the farmer. In this paper, we assume that the farmer will grow energy maize instead of fodder maize while continuing his dairy cattle farming activities and while selling milk products at the same level as before. Based on data from the yearly agricultural survey, we estimate the average acreage per farm in the contaminated area at 40 hectares. Thereof, the farmer will only use 50%, this is 20 ha, to grow fodder maize. The other 20 ha is used as grassland for the cows (Federale Overheidsdienst Economie, 2006; own calculations). When the farmer converts to energy maize, he will maintain this proportion to be able to continue his dairy cattle activities.

Opmerking [b20]: Geen probleem met metaalopname door gras ?

Therefore he needs the same amount of fodder maize as before. We also assume that the cost per hectare of growing energy maize is the same as the cost of growing fodder maize. These conditions are necessary for our assumption that the reference basic income per hectare of the farmer stemming from dairy cattle rearing (€ 1,123 ha^{-1}) does not change. The reference basic income will then be supplemented or reduced with the phytoremediation activities.

TABLE 41: COMPARISON OF CURRENT ECONOMIC SITUATION WITH THE ECONOMIC SITUATION DURING REMEDIATION (GROWING ENERGY MAIZE)

Situation before remediation	**Situation during remediation**
Growing fodder maize *(mF)* at cost *C* per hectare (ha) Selling milk products at price *M*	Growing energy maize *(mE)* at cost *C* per hectare (ha) Selling milk products at price *M* Buying fodder maize *(mF)* at price *P* Selling energy maize *(mE)* at price *P* Transport cost of energy and fodder maize per ton per kilometer *(T)* Support for energy crops *(S)*

As can be seen in table 41, reclamation of the soil is economically viable only if revenues from selling energy maize exceed the cost of buying fodder maize. This ~~is dependent~~depends on the yield of fodder and energy maize, their prices and the transport cost. In this study we will use a most likely fresh yield of 50 and 60 tons per hectare respectively for fodder and energy maize. Fodder maize (DM 30%) has a fresh yield *(mF)* of 50 tons ha^{-1} (assumed constant, given the assumption of feeding the same number of animals as before). Energy maize (DM 30%) has a fresh yield (*mE*) of 60 tons/ha (most likely value in the base case).

~~The maize price is volatile due to a high demand for biomass for energy purposes (a.o. in Germany).~~ In September 2007, farmers receive a price between € 1,800 and 2,000 ha^{-1} for their fodder maize, depending on the yield[2]. Given the 60 tons yield per ha, we assume the price per ton fresh material *(P)* in the base case at € 30 ton^{-1}. The production cost of maize is approximately € 1,200-1,250 ha^{-1} (De Boer et al., 2003). At a most likely fresh yield of respectively 50 and 60 tons per hectare, fodder and energy maize will not be sold below € 24-25 ton^{-1} FM and € 20-21 ton^{-1} FM

Opmerking [b21]: Hoe vertaalt zich dit met de 20 t/ha DM uit uw vorige paragraaf ?

Opmerking [b22]: Compleet fout

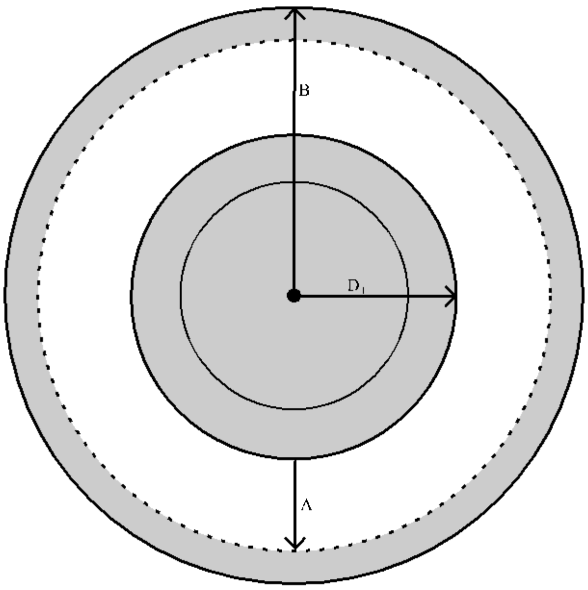
Opmerking [b23]: Jef Maesen personal communication is geen geldige referentie

[2] Maesen, Boerenbond, Personal communication, 17.09.2007

respectively. The energy maize will be sold immediately, this means that no extra ensiling is necessary.

Transport costs are studied separately as total transport costs differ for energy and fodder maize. This is explained in figure 1. We assume that the digester is geographically located in the centre of the region occupied by the cooperating farms (indicated by the two grey concentric circles in the middle). Energy maize sold by the farmers has to travel an average two-way distance *(D_1)* to the centre of the circle formed by the cooperating farmers, where the digester will be installed. Fodder maize bought by the cooperating farmers has to travel a longer average distance *($D_2 = (A+B)/2$)*. It has to come from the uncontaminated zone (the grey circle surrounding the contaminated zone), outside the polluted area of 280 km² (indicated by the area within the dotted lines). Calculations for D_1 and D_2 can be found in Appendix 1. Given the transport cost per ton per kilometer (T), the total transport costs are then calculated as: (i) for energy maize: $Te = D_1 * T * mE$; and (ii) for fodder maize: $Tf = D_2 * T * mF$.

FIGURE 1: STYLIZED REPRESENTATION OF TRANSPORT DISTANCES IN THE CAMPINE CASE STUDY



As a result, the extra revenue *(R)* from energy and remediation activities per hectare, including the compensation for transport costs, is given by the following formula:

$R = P*(mE-mF) + S + (D_1*T*mE*H - D_2*T*mF*H)/H$

$R = (P+D_1*T)*mE - (P+D_2*T)*mF + S$ (Eq. 1)

With:

P = price of fodder and of energy maize per ton fresh material (€ ton^{-1} FM)

mE and mF = yield of energy and fodder maize respectively, per hectare (ton FM ha^{-1})

S = the energy premium per hectare (€ 45 ha^{-1})[3].

T = transport cost per ton per kilometer (€ ton^{-1} km^{-1})

H = total number of ha remediated (number of participating farmers * 20 ha)

If the extra revenue, R, is positive, the income of the farmer is raised due to the remediation activities. When R is negative, the income goes down due to the remediation activities.

In what we will call the "base case", we assume the following numerical values for the determining variables: H= 300 ha, mE= 60 ton ha^{-1}, mF= 50 ton ha^{-1}, T= € 0.5 ton^{-1} km^{-1}, P= € 30 ton^{-1} and S = € 45 ha^{-1}. According to Eq. 1 we then arrive at a net result for the farmer of R= € 166.5 ha^{-1} remediated. This result is conditioned by the implicit assumption that all the determining variables are measured with full certainty, leading to only one numerical value for each of them. In reality though, all these variables have numerical values belonging to a range, i.e. we have to take account of uncertainty in calculating the extra revenue R. Therefore, Monte Carlo simulations using the model are performed.

[3] Due to the transition of fodder maize to energy maize, the farmer receives an extra support for growing energy crops of maximum € 45 ha^{-1} from the Agency for Agriculture and Fisheries (Agentschap voor Landbouw en Visserij, ALV). Thereto, the energy production does not have to occur on the site of the growing farmer (Put, ALT, Personal communication, 9.06.2007; Biogas-E vzw, ODE, 2006).

2.2.1.2 *Taking into account uncertainty*

The Monte Carlo technique calculates numerous values for the net extra revenue *R*, based on different values of the determining variables. For the latter we presuppose a minimum, maximum and most likely value (table 5). Consistent with these assumptions, the probability distributions of the variables have a triangular shape. The value for a specific determining variable is then obtained as a randomly drawn value from a triangular distribution. The most likely value is the value from the base case. Minimum and maximum values form a range of ±10% starting from the most likely value. The yield of energy maize does not follow this distribution. In the base case, we assume that energy maize has a minimum which is the same as the yield of fodder maize, the most likely value is 20% better and the maximum value is 30% better. Prices for energy and fodder maize are assumed equal. In the Monte Carlo simulations we weaken this assumption. We assume that changes in both prices are correlated according to a correlation coefficient of +0.5. This means that in 50% of the cases run during the simulations, the price of energy and fodder maize move in the same direction.

TABLE 5: BASE CASE VALUES OF THE DETERMINING VARIABLES AND FORECAST RESULT FOR THE EXTRA INCOME OF THE FARMER, ALL WITH A ± 10% RANGE, ACCOUNTING FOR UNCERTAINTY

	(1)	(2)	(3)	(4)
	Determining Variable	**Min**	**Most likely**	**Max**
(1)	*H* (number of hectares occupied by energy maize)	270	300	330
(2)	*T* (transport cost in € ton^{-1} km^{-1}	0.45	0.5	0.55
(3)	*P* (price of fodder maize in € ton^{-1} FM)	27	30	33
(4)	*P* (price of energy maize in € ton^{-1} FM)	27	30	33
(5)	*mE/mF* (relative yield of energy to fodder maize)	1	1.2	1.3
	Forecast	**Min**	**Most likely**	**Max**
(6)	Extra income for the farmer (€ ha^{-1} remediated)	-303.4	113.8	505.5

Given these assumptions, indicated as the 'base case', the average extra revenue per hectare is € 113.8. Compared with the revenue before remediation (i.e. € 1,123 ha^{-1}), this is an increase of more than 10%. Moreover, there is no longer uncertainty concerning the metals that might be accumulated in liver and kidneys. The probability that the average extra revenue per hectare is not negative – meaning that the farmer's income will not decrease – is 82.6%. The minimum extra revenue is € -303.4 ha^{-1}; the maximum extra revenue is € 505.5 ha^{-1}.

Monte Carlo sensitivity analysis shows the relative importance of the different variables in explaining the variance of the extra income (table 6). The first variable, the yield of energy maize, accounts for approximately 81.3% of the variance in forecast values of the extra income *R*.

TABLE 6: EXPLANATION OF THE VARIANCE OF THE EXTRA INCOME (*R*)

	Variable	**Contribution to the variance of R**
(1)	*mE* (yield of energy maize)	81.3%
(2)	*P* (price of energy maize)	13.4%
(3)	*P* (price of fodder maize)	-4.9%

Table 6 should be interpreted as follows. A larger yield of energy maize per hectare has a large positive impact on *R* (row 1). It is obvious that the price of energy maize has a similar – although smaller – positive effect (row 2). If the price of fodder maize rises, the expenditure for externally buying increases (row 3). The price of energy maize is more important than the price of fodder maize as energy maize involves more tons ha^{-1}.

2.2.2 Analysis

The extra income for the farmers (*R*) was calculated according to Eq. 1 above. To take into account uncertainty, the numerical values of the determining variables were described by ranges (table 5). The latter were characterized by an assumed probability distribution around a most likely value (table 5, column 3) for the specific determining variable (the so-called 'base case' values).

Now we investigate what the effect will be of significantly changing this most likely value - and accordingly its surrounding range - on the amount of the farmer's extra income and on the probability of obtaining a positive extra income. We focus on the sensitivity of the extra income by changing the most likely values of the yield of energy maize in tons FM per hectare (*mE*) – paragraph 2.2.2.1, table 7, and the price per ton fresh material (*P*) of energy and fodder maize – paragraph 2.2.2.2, table 8. In paragraph 2.2.2.3, table 9, we will discard the assumption that fodder and energy maize have an equal price. This means that prices of fodder and energy maize can move in opposite directions. This happens in the context of determining the minimum price of energy maize, (i) consistent with the condition that the probability of obtaining a positive extra income coming from the remediation activity is at least 90%, and (ii) given the values of the base case for the price of fodder maize and the other variables (table 5). This part of the analysis is motivated by the fact that the energy maize is contaminated. This might have a negative effect on its price. Finally, as the international cereal market is very volatile at this moment, we wonder what happens with the farmer's income when the price of maize goes up or down.

2.2.2.1 Sensitivity of the farmer's income to the relative yield of energy and fodder maize

TABLE 7: AVERAGE EXTRA INCOME PER HECTARE *R* (€ HA^{-1}) AND PROBABILITY OF A POSITIVE EXTRA INCOME (PROB(*R*>0)), GIVEN CHANGES IN THE RELATIVE YIELD OF ENERGY AND FODDER MAIZE (*ME/MF*), CETERIS PARIBUS

	Scenario	**Variable**	**Min**	**Most likely**	**Max**	**Average *R***	**Prob(*R*>0)**
(1)	Pessimistic	*mE/mF*	1	1.1	1.2	12.5	55.0%
(2)	Base case	*mE/mF*	1	1.2	1.3	113.8	82.6%
(3)	Optimistic	*mE/mF*	1.1	1.2	1.3	166.5	96.5%

In the base case (row 2), as calculated before, the probability of a positive extra income per hectare is 82.6%, with an average extra revenue per hectare of € 113.8. In row (1), the relative yield of *mE* and *mF* is changed in a negative way compared to the base case. Energy maize has a fresh yield that is at best 20% higher than that of fodder maize (in the base case energy maize can do 30% better than fodder maize). Keeping *mF* at the value of the base case (50 ton ha^{-1}), *R* goes down to € 12.5 ha^{-1}, a reduction with 89%! In row (3), the minimum yield of energy maize lies at least 10% higher than fodder maize. This has a positive impact on the extra revenue per hectare, which is now € 166.5 ha^{-1}, a raise of 46% compared to the base case. We can conclude that it is only economically justified to grow energy maize when the most likely value for the yield of energy maize per hectare lies 20% higher than the yield of fodder maize, accompanied by a maximum yield of energy maize that lies 30% higher.

2.2.2.2 Sensitivity of the farmer's income to the price of energy and fodder maize (P)

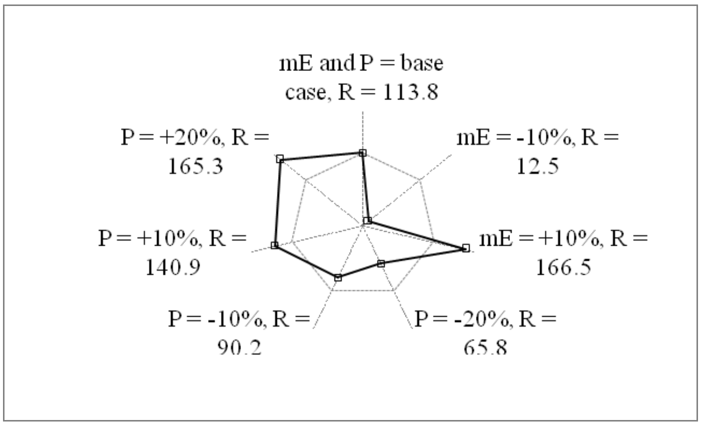
TABLE 8: AVERAGE EXTRA INCOME PER HECTARE *R* (€ HA^{-1}) AND PROBABILITY OF A POSITIVE EXTRA INCOME (PROB(*R*>0)), GIVEN CHANGES IN THE PRICE OF ENERGY AND FODDER MAIZE - ASSUMED EQUAL (*P* IN € TON^{-1} FM), CETERIS PARIBUS

	***P*(maize)** (€ ton^{-1})	**Average *R*** (€ ha^{-1})	**Prob(*R*>0)**
(1)	24 ±10%	65.8	75.2%
(2)	27 ±10%	90.2	79.8%
(3)	30 ± 10%	113.8	82.6%
(4)	33 ± 10%	140.9	85.9%
(5)	36 ± 10%	165.3	87.3%

In table 8, the price of maize per ton is equal for energy and fodder maize. In the base case *R*= € 113.8 ha^{-1} and Prob(*R*>0) = 82.6% (row 3). As a minimum price we assume € 24 ton^{-1} fresh material which is equal to the production cost per ton for fodder maize. As can be seen, a change in price does not have a large effect on the probability of a positive extra revenue coming from the phytoremediation activities. When the farmer grows energy maize, he has a fair chance to sustain and even increase his income, depending on the height of the prices (assumed equal for energy and fodder maize), within the assumed range of € 24 to € 36 per ton FM.

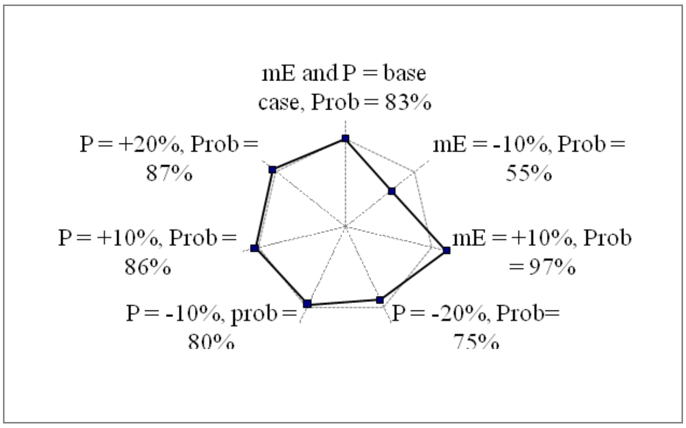
Comparing table 7 and 8, it seems that *R* is much more sensitive to changes in the relative yield *mE/mF* than to changes in the price of maize. This is shown in figure 2 (the axes show the value of the extra income per ha for changes in the different determining variables). Let's not forget that when *P* increases, revenue augments, this however is to a large extent neutralized by the larger expenses for fodder maize.

FIGURE 2: AVERAGE EXTRA INCOME PER HECTARE (*R*) WHEN MOST LIKELY VALUES OF PRICES OF MAIZE (P) AND RELATIVE YIELD (ME/MF) ARE LOWERED OR AUGMENTED WITH 10-20%, CETERIS PARIBUS, COMPARED TO THE BASE CASE



The same conclusions (but to a lesser extent) can be reached by comparing the effect of changes in the relative yield *mE/mF* and in the price of maize on Prob(*R*>0), as shown in figure 3 (the axes show the probability (%) of a positive extra income for given changes in the different determining variables).

FIGURE 3: SENSITIVITY OF THE CHANCE ON POSITIVE EXTRA INCOME (PROB(*R*>0)) WHEN MOST LIKELY VALUES OF PRICES OF MAIZE (P) AND RELATIVE YIELD (ME/MF) ARE LOWERED OR AUGMENTED WITH 10-20%, CETERIS PARIBUS, COMPARED TO THE BASE CASE



Evaluating both figures 2 and 3 together, we can say that changes in *mE/mF* lead to high uncertainty (i.e. low probability on a positive income): they can generate high revenues accompanied by a high certainty level, but they also can lead to very low revenues with a low certainty level. Price changes, on the contrary, keep the income more stable and do not lead to a much lower probability of a positive income.

2.2.2.3 Determining P(energy maize), given P(fodder maize) such that Prob(R>0)≈ 90%

We now discard the assumption that fodder and energy maize have equal prices and determine the minimum price of energy maize, given a price of fodder maize and values for the other variables as in the base case (table 4). The prices calculated for energy maize have to assure that the probability of a positive extra income coming from growing energy maize is very high (≈ 90%).

The yield of fodder maize is kept fixed at 50 tons ha^{-1}. The yield of energy maize (relative to the yield of fodder maize) is indicated by the different lines on figure 4. The price of fodder maize is indicated on the X-axis. By considering several values for these variables, we can calculate the price of energy maize that renders the chance to obtain a positive extra revenue per hectare ≈ 90%. This means that the income of the farmer during remediation would remain at least at a status quo relative to the situation before remediation. Table 8 shows for the base case how figure 4 is determined.

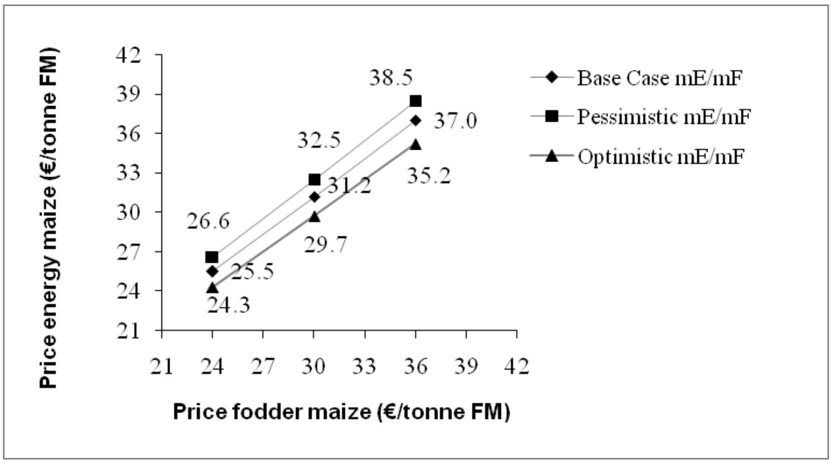
TABLE 9: CALCULATING THE ENERGY MAIZE PRICE, GIVEN *MF*=50, *ME/MF* AS IN THE BASE CASE, FOR DIFFERENT P(FODDER MAIZE), TO HAVE A PROB(*R*>0) ≈ 90%

	(1)	(2)	(3)	(4)
	***P* (fodder maize) (€ ton^{-1}, given)**	***P* (energy maize) (€ ton^{-1}, calculated)**	**Average *R* (€ ha^{-1}, calculated)**	**Prob(*R*>0)**
(1)	24 ±10%	25.5 ± 10%	151.2	90.3%
(2)	30 ± 10%	31.2 ± 10%	183.9	90.2%
(3)	36 ± 10%	37 ± 10%	223.6	90.6%

In table 9, we calculate the price range of energy maize (column 2) to have at least a 90% probability of a positive *R* (column 4), given a price range of fodder maize (column 1), when *mE/mF* = 1.2 as in the base case. This is done for three price ranges of fodder maize (rows 1, 2 and 3), resulting in three price ranges for energy maize. From table 9, it can be concluded that taking into account the base case values for *mE/mF*, the price of energy maize has to lie at least € 1 ton^{-1} higher than the price of fodder maize (compare columns 1 and 2). If the level of prices is lower, the difference between prices of fodder and energy maize has to be larger. If the level of prices is higher, this obviously increases *R* (column 3, rows 1, 2 and 3).

In figure 4, each curve represents a different scenario for the relative yield of energy to fodder maize, resulting in different levels of the necessary prices for energy maize to reach a probability of 90% that the farmer's income will not decrease. The results for the base case scenario (*mE/mF* = 1.2) which were presented in table 9, column 2, are found on the middle curve in fig.4. Such results are recalculated for a pessimistic and optimistic scenario for *mE/mF; mF*= 50 and the same price ranges for *P*(fodder maize) as in table 9.

FIGURE 4: DETERMINATION OF ENERGY MAIZE PRICE, GIVEN A FODDER MAIZE YIELD OF 50 TON FM, TO HAVE AN ALMOST CERTAIN POSITIVE EXTRA INCOME (PROB(*R*>0) ≈ 90%), AND DIFFERING ACCORDING TO THE RELATIVE YIELD OF ENERGY MAIZE TO FODDER MAIZE (*ME/MF*) AND FODDER MAIZE PRICE



From figure 4 it is clear that the necessary price of energy maize is dependent on its yield relative to the yield of fodder maize. Comparing the values for the price of fodder maize on the horizontal axis with the corresponding values for the necessary price of energy maize on each of the three curves, we have an idea of the necessary price difference. In the pessimistic scenario, the difference between energy and fodder maize prices has to be at least € 2.5 ton^{-1} FM (38.5-36) to have an almost certain positive extra revenue *R*. In the base case scenario, this minimum difference is lowered to € 1 ton^{-1} FM (37-36). In the optimistic scenario, the price of energy maize can even be € 0.8 ton^{-1} FM lower (35.2-36). If the farmer does not receive these calculated prices (for reasons stated before), the probability of a positive *R* will be smaller than 90%, so chances are growing that the phytoremediation activity might reduce the income of the farmer. In that case he needs to receive a compensation for his engagement in the reclamation of the soil so that his income can be kept at a level equal to the situation before remediation.

2.3 Discussion

For now, we assume that the biomass conversion installation will be situated in the centre of the contaminated area. The cooperating farmers are located around this installation. Fodder maize comes from outside the contaminated area of 280 km², conceived as a circle. The area with fodder maize surrounds the contaminated area as a concentric circle. These assumptions have an impact on transport distances (D_1 and D_2) and therefore on costs. In the future, data are needed on the differential degree of contamination of the area, the location of the farmers within this area and the location of farmers that grow fodder maize outside the area. The total transport distance of maize is determined using an average between the minimum and maximum distance. This could however be done by a continuous transport function, using an integral over the minimum and maximum distance. Moreover, we assume the transport cost per ton per kilometer (T) to be independent of the distance.

3 Conclusions

To date, most efforts have been concentrated on conquering the technical, agronomic and biological challenges involved in delivering phytoremediation as a working technology and in speeding up the rate at which phytoremediation occurs, and this mostly on a laboratory scale. The financial cost however is an often forgotten aspect in designing a remediation project. In the case of vast areas, although only moderately polluted, the economic aspect indicates the opportunity for the low cost phytoremediation technique. In choosing energy maize one opts for a long term scenario. It is a choice for durable land management instead of remediation pur sang. We started from the necessity that the farmer wants to perpetuate his revenue from dairy cattle activities. He keeps growing maize at the same cost, but energy maize instead of fodder maize. The energy maize is sold and can be used for energy production, namely for anaerobic digestion. To feed his cattle, fodder maize is bought from a region outside the contaminated area.

In relevant literature, the whole economic picture of phytoremediation is hardly studied. Moreover, as far as we know, the effect on the income of stakeholders who use contaminated land for their living has not been studied before. In this paper (the first of two), the first scenario is elaborated:

the farmer does not perform the digesting activity himself, but sells the energy maize. To take into account the uncertainty in assigning numerical values to the determining variables involved, a Monte Carlo simulation using the model is performed. Given certain assumptions, the average extra revenue per hectare amounts to € 113.8. This is an increase of more than 10% compared to its income before phytoremediation. Moreover the latter is uncertain due to possible changes in legislation. This result goes along with a probability that the average extra revenue per hectare is not negative – meaning that the farmer's income will not decrease – of 82.6%.

Monte Carlo sensitivity analysis shows that three variables account for the total variance of the farmer's extra income. These are the yield of energy maize, the price of fodder maize and the price of energy maize (table 6). The income of the farmer has a fair chance to be sustained and even increased by growing energy maize, only when the most likely yield of energy maize per hectare lies 20% higher than the yield of fodder maize per hectare. At the same time there should be a probability to have a yield that lies 30% higher, given equal prices for fodder and energy maize. At the minimum price for fodder maize (€ 24 ton^{-1} FM, given minimum production costs of € 1,200 ha^{-1}), the extra revenue per hectare reduces with 42% but remains positive (€ 65.8 ha^{-1}). The average extra income per ha generated from phytoremediation is much more sensitive to changes in the relative yield *mE/mF* than to changes in the price of maize. Varying *mE/mF* leads to high uncertainty (i.e. low probability on a positive income). Price changes, on the contrary, keep the income more stable and do not lead to a much lower probability of a positive income.

Finally, we discard the assumption that fodder and energy maize have equal prices, a.o. due to contamination resulting from the uptake of heavy metals. The analysis shows that, from the perspective of ensuring that the farmer's income does not decrease (Prob(NPV>0) ≈ 90%, the price of energy maize is dependent on the relative yield of the maize. To have an almost certain positive average extra income (*R*), differences in prices (€ ton^{-1} FM) for energy maize and fodder maize lie between -0.8 and +2.5; the price for energy maize being lower when min. 10% higher biomass yield is achieved compared to fodder maize. If the farmer does not receive the calculated price, there is no guarantee that *R* will be positive, i.e. the phytoremediation activity might reduce the income of the farmer. In that case the farmer should receive an extra compensation for his engagement in the remediation of the soil.

When extra income generated by phytoremediation can be combined with income from energy production, phytoremediation can become yet more appealing, given the upsurge of fossil energy prices. In the second part of the analysis (the following paper) therefore, we will investigate the potential profitability of a digestion installation fed with polluted biomass. All the conclusions reached in this paper (part I) will be embedded in part II in which the farmer is not only engaging in soil reclamation using energy maize and then selling it, but is also converting the harvested biomass to biogas via anaerobic digestion.

Appendix 1

On the regional level it is decided by the Flemish government that 60% of the digestion input has to be related to agriculture, to be allowed to build the digester in an agricultural area (Vlaamse regering, 2006). A digester fed with energy maize coming from the field is thus permitted. For now, we assume that transport costs are an income for the seller of energy maize and a cost for the buyer of fodder and energy maize.Each farmer dedicates half of his land to growing maize. The maize however, has to be transported over a distance that covers the whole land (40 ha per farmer). Therefore, to calculate the distance, the number of hectares with maize has to be multiplied by 2. A simplified calculation of the transport distance for energy maize D_1 is presented by the following equation:

$D_1 = ([H*2/(100*\prod)]^{1/2}+0)/2 *2$

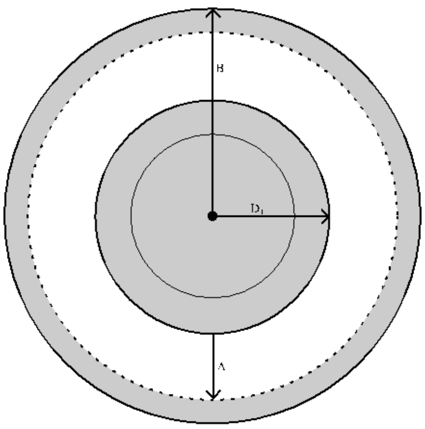
$D_1 = (H*2/(100*\prod))^{1/2}$ (Eq. 2)

H is the number of hectares grown with energy maize, D_1 is an average two-way distance. Total transport is a revenue for the seller of energy maize (cooperating farmer), a cost for the buyer of the energy maize (digester). The distance for fodder maize is given by D_2. Here again an average distance is calculated, but not a two-way distance:

$D_2 = [(280/\prod)^{1/2} – (H*2/100*\prod)^{1/2} + [(280/\prod) + (H*2/100*\prod)]^{1/2}]/2$

$D_2 = [A+B]/2$

$D_2 = [(9.44-D_1)+(89.13+D_1^2)^{1/2}]/2$ (Eq. 3)



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