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The economic value of the phytoremediation function – Assessed by the example of cadmium remediation by willow (*Salix* ssp)

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Abstract

The combination of biomass production with other land use functions in multiple land use systems can reduce biomass production costs if these land use functions generate an economic benefit. Aim of this study is to find and apply methods for the quantification of the economic value of the phytoremediation function (cleaning of the soil by plants). For the purpose the combination of biomass production from willow and the phytoremediation function in a cadmium-contaminated case study area in the Rhine valley (near Freiburg, Germany) was analyzed. Farmers in this area will either have to set the land aside or switch from the high value vegetable production to the production of cereals that generate a lower gross margin. An alternative is the production of heavy metal accumulating willow varieties, which would clean the soil to the cadmium threshold value at which the area can be taken into vegetable production again within a period of six years. Three methods were chosen and applied to

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quantify the economic value of the phytoremediation function to the farmers: willingness-to-pay, substitution costs, and hedonic pricing. The economic value of the phytoremediation function to farmers as assessed by the substitution cost and hedonic price analysis delivers similar results and is about 14,600 and 14,850 € ha^{-1}, respectively, over a period of 20 years. Farmers, however, are only willing to pay 0–1500 € ha^{-1}, mainly because they consider remediation as the government's duty. The study shows that the phytoremediation function generates an economic benefit for the farmers, but the amount considered strongly depends on the potential income from the cleaned area, the period of crop production after cleaning the soil and the time needed for cleaning the soil. The application of different methods to assess the economic benefit generates different results; here the use of hedonic price analysis is recommended.

Keywords: Multiple land use systems; Biomass; Phytoremediation; Economic value; Decision support

1. Introduction

Biomass production in multiple land use (MLU) systems is discussed as an approach for the reduction of biomass production costs and a more efficient use of space and natural resources (Londo, 2002). MLU concepts search for opportunities to combine the generation of different goods or services on the same area (Janssen and Suedmeier, 2000; Londo, 2002).

The quantification of the benefits of multiple land use systems requires the quantification of the land use functions in bio-physical and economic terms. That means in a first step the bio-physical performance, for example tonnes of soil prevented from erosion, numbers and kind of species being supported, and in a second step the economic value of this service are assessed. Here, we will show an approach for the quantification of a land use function in bio-physical and economic terms. For this purpose the land use function phytoremediation, which is the cleaning of heavy metal contaminated soils by plants, will be analyzed. This function was chosen because in previous studies (Ledin, 1998; Boerjesson, 1999a; Lewandowski, 2002) on land use functions it was identified as relevant in terms of quality (approach towards remediation of contaminated soils) and quantity. Probably several 100,000 ha in Europe and the US are contaminated by heavy metals. Glass (1999) estimates the potential European and US markets for phytoremediation to 36–54 billion US$, with a share of 1.2–1.4 billion US$ for the removal of heavy metals from soil.

In food, heavy metals are toxic to humans if critical concentrations are exceeded. Recently, threshold values for the concentrations of heavy metals in foodstuffs were set by EU legislation (EC, 2002). Because for several heavy metals a strong relationship was found between heavy metal concentrations in the soil and in the plants (Krauss et al., 2002), thresholds for soil heavy metal concentrations will have to be adapted to the new threshold values for foodstuff. Therefore, threshold values for heavy metals concentrations in soils, like given in the German soil protection prescription (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 1999) will in future have to become stricter.

Even when applying the less strict thresholds of the present soil protection regulation (BMU, 1999), only in Germany about several 10,000 ha of agricultural land would have to be taken out of food production because of contamination by heavy metals exceeding these thresholds. The alternatives to set aside are the cleaning of these areas or the production of biomass for the non-food sector. Phytoremediation allows for the combination of biomass production and cleaning of these areas. Phytoremediation can either be performed by growing crops, which reach high heavy metal concentrations in the biomass (hyperaccumulator) or by crops with higher aboveground yields but lower concentration of heavy metals in their biomass. Tabacco (*Nicotiana tabacum* L.) and *Thlaspi caerulescens* are examples for hyperaccumulators. For biomass production crops that combine significant heavy metal accumulation with high biomass yields are more suitable. Field trials with different potential biomass crops, like sunflowers, corn, ryegrass, willow and *Miscanthus*, have shown that willow (*Salix* ssp.) is most effective in taking up heavy metals (Fernando et al., 1996; Schmidt, 2003a). Specific varieties of willow are characterized by the ability of taking up high amounts of heavy metals (Riddel-Black, 1997). Therefore, in this study the combination of biomass production from willow with phytoremediation of heavy metal contaminated land is assessed. For the energetic use of the willow biomass we here assume combustion for two reasons. First, combustion is by far the most important conversion route for biomass. Second, technical options to deal with the combustion of heavy metal containing biomass have been identified (see Obernberger et al., 2002). Depending on the amount of heavy metals in the biomass and the available combustion technique, measures, like the installation of specific filters, are required to ensure that heavy metals during combustion are not emitted but are fixed in the fly ash. The fly ash has to be deposited, for which some extra costs should be included.

The *hypothesis* to be tested in this study is that economic tools are available to assess the added value of phytoremediation. Therefore, we show and discuss different approaches for the assessment of the economic value of the land use function phytoremediation. This is done in a regional context because we want to identify the stakeholder with interest in the performance of the phytoremediation function and use a bottom up approach that allows for a site-specific analysis of the performance of the phytoremediation function. A site-specific analysis is here useful because the bio-physical performance of the phytoremediation, like the time needed for cleaning the soil, strongly depends on site conditions.

The study is structured into four parts. In Section 2, the case study is described: the area and its essential characteristics, and main features of the phytoremediation option. In Section 3, different methods for quantifying the economic value of the phytoremediation function are described and discussed. The Section 4 contains the results of the quantification of the phytoremediation function in economic terms as performed by three valuation approaches: 'willingness-to-pay', 'substitution cost' and 'hedonic price analysis'. We end with discussion and conclusions.

2. Description of the case study and quantification of the phytoremediation function in bio-physical terms

The quantification of land use functions in bio-physical terms (i.e., the physical or biological performance, here the amount of heavy metals removed per ha and year) requires information on the reference system or landscape in which the multiple land use system is performed, on the site conditions relevant for the performance of the land use functions, on the crops that are used for biomass production and on the organisation of the crop management system (Lewandowski et al., 2004).

2.1. Description of the reference system and the site conditions

The study area is in the Rhine valley, near Freiburg (Germany). With a fertile soil, a yearly average temperature of 9.3 °C and precipitation of about 800 mm the study is area is very suitable for vegetable production.

Soil and crop sampling have shown that major parts of the 2300 ha agricultural land of the study area are contaminated with heavy metals. In-washes of cinder residues from historic mining activities carried cadmium (Cd), lead, zinc, copper and arsenic into the area. For Cd critical contents are measured, the soil contains of 45–75 μg mobile Cd kg^{-1} soil (extracted with 1 mol NH_4NO_3 solution) and 500 μg total Cd kg^{-1} soil (extracted with aqua regia) in the upper 30 cm. The Cd content decreases to 375 μg total Cd kg^{-1} soil to the depth of 90 cm. The German soil protection regulation of 1999 prescribes that soil with a concentration of more than 40 μg mobile Cd kg^{-1} has to be taken out of vegetable production. Since the use of the land before it was taken out of production was vegetable production in a rotation with grain cereals, this implies a significant loss of income for the farmers.

2.2. Description of the biomass crops, yield and management system

The data used here on the contents and behaviour of heavy metals in the soil stem from samplings, soil analysis and the characterization of the heavy metal binding in the soil, which were performed in the study area by Schmidt (2003b). The calculation of time needed to reach the given threshold is based on (1) the accumulation capacity of willow and (2) the kinetics of Cd release from soil compartments. Experiments on the release kinetics of Cd from soil compartments of the test soil by using a batch pHstat method showed that half of the total Cd (500 μg kg^{-1}) is solubilized easily, which means that it can be accumulated by crops. The other half of the total amount is bound to organic material and highly cristallized iron oxides and cannot be extracted by plant roots (Zeien and Brümmer, 1989). The yield potential of willow (*Salix viminalis*) in the study area is 10–14 t dry matter ha^{-1} y^{-1} (Kahnt et al., 1995). The capacity of willow to accumulate Cd is strongly determined by the genotype (Riddel-Black et al., 1999), whereas there was no linear correlation between the soil Cd concentration and Cd accumulation rates by willow (Dickinson and Pulford, 2005). Some genotypes are able to accumulate up to 100 mg Cd kg^{-1} dry matter (DM) (Riddel-Black et al., 1999). For selected willow varieties grown on soils with similar Cd contents to those in our case study area we measured Cd contents of 20–45 mg kg^{-1} DM stem wood (Schremmer et al., 1999). Dickinson and Pulford (2005) consider contents of 25 mg Cd kg^{-1} wood with a willow yield of 15 t ha^{-1} y^{-1} realistically achievable. We use a value of 33 mg Cd kg^{-1} stem wood (average from values measured in Schremmer et al., 1999) and an average willow yield of 10 t ha^{-1} y^{-1}(or 16.7 t fresh matter with a water content of 40%) for our calculations.

The release of heavy metals from soil follows an exponential decay curve (Schwarz et al., 1999), so when heavy metals are removed from the soil, the accumulation rates through plants decrease slightly. This decrease was considered in our calculation which shows, that in the study area the amount of Cd accumulated by willow sums up to nearly 2 kg Cd ha^{-1} after 6 years and that after this time the threshold value of 0.4 μ Cd kg^{-1} soil (at which the land can be taken into vegetable production again) will be reached.

After ploughing and harrowing willows are planted by stem cuttings in double rows with 70 cm within and 120 cm between two double rows. In the first year, chemical weed control is performed because the plantings are not very competitive and need to be protected from water shortage caused by weeds. Fertilization (N, P, K, Ca) is given in the second year and in the beginning of the fourth year after the first harvest had been performed. At the end of the third and the sixth year, willow is harvested with a Claas twin row willow harvester. For recultivating the land the stumps are cut down by a deep rotor tiller. Remerging shoots are sprayed with round up (Lewandowski, 2001).

2.3. Description of the hyperaccumulator crop and its management system

The second phytoremediation crop that is investigated here is *Thlaspi caerulescens*. This crop was identified as hyperaccumulator (crops which reach high heavy metal concentrations in the biomass) of several heavy metals and was also used in a number of comparative studies between hyperaccumulators and biomass crops (Schmidt, 2003a). *Thlaspi* was chosen as hyperaccumulator in this study because it is the best known and mostly mentioned and investigated metallophyte species around the world (Gardea-Torresdey et al., 2005), was successfully grown under different climatic conditions and accumulates, compared to other hyperaccumulator plants, heavy metals at high rates (McGrath, 1998). It is a two-year crop that builds an average yield of 0.5 t TM ha^{-1} y^{-1} (Gardea-Torresdey et al., 2005). The measured Cd concentration in *Thlaspi caerulescens* grown on Cd contaminated areas is 0.2–0.4 g kg^{-1} dry matter (Ebbs et al., 1997; Kayser et al., 2000; Gardea-Torresdey et al., 2005). With this plant, up to 0.1–0.2 kg Cd ha^{-1} a^{-1} can be removed. The time needed until the threshold values of 0.4 μg Cd kg^{-1} soil are reached is 6–12 years. After soil preparation *Thlaspi caerulescens* is sown at a rate of 8 kg seeds ha^{-1}. Because the crop is not very competitive to weeds we assume here a crop protection program including dressing of the seeds, pre and after emergence herbicide application against weeds and one application against grasses. In the second year, the harvest is performed by a mower and a collection of the dry biomass from the field by a baling machine.

3. Methods for the assessment of the economic value of the phytoremediation function

To assess the economic value of a land use function first the target group, i.e., the people, organization or interest group for which the land use function has a value and who would be willing to pay for it, have to be identified.

3.1. Identification of the target group

The phytoremediation function can be of use for different groups as shown in Table 1.

No company can legally be made responsible and be forced to pay for the decontamination of land because the contamination by heavy metals in our study area is from historic activities. The food consumers are protected since the vegetables are controlled for heavy metal contents. Food exceeding given thresholds is taken from the market. For the authorities, there is today not yet an obligation to deal with heavy metal contaminated farmland, what may change in future. Because the activities of biomass production and use can have a positive impact on the economic development, especially in rural areas, authorities could have an interest in phytoremediation. In our case study, the farmers are the group that would most benefit from phytoremediation. If they do not clean their farmland from heavy metals they cannot use it for the production of high value crops like vegetables. That means they either have to set aside the contaminated farmland or experience a loss of income because they have to grow crops that take up less heavy metals than vegetables;

Table 1
Benefits that the phytoremediation function can have for different target groups

Group	Precondition	Benefit
Farmer	Own farmland that is contaminated with heavy metal to an extent that it has to be taken out of (high value) production	Cleaning of the farmland, which can then be taken into (high value) production again
Authority	Needs to find a method to deal with heavy metal contaminated land	Phytoremediation is a cheap method for the cleaning of heavy metal contaminated soil Biomass production is easy to implement (e.g., technology and knowledge is available) and delivers renewable energy sources The combination of biomass production and cleaning of high value agricultural soil involves a macro-economic benefit for the region or country
Industry	Has caused contamination of land and is willing to, asked or forced to clean it	Phytoremediation is a cheap method for the decontamination of heavy metal contaminated soil The production of biomass is a source for renewable energy
Consumer	Is willing to pay more for less polluted food and for green energy	Healthier food Green energy available Clean soils and environment

alternatives, like for example wheat, sell cheaper and provide less income per hectare to the farmer.

3.2. Choice of a method for the assessment of the economic value of the land use function phytoremediation

The concept of multifunctional agriculture implies that several public goods or positive externalities can be attached to agricultural production (Vatn, 2002). Thus, services and goods provided by a function being combined with biomass production could be considered as positive externality and valued as such. Externalities are those consequences of a production process, imposed on society or the environment, which are not taken into account in the product price. They occur whenever production processes, or consumers' utility, are affected by variables not controlled by themselves, but by other economic agents. These effects may be positive (external benefits) or negative (external costs) (Saez et al., 1998). We therefore searched the literature on methods for valuing externality as well as the literature on the valuing of ecological or other non-production functions in agriculture (Constanza et al., 1997; Faaij, 1997; Boerjesson, 1999b; Vatn, 2002); the methods found are listed in Table 2. Generally, the appropriate choice of a method depends on the specific case, desired reliability and availability of data. Here, we discuss the methods that appeared to be applicable to the Cd phytoremediation case.

3.2.1. Market price

A direct method to assess the value of the service of the phytoremediation function would be to find out at what price the service sells on the market. Some land use func-

Table 2
Overview on methods, as described in Boerjesson (1999b), Saez et al. (1998) and Randall (2002), to assess the value of land use functions

Methods	Explanations
Market price	The value is determined by the price at which the good or service sells on the market
Contingent valuation/willingness-to-pay	Explores the willingness of individuals to pay for a service or good
Substitution costs/replacement costs	Refers to the cost of achieving a similar environmental effect to that from the function being studied, but in another way
Hedonic price analysis	Refers to the marginal value that is created by the function, for example the analysis marginal value of an amenity that is close to a nature area
Avoidance costs/control costs	Refers to the costs of avoiding environmental damage, for example the costs for reducing pollutants causing the damage
Restoration costs	Refers to the costs of restoring environmental damage
Travel costs	Explores the amount of money recreationists would spend to travel to visit the area, which services are to be evaluated, for example a forest. Only relevant to evaluate functions of recreation facilitation

tions result in the delivery of marketable goods (e.g., biomass) or services (e.g., cleaning sewage sludge). For those goods and services for which a market exists and for which the biophysical effect of the function is quantified, too, the market price can be used to derive the economic value of the function. There is, however, not yet a market for the phytoremediation service. Therefore no market price can be assessed here.

3.2.2. Willingness-to-pay

Many valuation techniques to assess the value of ecosystems services or on functions that are considered difficult to quantify (e.g., like landscape beauty) use attempts to estimate the 'willingness-to-pay' of individuals (Constanza et al., 1997). This method, also referred to as contingent valuation method (Blumenschein and Johannesson, 1999), is an indirect evaluation method and applied with the aim to receive a kind of market price for a good or a service by asking respondents how much they are hypothetically willing to pay for a defined good or service. The potential advantage the willingness-to-pay method (WTP) offers, is that it reflects, in a single monetary amount, the entire range of attributes (both benefits and "nonbenefits") offered by the good or service being valued (Blumenschein and Johannesson, 1999). WTP is among the most popular approaches to value non-market natural and environmental resources because of its simplicity and flexibility (Zhang and Li, 2005). But the accuracy of WTP is strongly debated for several reasons (for an overview see Zhang and Li (2005)). Major objections are that the results are biased and do rather reflect values on individual than on society level, that individuals inquired may be ill-informed, might seek to answer strategically or carelessly (Constanza et al., 1997; Randall, 2002; Zhang and Li, 2005).

We applied this method here to get information about the amount the farmers in the case study area would be willing to pay for the phytoremediation function and to compare the results of the application of WTP to the outcome of the other methods applied here. Six farms in the study area are affected by heavy metal contamination. We developed questionnaires and had them answered by all the farmers that have cadmium-contaminated land in the study area via the official agricultural extension worker (Klapwijk, J., Amt für Landwirtschaft, Landschafts- und Bodenkultur Freiburg (Office for agriculture, landscape and soil culture Freiburg), Germany, pers. comm., 2004).

3.2.3. Substitution costs

Another approach to indirect assessment of the value of the phytoremediation function is the use of the substitution cost method, also called replacement cost method (see e.g. Faaij, 1997; Randall, 2002). By this method the value is assessed via the economic benefits or costs of an alternative approach; e.g., the value of water catchment service is assessed by calculating the cost of additional reservoir capacity that would serve the same purpose (Randall, 2002). In case of phytoremediation this method describes the cost of achieving a similar environmental impact to that of biomass crop cultivation, but in another, relevant and cost-efficient way. Boerjesson (1999b) and Berndes et al. (2004) write that no substitution costs can be calculated for the value of cadmium removal by willow (*Salix* ssp.) because today there is no realistic alternative method of purifying arable land of cadmium. Indeed, the excavation and land filling or ex situ cleaning of the soil, would cost about 280,000 and 680,000 € ha^1, respectively, and generally decrease soil fertility because the soil is either dumped or the silt particles are washed out during the cleaning process (source: cost data received come from personal communication with German transport, waste management, soil cleaning and earthwork companies). Therefore, these options are not considered by the farmers. Instead here we assess the alternative costs of land decontamination by the use of hyperaccumulator plants (description see above). Cleaning the soil with the hyperaccumulator *Thlaspi caerulescens* would, at the given concentration of heavy metals, need 12 years. The Cd contaminated biomass of *Thlaspi caerulescens* would have to be deposited and cannot be used for energy production. Because phytoremediation with the hyperaccumulator needs 6 years longer than with willow, the farmer experiences a loss of potential income from high value vegetable production in the years 7–12. The value of the phytoremediation function (β_{PF}) in combination with willow production therefore is calculated by summing up the costs of phytoremediation by *Thlaspi* in the years 1–12 ($C_{\mathrm{HA}(1-12)}$), the costs for dumping the heavy metal contaminated biomass ($C_{\mathrm{depHA}(1-12)}$) and the gross margin of vegetable production in the years 7–12. The gross margin of vegetable production is calculated by subtracting the costs of vegetable production ($C_{\mathrm{vp}(7-12)}$) from the income from vegetable production ($\beta_{\mathrm{vp}(7-12)}$)

$$\beta_{\mathrm{PF}} = C_{\mathrm{HA}(1-12)} + C_{\mathrm{depHA}(1-12)} + \beta_{\mathrm{vp}(7-12)} - C_{\mathrm{vp}(7-12)}. \tag{1}$$

3.2.4. Hedonic price analysis

In a last approach, we calculate the economic loss the farmer would experience if he could not apply the phytoremediation function and had to set aside heavy metal contaminated land. According to Randall (2002) this approach is a hedonic price analysis, which measures the marginal value that is created by the function. Berndes et al. (2004) used hedonic pricing for quantifying the economic benefit of Cd removal by willow. They calculated a price reduction of 10% for the goods produced on Cd contaminated area. This approach is here not applicable because if Cd thresholds in food in Germany are exceeded, the area it stems from has to be taken out of production or be used for crops that accumulate Cd to a lesser extent. Therefore in our approach the following assumptions are used: The farmer plans to continue his farm activities for a period of 20 years. Because of legislative restrictions the farmer cannot use the contaminated land for vegetable production anymore. He has two feasible alternatives (a) the production of food crops that are not as susceptible to heavy metal accumulation as vegetables, like the cereals wheat and maize, for a period of 20 years, (b) the production of biomass crops which can be combined with the phytoremediation function for the first six years (which is the period that is needed to clean the soil) and the production of vegetables in the years 7–20. The economic benefit of the phytoremediation function for the farmer (β_{PF}) is calculated by Eq. (2).

$$\beta_{\mathrm{PF}} = \beta_{\mathrm{BC}(1-6)} - C_{\mathrm{BC}(1-6)} + \beta_{\mathrm{vp}(7-20)} - C_{\mathrm{vp}(7-20)} - \beta_{\mathrm{CP}(1-20)} + C_{\mathrm{CP}(1-20)} - C_{\mathrm{Cd}(1-6)}, \tag{2}$$

where $\beta_{\mathrm{BC}(1-6)}$ is the income from selling willow biomass and $C_{\mathrm{BC}(1-6)}$ the cost of willow production in years 1–6, $\beta_{\mathrm{vp}(7-20)}$ is the income from vegetable production and $C_{\mathrm{vp}(7-20)}$ cost of vegetable production in years 7–20, $\beta_{\mathrm{CP}(1-20)}$ is the income from cereal production and $C_{\mathrm{CP}(1-20)}$ the costs for cereal production in the years 1–20 and $C_{\mathrm{Cd}(1-6)}$ is the additional cost for the combustion of cadmium containing biomass in the years 1–6.

The economic benefit for the farmer by the phytoremediation function result from the fact, that he can take the land into vegetable production again after a cleaning period of six years. If the farmer would not perform phytoremediation, he could grow cereals like wheat and maize with a gross margin of 395 € ha^{-1} y^{-1}. The production of vegetables (including carrots, radish, rhubarb, kohlrabi, spinach and lettuce) generates an average (average over the whole rotation including cereals every 3rd year) gross margin of 2569–3198 € ha^{-1} y^{-1}. The gross margins are calculated as the difference between the market price of the products sold from one hectare and the costs to produce them. The costs are the sum of operational costs (like soil cultivation, sawing, fertilization, harvesting etc.) and fix costs (see Tables 3 and 4).

Table 3
Production costs for willow biomass for German conditions in combination with phytoremediation for a period of 6 years

Operation	Specification	Times cost items appears	Costs per ha in 6 years (calculated to present value)[a] (€)	Source
Establishment of plantation	Ploughing, harrowing, seed bed preparation	1	198	KTBL (2002)
	Cuttings (7000 pieces á 0,14 ct)	1	980	Bertholdsson, Svalöv Weibull AB, Sweden pers. comm. (2000)
	Planting	1	237	Kueppers (1999)
	Weed control in first year	1	144	Kueppers (1999)
Fertilization[b]	Fertilization first and fourth year	2	244	Kueppers (1999)
Harvest[c]	Claas twin row willow harvester	2	814	Gigler et al. (1999)
Stump clearing	Deep rotor tiller and round up application	1	549 (year 6)	Coelman et al. (1996)
Fixed costs[d]		6	1076	Hartmann (2002)
Total costs			4242	

[a] For calculating the present value an interest rate of 5% was used.

[b] Fertilizer costs of 5.70 € per Mg DM.

[c] Harvest costs of 12.31 € per Mg DM.

[d] Fix costs are those costs that cannot be attributed to certain crop, but arise for the farm as a whole. Here fix costs include electricity and water (5.11 € ha^{-1}), repairs and fuel (25.56 € ha^{-1}), maintenance of buildings and soil improvement (35.79 € ha^{-1}), taxes, insurances and contribution to co-operatives (76.69 € ha^{-1}) and other farm expenditures (66.47 € ha^{-1}).

Table 4
Costs for the production of *Thlaspi caerulescens* (data from KTBL, 2002)

Operation	Specification	Times cost items appears in 12 years	Costs per ha in 12 years (present value) (€)
Establishment of crops	Ploughing, harrowing, seed bed preparation	6	908
	Seeds (8 kg ha^{-1})	6	550
	Sawing	6	147
Crop care (crop protection)	Dressing of seeds, pre and after emergence herbicide against weeds and one application against grasses	6	679
Harvest		6	450
Fix costs[b]		12	1871
Total costs			4605

[a] This is a conservative estimate. No prices for the seeds are available yet.
[b] For explanation of fix costs see footnote d in Table 3.

The range of gross margin results from yield variations in different years. For further calculation we here use the conservative value for the gross margin of 2569 € ha^{-1} y^{-1}.

3.2.5. Avoidance costs

Berndes et al. (2004) calculate the cost of decadmiation, which is the process that lower the Cd content of phosphate fertilizer, to value the economic benefit of Cd removal by willow. The application of the avoidance cost method in that case bases on the assumption that Cd contamination stems from the application of phosphate fertilizer. In our case study, we did not see an approach to avoid costs, mainly because the damage was caused in the past and no measures can be taken to compensate for this damage.

3.3. Assessment of cost data

To calculate the value of the phytoremediation function data on costs of the production of willow and *Thlaspi caerulescens*, on the income from crop production and on costs for combusting and depositing heavy metal containing biomass are needed.

3.3.1. Assumptions for the assessment of the costs for phytoremediation in combination with willow production

The biomass crop used is willow (*Salix viminalis*). The production costs are presented in Table 3. The costs or benefits from willow production were calculated to present value (*PV*) by Eq. (3).

$$\mathrm{PVq} = \sum_{a=0}^{n} q(a)/(1+r)^a, \tag{3}$$

where q are costs or income, a is the year within the planning period in which cost or income items appear and r is the interest rate; here, we used an interest rate of 0.05.

One ton of fresh willow biomass (about 35–40% water content) can be sold at a price of 60 € (Kralemann, M., Niedersächsische Energie-Agentur GmbH, pers. Comm., 2003). The biomass harvest is performed in the third and sixth year (a total of 100 t biomass harvested) and the income from this biomass is calculated to present value. Another source of income for the farmer is a premium for energy crop production (45 € ha^{-1} a^{-1}), which was also calculated to present value. The phytoremediation costs are calculated from the willow production costs (see Table 3) minus the income from the willow biomass and plus the additional costs for the combustion of the heavy metal containing biomass.

Our calculation on additional costs for heavy metal contaminated biomass are done by the Horteb programme (Brökeland, 2003), based on the assumption that an electro filter for 109,000 € has to be installed in a combustion plant with a capacity of 20 MW and a depreciation period of 20 years.

The disposal of the ash costs 60 € t^{-1} (no limits for contents of contaminants given). The fine fly-ash usually represents 5–15 wt% of the overall ash amount in fixed bed biomass combustion systems (Dahl et al., 2002). Willow biomass contains 2% of ash (Hartmann, 2001). We here calculate with an amount of 0.33 kg fly-ash t^{-1} willow biomass.

3.3.2. Assumptions for the assessment of the costs for the decontamination of the soil by the hyperaccumulator

The hyperaccumulator used is *Thlaspi caerulescens*. There is no information available about the production costs of *Thlaspi caerulescens* because so far it has only been grown on experimental fields. Because it is also a small seeded plant we here estimate the costs for producing *Thlaspi* on basis of the production costs of lin seed (*Linum ussitatissum*), which are described in KTBL (2002). Generally, conservative cost data were used in order to not underestimate the production costs. Because of the comparatively low yield of *Thlaspi* of 0.5 t DM per year no fertilization is needed.

The production costs for *Thlaspi* over these 12 years are calculated to present value and are 4605 € ha^{-1} (see Table 4). It is emphasized here that these costs rely on estimates and therefore have to be used with care.

Additionally, the heavy metal contaminated biomass of the hyperaccumulator, which sums up to 6 t DM ha^{-1} over 12 years, has to be deposited at costs of 60 € t^{-1}. Compared to willow the hyperaccumulator needs 6 years longer to clean the soil. Therefore, we account a loss of income from the alternative use (gross margin 2569 € ha^{-1} y^{-1}) for the years 7–12. During the period of decontamination by hyperaccumulator no other crops can be grown on the land.

3.4. Sensitivity analysis

With the substitution cost and economic benefit method a sensitivity analysis was done for those parameters that have the strongest influence on the value of the phytoremediation function. These parameters are (1) the length of period that the farmer is planning to use the land after it has been cleaned, (2) the height of potential

Table 5
Parameter and their values for the sensitivity analysis applied in the substitution cost and additional benefit methods

Parameter	Baseline case	Variant 1	Variant 2
Depreciation period	20 years	10 years	30 years
Gross margin attainable on clean soil	2569 € ha^{-1} y^{-1} (lower range of gross margin for vegetables)	395 € ha^{-1} y^{-1} (cereal production)	3198 € ha^{-1} y^{-1} (higher range of gross margin for vegetables)
Time needed for cleaning the soil by willow and by *Thlaspi* (numbers in brackets)	6 years (12 years)	12 years (24 years)	18 years (36 years)

[a] *Source*. http://www.liz-online.de/gi/bw/liz-anbauplan.htm; average gross margin for rotation with sugar beet, wheat and barley.

income from the contaminated area after it has been cleaned and (3) the extent of contamination, i.e., the concentration of heavy metals in the soil and the time needed to clean the soil.

The potential income and the extend of contamination are determined by the conditions in our case study area but will be different for other areas in Germany or Europe. The length of the depreciation period depends on the conditions of every single farm and can vary, for example, with the age of the farmer. Table 5 gives an overview on parameter variation.

4. Results

4.1. Results of the farmers inquiries – application of willingness-to-pay method

The results of the farmer inquiries are presented in Table 6. All farmers are the so-called full time farmers, that means that they get their income mainly from farming and are therefore dependent on farming. The acreages of their farms vary from 12 to 80 ha. The farmers are less willing to pay for decontamination if they expect to have uncontaminated areas left where they can move their vegetable production to. The farmers are willing to pay more (or at all) when they had already been investing into the areas; in our case by sharing the investment costs for a well for irrigation of the land. Interestingly, all farmers just estimated the value that the cleaning of the contaminated area would have for them, but none of them tried to calculate the value. However, when being asked how much they would pay for cleaning when they had a less valuable production alternative on the contaminated area, they were willing to pay less money (up to 500 € ha^{-1}) for cleaning compared to the case that the contaminated area would have to be set aside completely (up to 1500 € ha^{-1}). This means that the willingness-to-pay methods leads to a value for the phytoremediation function of 0–1500 € ha^{-1}.

Table 6
Results of farmer inquiries on their willingness to pay for phytoremediation

Questions	Farm number					
	1	2	3	4	5	6
How much area are you cultivating?	15 ha	80 ha	20 ha	80 ha	12 ha	45 ha
How is the share of rented to own land in %?	20/80	90/10	50/50	85/15	60/40	65/35
How much would you be willing to pay for the cleaning of your own contaminated production land if						
The area has to be set aside completely without cleaning?	0 € ha^{-1}	0 € ha^{-1}	1000 € ha^{-1}	1000 € ha^{-1}	1500 € ha^{-1}	1000 € ha^{-1}
Without cleaning the area is not to be used for vegetable production but for the production of cereals (including maize)?	0 € ha^{-1}	0 € ha^{-1}	300 € ha^{-1}	0 € ha^{-1}	500 € ha^{-1}	350 € ha^{-1}

4.2. Economic value of the phytoremediation function for the farmers as assessed by the substitution costs method

Fig. 1 gives an overview on the factors that determine the economic value of the phytoremediation function when determined by the substitution cost method or hedonic price analysis.

Table 7 shows which of the parameter shown in Fig. 1 are used for calculating the economic value of the phytoremediation function by different methods.

The phytoremediation costs with hyperaccumulator sum up to 4864 € ha^{-1} over a period of 12 years. This sum includes the production costs and deposition costs for the heavy metal contaminated biomass. Because the hyperaccumulator needs six years longer to decontaminate the soil than willow, the loss of income for these six years of 9730 € ha^{-1} is accounted for. The costs for this alternative method and thus the value of the phytoremediation function is herewith calculated as the sum of cleaning costs and missed income to 14,594 € ha^{-1}.

The sensitivity analysis shows that the value of the phytoremediation functions, as assessed by the substitution cost method, mainly depends on the gross margin that can be attained after the soil has been cleaned, but also on the time period that is needed for cleaning the soil (see Fig. 2).

The lower gross margin that can be attained by cereals compared to vegetables reduces the economic value of the phytoremediation for the farmer to 6360 € ha^{-1} (see Fig. 2(a)). A higher gross margin of 3198 € $ha^{-1}\,y^{-1}$ would be attainable if the farmer could stabilize yields on a high level (e.g., by improved production techniques and varieties); then the value of the phytoremediation function would increase to 16,977 € $ha^{-1}\,y^{-1}$.

When 12 instead of six years are needed for phytoremediation by willow, the value of the phytoremediation increases to about 16,874 € ha^{-1}; this is because the remediation time by *Thlaspi* increases to 24 years and the number of years for which a loss of income is accounted for to 12 years. A decrease to 12,178 € ha^{-1} with a

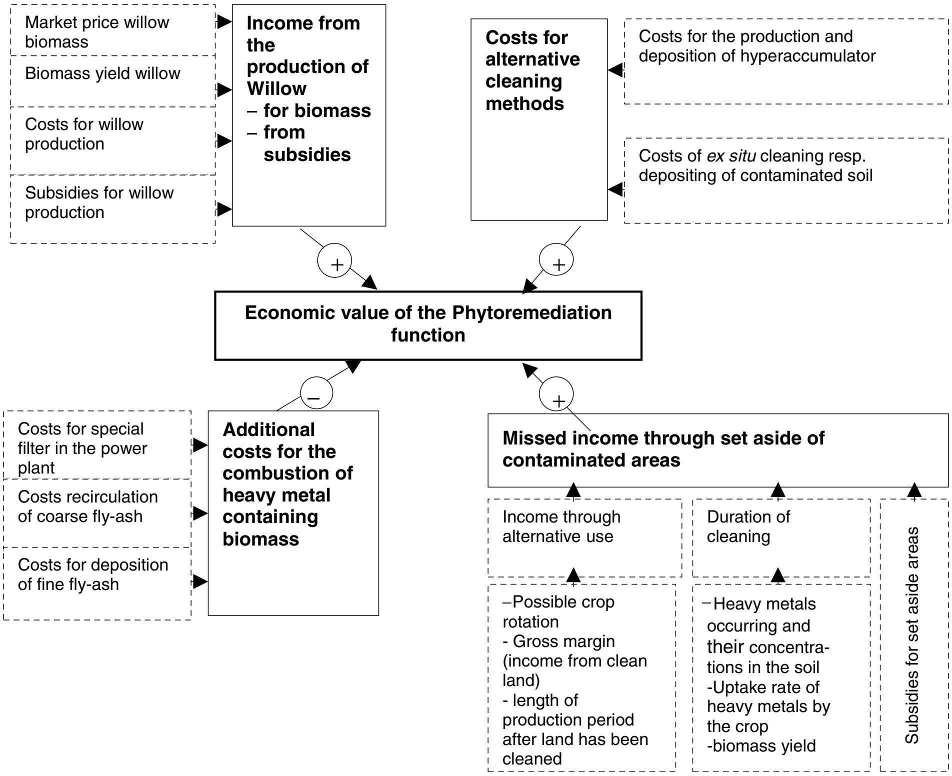

Fig. 1. Determinants for the economic value of the phytoremediation function in combination with the production of biomass from willow (*Salix* ssp).

remediation time of 18 years (see Fig. 2(c)) results from the fact that we here assumed a planning period of 20 years. When cleaning the soil by willow lasts 18 years, only the gross margin attainable in the years 19 and 20 can be accounted for calculating the economic value of the phytoremediation function.

4.3. Economic value of the phytoremediation function for the farmers as assessed by the hedonic price analysis

Table 7 shows the parameters for the calculation of the value of the phytoremediation function by hedonic price analysis. The total benefit from willow production, calculated by subtracting the costs of willow production and combustion from the income from selling biomass and the energy crop premium, are 798 € ha^{-1} over the six years.

We assumed that the farmer plans to produce vegetables on this area for another 14 years after remediation. Discounting the income of 2569 € ha^{-1} y^{-1} for the years 7–20 to present value results in 18,976 € ha^{-1}. If we consider an alternative use of the contaminated area by summer cereal and maize production (which is a feasible alter-

Table 7
Overview on interim results as input for calculating the economic value of the phytoremediation function by the substitution cost and hedonic price analysis methods

Method	Hedonic price analysis (€ ha^{-1})	Substitution cost (€ ha^{-1})
Parameter adding value to the phytoremediation function in € ha^{-1} (years $x-y$)		
Income from willow biomass (1–6)	4830	
Premium energy crop production (1–6)	240	
Gross margin vegetable production (7–20)	18,976	
Gross margin vegetable production (7–12)		9730
Costs for the production of hyperaccumulator *Thlaspi* (1–12)		4605
Cost for deposition of biomass from hyperaccumulator (1–12)		259
Parameter reducing the value to the phytoremediation function (years $x-y$)		
Production costs of willow (1–6)	4242	
Additional costs for the combustion of heavy metal containing biomass from willow (1–6)[a]	30	
Gross margin cereal production (1–20)	4923	
Result: economic value of the phytoremediation function in € ha^{-1} (years 1–20)	*14,851*	*14,594*

[a] Costs for the electro filter 0.3034 € t^{-1} biomass, costs fro dumping ash of 0.016 € t^{-1} biomass.

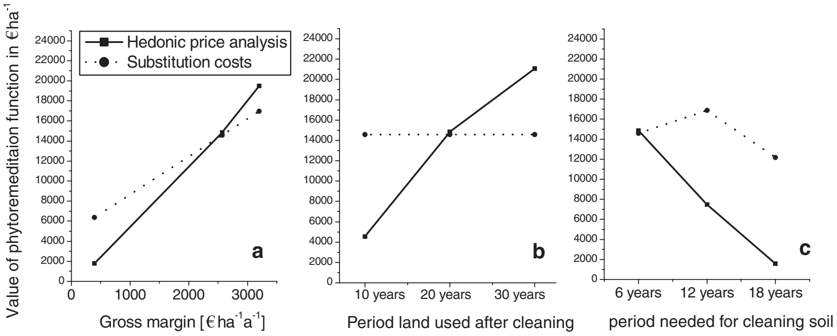

Fig. 2. Changes in the economic value of the phytoremediation function for the farmer when analyzed by the methods of substitution costs and hedonic price analysis. Parameter varied is the gross margin of crop production attainable on clean soil (a), the length of the period for which crop production on the cleaned area is planned (b) and the period needed to clean the soil (c).

native because both crops do not take up as much Cd as vegetables) with an income of 395 € ha^{-1} y^{-1} and subtract the potential income from summer cereal and maize production and the costs of phytoremediation from the potential income from vegetable production the economic value of the phytoremediation function becomes 14,851 € ha^{-1}.

The attainable gross margin, the planning period and the time needed for cleaning the soil have strong impacts on the economic value of the phytoremediation function as assessed by the hedonic price analysis (see Fig. 2). These three parameters influence the potential income from the area after it has been cleaned, either by the height of the yearly income (gross margin) or by the period in which this income can be attained (period land used after cleaning, period needed for cleaning the soil). The potential income dominates the economic value in the phytoremediation function in this approach (see also Eq. (2)). When these parameter are varied the value of the phytoremediation function ranges between 1774 and 21,078 € ha^{-1} (see Fig. 2).

5. Discussion

Our analysis has shown that the land use function phytoremediation has a positive economic value, whatever method for the assessment of this economic value was used. However, the values vary between these methods. The economic value of phytoremediation as assessed by asking the farmers what they would be willing to pay for it is 0–1500 € ha^{-1}. This value is significantly lower than the values of about 14,850 and 14,600 € ha^{-1}, which are the results of the assessment via the hedonic price analysis and substitution cost method, respectively.

5.1. Determinants of farmers' willingness-to-pay

Three reasons, explaining the low value farmers are willing to pay for phytoremediation, were identified.

First, the willingness to pay for the cleaning of contaminated soils by the farmers is negatively influenced by the fact that they consider the contamination as not being their 'fault'. Their opinion is that it is the government's duty is to organize and pay the cleaning of land that was contaminated in previous times (The farmers the study areas gave this information during personal communication on their perception towards phytoremediation and their willingness to apply it).

The second reason for a comparatively low subjective value of the phytoremediation function for the farmers interrogated here is that they consider them independent on the contaminated land. When the inquiries were performed the farmers thought that they still had areas left to which they can move the vegetable production. However, the ongoing mapping of contamination in the area shows that there will be no uncontaminated area left, which means that it is to be expected that the value of cleaning the available land will automatically increase for the farmers when they realize that they do not have access to alternative land that is suitable for vegetable production.

Thirdly, none of the farmers tried to calculate the benefit that phytoremediation could have, all of them gave a 'subjective' value. Most important determinant for value they gave was the height of the money, that had already been invested into land. In our case, the farmers shared the costs for a well for the irrigation of the land.

The WTP approach here resulted in a value for the phytoremediation function that is strongly influenced by the perspectives and preferences of the farmers and kind of information that they got before being inquired. This result confirms doubts rose by Randall (2002) and Zhang and Li (2005) about the suitability of the WTP approach for the assessment of the economic value of land use functions or ecological services.

5.2. Comparison of the substitution cost method and hedonic price analysis

Three parameter, i.e., the attainable gross margin of foods produced on clean land, the length of the period of food crop production after the soil has been cleaned and the time needed for cleaning the soil, have strong influence on the value of the phytoremediation function to the farmers. Ranges assessed here are about 1800–21,100 € ha^{-1} (hedonic price analysis) and 6400–17,000 € ha^{-1} (substitution costs). By the application of hedonic price analysis nearly linear relations were found (see Fig. 2). The value of the phytoremediation function increases with the height of income that can be attained from the cleaned area and the length of the period that the cleaned area can be used for food crop production. It decreases with the period needed for cleaning the soil. The assessment by the substitution cost method, however, shows other trends for the two parameter 'length of period that land can be used after cleaning', which has no influence on the value of the phytoremediation function, and 'length of period needed to clean the land', for which no clear trend developed (see Fig. 2(c)). The reason therefore is the rather indirect approach of the substitution cost method, in which the economic value of the phytoremediation function with hyperaccumulator is determined in comparison to the performance of phytoremediation by willow. In the substitution cost method the value of the phytoremediation function increases with the value of the gross margin that cannot be realized in the period that the hyperaccumulator needs longer than willow to clean the soil.

The assumptions used in the substitution cost method, i.e., the use of the hyperaccumulator *Thlaspi caerulescens*, also appears somehow constructed. Why using the hyperaccumulator when phytoremediation can be performed quicker and cheaper by willow? Another disadvantage of cleaning the soil by hyperaccumulator is that the heavy metal contaminated biomass has to be dumped while willow biomass can be used for the generation of energy. However, we choose the comparison with the hyperaccumulator here because for testing different methods for the assessment of the value of the phytoremeidation function we needed an example that is sufficiently different from the system of biomass production combined with phytoremediation.

5.3. Choice of the optimal biomass systems to be combined with phytoremediation

In our case study area the production of willow for phytoremediation is the best choice because amongst all biomass crops willow is most effective in removing Cd, the critical contaminant in the study area, from the soil (Fernando et al., 1996; Schmidt, 2003a) and therefore allows the farmers to perform (high valuable) vegetable production within short term. In our case study the short time needed to clean the soil was the most important reason to choose willow and even if the farmer would not be rewarded for the biomass, phytoremediation would have a benefit for him. Because heavy metal containing biomass needs specific technologies, phytoremediation by willow may appear as a feasible option only in regions where adequate combustion technology is available. However, the costs and the energy consumption of biomass transport are not dominant over biomass production (Hamelinck et al., 2005). Therefore, phytoremediation by willow and a (long distance) transport of the biomass to the nearest combustion unit that can deal with the combustion of heavy metal containing biomass appears here as the best feasible option.

There are other biomass crops that can also be attractive options for the combination with phytoremediation under different settings. Corn is known as a crop being able to accumulate mainly lead (Pb), but also zinc and Cd (Huang and Cunningham, 1996; Schmidt, 2003a), and would therefore be an appropriate crop for the cleaning of Pb contaminated areas. Compared to willow corn has the advantage that it can be managed with conventional farming equipment. A potential biomass application system for corn is the production of ethanol from the grain and the combustion of the straw. Sunflower, effective in accumulating mainly copper (Cu) and Pb (Kayser et al., 2000), can be an alternative for a system combining the production of oil (e.g., for biofuels) and phytoremediation on sites contaminated with Cu. However, for all these crops and contaminants, calculations and preferably practical experiments, should prove suitability in a specific situation.

The choice of the best biomass crop for phytoremediation in the first place depends on the kind of contamination to deal with. Further determinants are the potential value of the cleaned area, the options of using the biomass and the potential income from biomass production. The hedonic price analysis can provide decision support because it can be used to calculate the value of phytoremediation under different settings and deliver results that enable the choice of the most economic system.

6. Conclusions

The land use function phytoremediation has a positive economic value for farmers and for authorities. This value depends on:

1. The methodology used for the assessment of the value.
2. The value of the products that can be produced after the contaminated soil has been cleaned by phytoremediation. This value is determined by the ecological-climatic and soil conditions of the area, i.e., the potential for producing high value crops, and the market situation, i.e., the possibility to sell high value products.
3. The depreciation period, which is here the length of the period in which high value crops will be produced after cleaning of the soil.
4. The time needed to clean the soil, which depends on the kind of contaminating heavy metal and the contents of heavy metals in the soil.
5. The height of previous investments done by the farmers on the contaminated area, e.g., for irrigation facilities.

6. The costs for phytoremediation, which depend on the production costs for the remediation crop, the additional costs for the treatment of heavy metal containing biomass and the income from selling biomass and subsidies.

The valuation methods applied here do not deliver results of the same quality. For the assessment of the economic value of the phytoremediation functions we recommend the hedonic price analysis because:

(a) the value assessed by the willingness-to-pay approach is too strongly influenced by the individual perception and preferences of the people,
(b) the results of the hedonic price analysis better reflects the realistic value of the phytoremediation function for the farmers than the results from the substitution cost method,
(c) it can serve as decision support for choosing the optimal biomass/phytoremediation system,
(d) it delivers results that are relevant also on macroeconomic level.

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