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Willow short-rotation coppice in multiple land-use systems: evaluation of four combination options in the Dutch context

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Abstract

Introduction of energy crops in multiple land use may be an opportunity to increase the overall land-use efficiency, improve energy crop competitiveness and enhance its introduction in regions with intensive land-use, such as Northwest Europe. In this study, we evaluated the opportunities for energy crops in multiple land-use on three criteria: combinations should be biophysically feasible, they should have a positive effect on energy crop financial competitiveness, and their potential area should be significant. We studied four land-use combination options for willow short-rotation coppice in The Netherlands: with groundwater quality protection, drinking water production, conservation of traditional willow coppice flora and fauna, and use as an ecological corridor.

Biophysically, almost all combination options studied are feasible, although some have sub-optimal willow yields. Two out of four of these options had a significant positive effect on energy crop competitiveness, but calculations contain major uncertainties. The potential area of these two may be significant to the Dutch renewable energy targets. The results imply that multiple land-use improves opportunities for energy crops in The Netherlands, but it will not be a panacea for large-scale introduction.

Keywords: Willow short-rotation coppice; Multiple land use

Abbreviations: GEA, groundwater extraction area; GPA, groundwater protection area; LUR, land-use requirement; LUT, land-use type; MLU, multiple land use; SLU, single land use; SRC, short-rotation coppice.

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1. Introduction

Land, as a resource to fulfil human needs, has become increasingly scarce [1]. In a densely populated country like The Netherlands, this can be observed in rising land prices and increasing land-use efficiency and intensity, in terms of value added per ha per year, in agriculture as well as other sectors. In this context, the introduction of energy crop cultivation (energy farming) as a new type of land use will be difficult,

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especially since the value added of energy crops as a production means is relatively low compared to, e.g. food crops, being an end product. Production costs do not easily meet the prices a power plant is willing to pay for energy crops.

The urge for overall efficient land use is an incentive for multiple land use: producing more than one type of product or service on the same tract of land, thereby raising the total value added [2]. Since the cultivation of energy crops like willow is generally described as low input and environmentally friendly compared to common high-input agriculture (e.g. [3]), combination with the production of other products or services may improve opportunities for energy crop introduction. The purpose of this study is to evaluate whether multiple land use is a useful strategy for the enhancement of energy crop introduction in The Netherlands.

We assume that this is the case if three criteria are met (methods shortly described in Section 2):

1. There are types of land use that can be combined to energy cropping in biophysical terms, i.e. in terms of their land-use requirements such as fertilisation, biocide use and other inputs and activities on the land;
2. In such combinations, production costs for energy crops are lower compared to single land-use energy cropping;
3. The potential energy crop production area in multiple land use is significant, e.g. compared to the national demand for energy crops as indicated in policy documents.

A wide range of potential combination options for energy farming has already been suggested [4–8], especially with willow in short-rotation coppice (SRC) as the energy crop. We selected four combination options, based on our initial estimate of feasibility, and on data availability. These are groundwater protection and willow SRC (Section 3), drinking water production and willow SRC (Section 4), conservation of the traditional willow coppice natural features and willow SRC (Section 5), and willow SRC in ecological corridors (Section 6). We end with discussion and conclusions, on the proposed methods as well as the results.

2. Methods and general assumptions

2.1. Biophysical feasibility

As stated, multiple land use will only be useful for energy crop introduction if there are combinations that are biophysically feasible. In Londo et al. [2], we have proposed a method for exploration of multiple land-use options within a land holding (farm or comparable). This method contains a 'rapid appraisal' phase for a qualitative or semi-quantitative biophysical feasibility estimation of multiple land-use types. The method is based on common methodology in land evaluation and land-use planning [9]. For the combined production of two products or services, this phase can be schematised as in Fig. 1. First, for each product or service to be combined, the Land Use Type (LUT) is specified: a general description of the land use delivering the product or service. Examples of LUTs are 'arable agriculture,' and 'nature conservation.' These types are specified in their Land Use Requirements (LURs); i.e. the physical or other inputs or land characteristics necessary for the LUT. Examples of LURs are 'a minimum fertilisation level

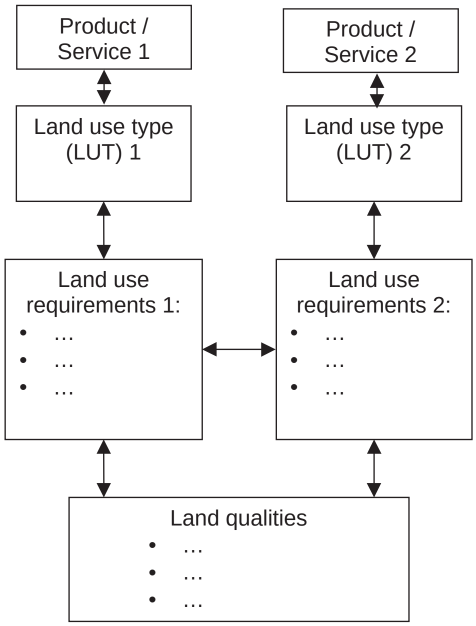

Fig. 1. A rapid appraisal for potential multiple land-use types [2].

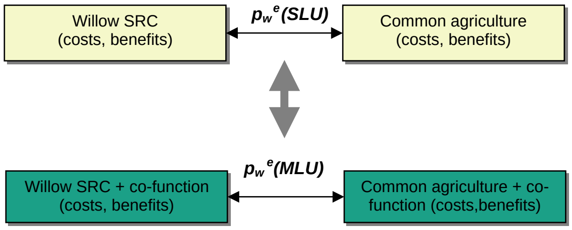

Fig. 2. Comparison between break-even prices for willow ($p_{\mathrm{w}}^{\mathrm{e}}$) in single land-use (SLU) and multiple land-use (MLU) systems.

of x kg N ha^{-1} year^{-1}', or 'an average groundwater table of y cm below ground level'. Subsequently, the LURs of two different LUTs are compared with each other, to see whether they conflict or compete for a shared resource. If the requirements do not exclude each other, the combination is biophysically feasible. Finally, the available land qualities should meet the combined set of LURs.

2.2. Financial evaluation

In this study, production costs for willow wood for energy are assessed in a situation where willow as a crop has to compete for land with other (food) crops. This competition can be expressed in a break-even price: the price a willow buyer (e.g. a power plant) has to pay a land holder to make willow SRC equally attractive as its competing (current) land use, such as common agriculture for food crops (see Fig. 2). In a single land-use situation, the cultivation of willow SRC will be attractive for a land holder when his profits for this crop are at least equal to those of the common agriculture he currently practices. The break-even price for willow in single land use ($p_{\mathrm{w}}^{\mathrm{e,slu}}$), at which the land holder's profits for both types of land use are equal, can be calculated by

$$p_{\mathrm{w}}^{\mathrm{e,slu}} = \frac{(B_{\mathrm{c.a.}}^{\mathrm{slu}} - C_{\mathrm{c.a.}}^{\mathrm{slu}}) + C_{\mathrm{w}}^{\mathrm{slu}}}{y_{\mathrm{w}}^{\mathrm{slu}}}, \quad (1)$$

in which $y_{\mathrm{w}}^{\mathrm{slu}}$ is the willow yield, $B_{\mathrm{c.a.}}^{\mathrm{slu}}$ are the common agriculture benefits, $C_{\mathrm{c.a.}}^{\mathrm{slu}}$ the management costs of common agriculture, and $C_{\mathrm{w}}^{\mathrm{slu}}$ the management costs of willow SRC, all for the single land-use systems (all quantities ha^{-1} year^{-1}). Note that other costs, such as land rent, can be deleted from the comparison.

In multiple land use, i.e. on land where either common agriculture or willow SRC is combined with another land-use type, this break-even price may be different (see Fig. 2). When, for example, willow as well as common agriculture are combined with another land use type 1, and both combinations deliver the same amount of the corresponding product or service 1, the break-even price for willow SRC in multiple land use $p_{\mathrm{w}}^{\mathrm{e,mlu}}$ can be calculated as

$$p_{\mathrm{w}}^{\mathrm{e,mlu}} = \frac{(B_{\mathrm{c.a.}}^{\mathrm{mlu}} - C_{\mathrm{1+c.a.}}^{\mathrm{mlu}}) + C_{\mathrm{1+w}}^{\mathrm{mlu}}}{y_{\mathrm{w}}^{\mathrm{mlu}}}, \quad (2)$$

$y_{\mathrm{w}}^{\mathrm{mlu}}$ being the willow yield, $B_{\mathrm{c.a.}}^{\mathrm{mlu}}$ being the benefits of common agriculture, $C_{\mathrm{1+c.a.}}^{\mathrm{mlu}}$ being the management costs of the system (1+common agriculture) and $C_{\mathrm{1+w}}^{\mathrm{mlu}}$ the management costs of the system (1+willow), all for the multiple land-use systems. Note that, in this comparison, the benefits of product or service 1 need not be known, as they appear on both sides of the equation.

If the break-even price in multiple land use ($p_{\mathrm{w}}^{\mathrm{e,mlu}}$) is lower than the break-even price in single land use ($p_{\mathrm{w}}^{\mathrm{e,slu}}$), willow SRC in multiple land use will be cheaper than willow SRC in single land use, and vice versa. In short, this ratio indicates the effect of the multiple land-use option on willow SRC financial competitiveness.

A disadvantage of this method is that it is a comparison between two systems which do not deliver identical sets of products and/or services. A large-scale shift from combination (1+2) to (1+3) may cause macro-economic effects such as changes in market prices, thereby changing inputs for the comparison. In this study, we do not deal with this effect: we assume that a shift to willow SRC systems, in whatever form, will develop at first on a relatively small scale, thereby having a negligible effect on market prices.

In this kind of calculations, assumptions on the valuation of the farmer's capital and labour are always subject to discussion [10], as well as transaction costs of a farmer's shift from food to energy cropping. These assumptions may strongly influence the calculated break-even prices, in a comparable manner for multiple as well as single land use. However, we are mainly interested in relative break-even price *differences* between the multiple and single land-use options, which are less vulnerable to differences in these assumptions.

Table 1
Willow cultivation in SRC as a land-use type in The Netherlands: summary of land-use requirements, corresponding ranges and optima

Variable	Range of tolerance[a]	Optimum	Source
Plantation area	10–100 ha	—	
Edge-to-area ratio	Perfectly square—irregular	Square	
Soil type	Practically any soil	—	
Groundwater table	'Moist-dry' (Dutch Groundwater tables I–V[b])	Gt III	[53]
Willow species and variety	*S. viminalis*, *S. alba*, diverse varieties	—	[15,54]
Planting density	5000–30, 000 cuttings ha^{-1}	Depends on variety and situation	[11,15,54]
Fertilisation	From absent to intensive	N: 60–120 kg ha^{-1} P: 20–50 kg ha^{-1} Dependent on, e.g. soil type	[16,53,55]
Protection against weeds	From absent to intensive Chemically, mechanically	Intensive management in year of establishment. Thereafter, willow outcompetes most weeds	[56,57]
Prevention/abatement pests/diseases	From prevention: mixing varieties, using resistant varieties to (chemical) abatement	Prevention of severe outbreaks by variety choice and mixing	[15,28,58]
Rotation time	2–5 years	3–4 years	[16,53,55]

[a]Within these ranges yield reduction may occur: this need not be problematic if the total performance of the combined LUT is better than that of separated single LUTs on the same amount of land (see Section 2.1).

[b]In Dutch agro-hydrology, soil wetness is often expressed in groundwater table classes (Gt's). The lower the Roman number, the wetter the soil. Gt I: groundwater level in winter < 20 cm, in summer < 50 cm. Gt V: winter < 40 cm, summer > 120 cm.

2.3. Potential area evaluation

The third criterion is whether the potential area for the multiple land-use combinations is significant in relation to the targeted area for energy cropping in The Netherlands. These targets were derived from several policy studies.

The potential area is derived from the area needed for the land-use type with which willow SRC is combined:

- For land-use types that are currently fulfilled on a given area, this existing area is considered the potential area for the combination with energy crops;
- Furthermore, attention is paid to policy targets. For example, if there are ambitions to increase or decrease the area with that land-use type, these ambitions are taken into account.

2.4. Assumptions on willow SRC

In the following sections, willow SRC as a land-use type is compared to other land-use types. In Table 1, we shortly give the main land-use requirements of willow SRC, as input for this comparison. For each LUR, we estimate a range within which willow SRC is possible, and a value optimal for the cultivation.

Furthermore, we assume that, in the Dutch situation and with proper management, average yields of 10 odt ha^{-1} $year^{-1}$ are feasible. When management is sub-optimal, yields will be lower. However, current knowledge is insufficient to predict exactly what yield a specific suboptimal management set will give: in such cases, a yield reduction is estimated based on literature or expert guess. Willow management costs were derived from Coelman et al. [11].

3. Groundwater protection: groundwater protection areas

The protection of Dutch groundwater quality is important, since circa 60% of total Dutch drinking water is extracted groundwater [12]. Furthermore, many nature reserves in The Netherlands depend on clean,

Table 2
Land-use requirement comparison of biomass for energy and groundwater protection. The digit 1 indicates that the land-use type sets a (positive or negative) demand on this requirement, a 0 indicates indifference. A combination 1-1 therefore indicates a potential conflict

Product/service:	Biomass for energy	Clean groundwater suitable for consumption[a]
LUT: land-use type characteristics	• Willow plantation • High productivity per ha • Mechanical management	• Groundwater layer • Water is extractable • Water is and remains clean
LURs: land-use requirements		
Land characteristics:		
1. Area size	1	1
Specification:	10–100 ha	10–100 ha
2. Edge-to-area	0	0
3. Soil type	0	0
3a Soil type drillability	0	1
4. Groundwater table	1	0
5. Extractable groundwater volume	1[b]	1[b]
Land design/arrangement		
6. Willow species	1	0
7. Planting density	1	0
8. Planting structure	1	0
Land management		
9. Fertilisation	1[c]	1[c]
10. Weed control	1	1
Specification:	See text	See text
11. Pest/disease control	1	1
Specification:	See text	See text
12. Rotation	1	0
13. Ploughing of soil	1	1
Specification	max. ca 1 m	< 2.5 m

[a] Here, we mainly consider groundwater protection areas for drinking water, not for groundwater-dependent reserves. Regulations in these areas are determined by provinces (regional authorities) and vary slightly per province. This table is based on the province Zuid-Holland's regulations [37]. In these regulations, some specific types of land-use are also banned (such as industrial activities, waste dumping, and graveyard establishment). These are not relevant in the case of combination with energy farming.

[b] Willow SRC as well as drinking water production extract groundwater from the soil, but from different soil layers; willow SRC uses shallow groundwater, drinking water is extracted from deeper aquifers. Willow SRC water use is comparable to that of grassland, winter wheat, sugar beet and maize [3] which are common crops in groundwater protection areas. Considering the general precipitation surplus in The Netherlands, we assume that the land-use types are not conflicting on this requirement.

[c] In groundwater protection areas, national standards for net nutrient emissions to the soil apply. Willow SRC meets these standards [24].

nutrient-poor groundwater. In order to protect the quality of this resource, the regional governmental authorities (provinces) assign *groundwater protection areas* (GPAs), relatively broad zones around extraction wells or reserves, in which they can apply special regulations [13]. There is circa 140,000 ha of GPAs in The Netherlands [14], mainly surrounding drinking water extraction wells. Several types of land use are still possible in these areas, including agriculture. However, the regulations can be a limiting factor, e.g. when fertilisation is restricted. This may generate a competitive advantage for willow SRC with its low inputs. In this section, we compare willow SRC within the restrictions of GPAs to common agriculture within the same restrictions.

3.1. Biophysical feasibility

A comparison of land-use requirements for willow SRC and groundwater protection is given in Table 2. All shared requirements of willow SRC and ground-

Table 3
Biocide use in willow SRC, grassland, and some arable crops, and their corresponding threat to groundwater quality expressed in groundwater pollution points

	In kg ha^{-1} year^{-1}		In gpp ha^{-1} year^{-1} [a]	
	Average	Range	Average	Range
Willow[b]	0.7	—	100	—
Grassland[c]	0.1	0–0.8	70	0–350
Winter wheat[c]	3.0	—	1000	200–1500
Potatoes[c]	5.7	—	4200	50–20,000
Sugar beet[c]	3.4	—	1300	100–3500

[a]For details on groundwater pollution points (gpp) calculations see [18]. This method is applied with increasing popularity to evaluate and compare chemical crop protection regimes. Roughly, a 100 gpp score of a substance will cause a concentration of 0.1 μg l^{-1} of that substance in the underlying groundwater layer between 1 and 2 m depth. This 0.1 μg l^{-1} is the EU standard for any biocide in drinking water [61]. Calculated for a soil with 1.5–3% organic matter.

[b]Sources: [3,59]. Constructed biocide regime for a 25-year plantation lifetime. General herbicide Roundup (glyphosate) every first year after planting or harvest; Starane (fluroxipyr) treatment against hedge bindweed (*Calystegia sepium*) every first year after planting or harvest; Tilt (propiconazool) treatment against rust (*Melampsora spp.*) total 3 times in 25 years, Decis (deltamethrin) treatment against *Phyllodecta vulgatissima/vitellinae* 7 times in 25 years. This is a relatively intensive biocide use regime.

[c]Source: [60]. Data are examples of plausible biocide regimes for GPAs, generally lower than the national averages. Data on ranges in applied kilograms in arable crops are lacking in this study.

water protection appear to be combinable, which implies that the combination is biophysically feasible. The LUR weed, pest and disease control needs some explanation.

3.1.1. Weed, pest and disease control

Although successful experiments have been carried out in willow SRC with integrated pest management, and the selection of varieties and variety mixes to prevent disease outbreaks, limited amounts of biocides are commonly used, as well as weed-controlling chemicals in the establishment phase of the crop [11,15,16]. In GPAs, national regulations on biocide use apply, aiming at a reduction of biocide use, and a long-term ban on the most polluting substances. For this study, we constructed a regime for willow SRC, and compare this regime to other types of agriculture (Table 3). Biocide use is evaluated in terms of kg active substance ha^{-1} year^{-1}, and in groundwater pollution points (gpp) ha^{-1} year^{-1}. The latter unit is part of the Dutch environmental yardstick for biocides [17,18], which takes specific substance mobility and persistence into account.

In willow SRC, biocide use (in kg ha^{-1} year^{-1}) can be on average a factor 4–5 lower compared to arable land. Compared to grassland, there is no advantage. Furthermore, according to the gpp calculations, the biocides used in willow SRC are relatively harmless to groundwater quality.

3.2. Financial competitiveness

For the nutrient emissions, the current fertilisation policy is valid on The Netherlands as a whole, not only to the GPAs, and the advantage of willow SRC is not specific for the combined land use. Only if drinking water companies are to set up a bonus system for an extra reduction of nutrient outputs to groundwater, the low mineral losses may be valued financially. Former incentive schemes by drinking water companies, that have been abandoned since the new fertilisation policy was introduced, lie in the order of magnitude of tens of euros ha^{-1} [13], leading to break-even price reductions of 1% or 2%.

For biocides, several drinking water companies have introduced financial incentives towards farmers for decreasing their biocide use. Illustrative are the agreements two drinking water companies made with farmers unions, in which individual farmers can obtain allowances of ca. €50 ha^{-1} year^{-1}, if they reduce their biocide emission in terms of gpp substantially [19,20]. When we use data of Vlasblom [21] for competition with winter wheat, a break-even price without subsidies would be €137 odt^{-1}; in GPAs with a biocide subsidy it would be €133 odt^{-1}, a decrease of less than 3%.

The relatively low mineral losses and biocide use of willow SRC only lead to a minor financial competitive advantage compared to common agriculture, and only if drinking water companies or provinces will be willing to set up allowance schemes. Therefore, we consider the financial advantage of this option negligible in current settings.

3.3. Potential area

The potential area of this option is considerable: assuming that 55% of all groundwater protection areas is agricultural land (which is the national land use average [22]), this means a physical potential of 77,000 ha. For the future, this area is not likely to increase.

4. Production of drinking water: groundwater extraction areas

Groundwater extraction areas (GEAs) are located within the groundwater protection areas, in the zone directly surrounding the extraction wells. Regulations for land use in these areas are stricter than those for protection areas, but apply to the same LURs as in GPAs. As a consequence, common agriculture with fertilisation and biocide use is a rare phenomenon in extraction areas: most of the land is owned and managed by the drinking water companies themselves [23]. Relatively often, they choose for an ecological type of management, like (conversion into) woodland or other kinds of nature, or low-input cereal production [14]. In this section, we consider these types of management to be the land-use types competing with willow SRC.

4.1. Biophysical feasibility

The land-use requirements for drinking water production in GEAs are of identical types as in GPAs (see Table 2). Regulations on shared requirements with willow SRC (fertilisation and biocide use for weed, pest and disease control) are stricter. Willow SRC will meet these requirements, but possibly with a decrease in productivity. Nevertheless, the combination is still biophysically feasible.

4.1.1. Fertilisation

In most provincial regulations, fertilisation is forbidden in GEAs. This is one of the reasons why there is hardly any common agriculture. However, in some cases, artificial fertiliser is allowed [24], and exemptions may be obtained, e.g. for compost or solid manure [25]. Given the relatively low mineral losses in willow SRC, we assume that two situations may occur:

- Fertilisation on willow SRC remains strictly forbidden. This will lead to decreased yields in the long term. However, since most Dutch lands are relatively nutrient-rich, this yield decrease will occur after a significant number of years. Based on Herder [26], we assume that in a 15-year period yields will drop to 50% and then remain constant.
- Limited fertilisation with artificial fertiliser or compost is allowed; fertilisation is no limiting growth factor.

4.1.2. Biocide use

In most GEAs, the use of biocides is forbidden [24], although exemptions may be obtained. Many experiments exist in which willow SRC is successfully protected with non-chemical methods such as mechanical weed control and mixed planting of different (resistant) varieties [27,28]. Given these results, and given a possible exemption for use of a well-degradable herbicide such as glyphosate in the establishment year, we assume that willow SRC will not be severely hampered by this prohibition, and that yields will not be diminished by it.

4.2. Financial competitiveness

In GEAs, willow competes with other co-land use types such as low-input (minerals and biocides) agriculture of cereals, and the development of natural systems like marshes, heathland, and woodland [23]. The comparison with low-input arable farming can be done on the basis of break-even prices. Since no data are available on arable crops under limited or non-fertilisation and non-biocide regimes,

Table 4
Willow break-even prices in and outside groundwater extraction areas, with different fertilisation regimes and yield assumptions

Item	GEA: assuming no fertilisation		GEA: assuming limited fertilisation[a]		Non-GEA: standard fertilisation[b]	
	Winter wheat	Willow SRC	Winter wheat	Willow SRC	Winter wheat	Willow SRC
Relative yield compared to normal fertilisation	50%	67%	67%	100%	100%	100%
Crop benefits (€ ha^{-1} $year^{-1}$)[c]	1100		1300		1800	
Crop management costs (€ ha^{-1} $year^{-1}$)[d]	450	380	540	430	620	490
Willow break-even price (€ odt^{-1})	150		120		160	

[a]Limited fertilisation defined as 50% of normal level.
[b]Standard organic farming option, not comparable to the conventional winter wheat option in Section 3. Currently, the margin on organic wheat is higher than the margin on conventional wheat in The Netherlands [62].
[c]Benefits based on agricultural statistics [62]. Including a EU grant of €380 ha^{-1}.
[d]Source: Jalink et al. [23], Spigt and Janssen [62].

this can only serve as a (hypothetical) illustration. Assuming that willow SRC in GEAs competes with low-input winter wheat, we calculated the corresponding willow break-even prices for a situation with limited fertilisation and with non-fertilisation (see Table 4). We assumed dissimilar yield reductions for wheat and willow, because willow needs significantly less fertilisation than arable crops [3]. Compared to the situation in single land use outside GEAs, the willow break-even price is ca. 25% lower in GEAs, indicating improved competitiveness. However, given the uncertainties in the assumptions underlying these calculations, we consider this only an indication that willow SRC may be financially more attractive in GEAs compared to common, non-restricted areas, when it competes to arable land.

For the natural systems, we compared the costs of several of these ecological management types [23] to that of willow SRC. We excluded management types that can only apply in specific (naturally valuable) situations such as bogs and open water. Costs were specified in establishment costs (like removal of an over-fertile topsoil) and (yearly) management costs. Establishment costs were converted into annuity (7%) over 25 years. Fig. 3 indicates that willow SRC is a relatively low-cost way of management of the land compared to the other options.

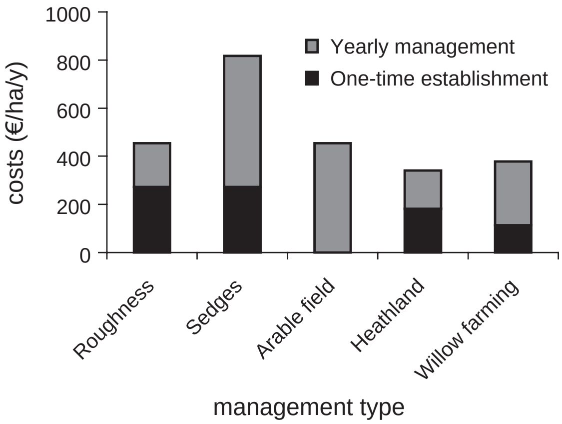

Fig. 3. Comparison of management costs for different land-use types in groundwater extraction areas. Data from Jalink et al. [23] and Coelman et al. [11].

In GEAs, the financial competitiveness for willow SRC is considerably better than in single land use.

4.3. Potential area

The total area of GEAs is ca. 8000 ha. Approximately 5000 ha of this is currently owned by the drinking water companies [23]. Especially these areas can be interesting for willow SRC. This number should be regarded an upper limit, however, since part of this area may be nature reserve or open water. This area is not likely to increase in the coming decades.

5. Willow production for energy on traditional willow coppice

Traditional willow coppice is well known in The Netherlands for its nature and landscape features. The question is whether this nature and landscape land-use type can also be combined to modern willow SRC for energy. Traditional willow coppice has a long history producing wood for all kinds of purposes, e.g. baskets, barrel hoops and bean poles [29,30]. Up to these days, willow switches have also been used as materials for the construction of dikes. However, due to material substitution most of these markets have declined, and most coppice plots have been converted into other types of land use. The major part of the remaining traditional coppice is maintained by governmental and private nature management organisations for landscape and conservation purposes. This is because traditional willow coppice, especially in the river and tidal floodplains, has a characteristic flora and fauna [31], also acknowledged in Dutch nature policy [32]. However, given the poor market perspectives for willow twigs and the costs of traditional management, the traditional willow coppice land use is under pressure. While the former outlets decline, wood for energy can be a new product, improving the opportunities for conservation of the specific nature qualities. Two options can be identified in this context:

1. Energy wood as a new product for the traditionally managed coppice;
2. Introduction of modern techniques in willow coppice management in order to increase productivity and/or reduce management costs, while conserving the specific natural characteristics of the coppice.

Both options are regarded in the context of the current use of willow switches for (mainly) infrastructure as a competing market to energy wood.

5.1. Biophysical feasibility

In the first option, biophysical feasibility of the combination is already proven: the current land use need not be altered; only the use of the product will change. However, more wood may be harvested for energy, since only switches with a minimal length can be used in infrastructure. We assume that a 10% yield increase is possible, compared to the current yield for infrastructural purposes.

In the second option, the question is whether the specific nature and landscape qualities of traditional willow coppice can be combined with modernised willow energy farming. The potentials for traditional coppice flora and fauna in modern willow SRC for energy are illustrated by a comparison of fauna in Dutch within-dike traditional willow coppice to fauna in British experimental willow-for-energy plantations, which indicated that species compositions are relatively similar [24].

We translated the characteristics of traditional willow coppice relevant for its specific natural qualities into a set of land-use requirements. The comparison with the modern willow SRC land-use requirements is shown in Table 5. Of all potential conflicts, the connected requirements of planting density, planting structure, plantation lifetime, and stool management appear to be the major bottlenecks. In order to obtain a well-developed ground vegetation, the plantation should not be ploughed for several decades. In modern plantations, lifetime is restricted to 20–25 years [11,33], mostly because of increasing stool mortality. In order to keep vital stools for over 25 years, natural thinning should occur, and the remaining stools should be harvested with care to keep them 'round', and well developed. Such broad, vigorous stools are another characteristic feature of traditional willow coppice. Modern machinery usually harvests in a flat surface, making the stools more broad and open (see Fig. 4), and thereby more vulnerable to frost, diseases and tearing [34]. Such harvesting entails poor stool development and a relatively short plantation lifetime. Therefore, technical innovations are needed to make more stool-friendly mechanical harvesting possible and reconcile these conflicting LURs.

5.2. Financial competitiveness

In the option with traditional coppice management, i.e. with manual harvesting, we can estimate the biomass price needed to make willow for energy-competitive to traditional uses such as

Table 5
Land-use requirement comparison of biomass for energy and specific traditional willow coppice natural vegetation

Product/service:	Biomass for energy	Specific natural vegetation of traditional willow coppice[a]
LUT: land-use type characteristics	• Willow plantation • High productivity per ha • Mechanical management	• Willow plantation • Dense undergrowth • High densities of e.g. insects, birds • Broad, well-established stools
LURs: land-use requirements		
Land characteristics:		
1. Area size	1	1
Specification:	10–100 ha	ca. 0.5–5 ha[b]
2. Edge-to-area	0	0
3. Soil type	0	0
4. Groundwater table	1	1
Specification:	Gt II–Gt V[b,c]	Gt I–Gt III[b,c]
Land design/arrangement		
5. Specific willow species	1[d]	1[d]
Specification:	*S. viminalis*, *S. alba*, mixtures	*S. alba*, *S. triandra*
6. Planting density	1	1
Specification:	5.000–30.000 st ha^{-1}	2.000–5.000 st ha^{-1}
7. Planting structure	1	1
Specification:	Regular, for mechanisation	Irregular, for 'natural' effect
Land management		
8. Fertilisation	1[e]	1[e]
9. Weed control	1[f]	1[f]
10. Pest/disease control	1[g]	1[g]
11. Rotation	1	1
	3 or 4 years	3 or 4 years
12. Plantation lifetime	1	1
Specification:	See text	See text
13. Harvest method	1	1
Specification:	See text	See text
14. Accessibility	0	1

For digit explanation, see header Table 2.
[a]Based on [32,63].
[b]We assume there is sufficient overlap between the two LUTs not to let this LUR be problematic.
[c]See note 2, Table 1.
[d]*Salix alba* and *S. triandra* usually give better-developed stools than *S. viminalis*, and are most popular in traditional willow coppice [64]. The current tendency to mix species and varieties for pest and disease prevention implies that there will be no conflict in these LURs.
[e]Traditional willow coppice fields are mostly located on relatively nutrient-rich, clay soils, and host corresponding undergrowth. Modest fertilisation will not drastically change their environmental conditions.
[f]Rich undergrowth is an essential feature of traditional willow coppice, will lead to some yield reduction.
[g]Willow coppice is also well known for its rich insect fauna, and the use of chemical pesticides should also be avoided. Given currently developed alternative methods, pest and diseases need not be an inhibiting factor.

hydraulic engineering. This is not a break-even price as in Eqs. (1) and (2), since only product application changes, not the land use. Nevertheless, such a price can be compared to break-even prices for energy wood in single land use on agricultural land, to indicate the competitiveness of this type of production. In practice, willow coppice management organisations allow specialised workers to harvest the coppice for free and sell the wood by themselves. A coppice manager indicated this price around €0.8 per bundle of 13 kg [34] (or €125 odt^{-1}, assuming a 50% moisture content), a price below the current harvesting costs, assuming a reasonable hour's wage for the worker [34]. This is in the same order of magnitude of other

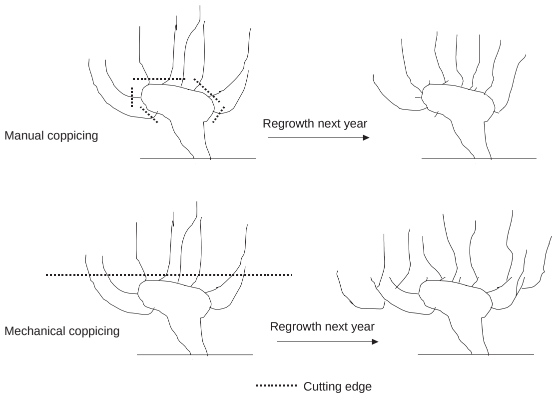

Fig. 4. Effects of manual and mechanical harvesting on well-developed coppice stools.

willow-producing systems, such as intensive culture on agricultural land (ca. €100–140 odt^{-1} [8]). This reasoning implies that this energy wood production strategy in multiple land-use will not be significantly cheaper than energy wood production in single land use.

In the second option with mechanical harvest, the same reasoning can be followed if the harvested material is also of sufficient quality for use in, e.g. hydraulic engineering. However, if the quality would be lower, this competing use is eliminated, and simple production costs may be calculated. Assuming machinery prices as in Coelman et al. [11], standard agricultural hour's wages, and an average (relatively low) yield of 5 odt ha^{-1} year^{-1}, give a willow production price of €57 odt^{-1} in a 3-year rotation, and €42 odt^{-1} in a 4-year rotation. This is a significantly lower price than other willow production systems [8], mainly due to the fact that in this reasoning there is no competing land use or product application. Therefore, if it is possible to modernise traditional willow coppice by modern SRC techniques (especially in stool-friendly mechanical harvesting), maintaining nature and landscape features, this option will probably provide cheap energy wood.

Besides financial considerations, it should be borne in mind that willow SRC for energy on existing traditional coppice lands may be introduced more easily than willow SRC on common agricultural land. Adapting current product application or modernising existing coppice, provided the nature and landscape features are maintained, is a more logical shift than replacement of annual foods with perennial willow.

5.3. Potential area

While in the past, large areas in the Dutch river areas were planted with willow, this area has decreased strongly in the last decades. Most recent coppice data on areas were found in Schepers and Haperen [31], and were derived from 1988 Dutch woodland statistics. These data indicate areas of 500 ha coppice in the floodplains, and 1000 ha in-dike coppice. These areas may still have decreased in recent years. However, traditional willow coppice might be re-introduced in some ecological restoration plans for Dutch floodplains and in more recent plans for floodplain draining capacity improvement.

6. Willow SRC as an ecological corridor

A major feature in current Dutch nature policy is the establishment of a National Ecological Network of nature conservation areas. This network, introduced in the first Nature Policy Plan [35], will also contain ecological corridors, enabling species to migrate from one core reserve area to another.

For willow SRC, ecological corridors may be interesting since they are relatively open to combination with other land-use types [35,36]. Therefore, we explored to what extent willow SRC can serve as a building block for an ecological corridor. It is relatively difficult to compare the corridor function of willow SRC to other land-use types with that function, since currently ecological corridors are only roughly sketched on paper (e.g. [37,38]). Therefore, we could solely assess the suitability of willow SRC as a corridor, and did not compare it to other land-use types. This also implies that we do not deal with other types of corridor that may generate energy wood as a by-product, such as common woodland.

6.1. Biophysical feasibility

Many of the 12 Dutch provinces responsible for ecological corridor policy [35] have developed a specific ecological corridor plan, and have selected guide species, animal species for which the corridor should

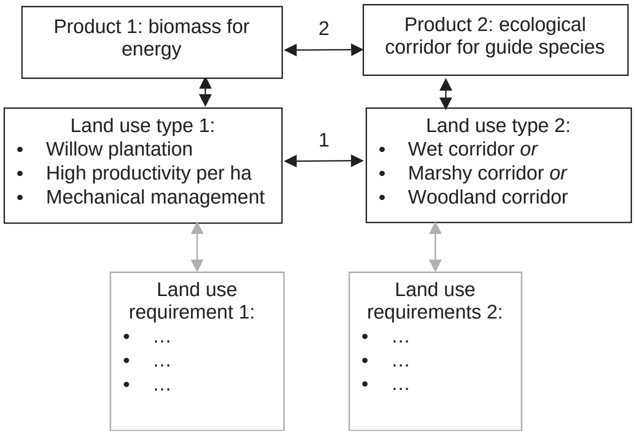

Fig. 5. Simplified feasibility assessment method for willow SRC as an ecological corridor.

function. Their assumption is that guide species serve as indicators for many others. Most provinces already have selected their guide species, but the specific location and design of the corridors is still under discussion.

For the feasibility assessment, one should ideally identify all guide species and, given their habitat and other ecological characteristics, define the corresponding corridor land-use types and accompanying land-use requirements. However, such an approach would require extensive research. We simplified this approach in order to estimate the suitability of willow cultivations as an ecological corridor. This method, shortly summarised in Fig. 5, consists of two steps:

1. Identification of ecological corridor land-use types in a number of policy reports on the subject [37–43]. Since willow SRC most resembles (young) woodland, we limited ourselves to guide species for woodland-like corridors, and excluded LUTs such as wet or meadow-like corridors.
2. From several field surveys of fauna in willow SRC [44–46], we checked whether these guide species were observed (structurally or incidentally) in willow SRC plantations. If so, we assume that these plantations will or may be suited as an ecological corridor for this guide species. Since plantation survey data were only available on songbirds, butterflies and mammals (comprising approximately 75% of all guide species), we limited the comparison to these three species groups.

Table 6 summarises the total numbers of guide species per group, and the part of these numbers that can be expected to use willow plantations as a corridor. It illustrates that willow SRC plantations can be a functional part of certain ecological corridors, since ca. 30–50% of the selected guide species have been found in willow SRC.

It should be noted, however, that a substantial part of the survey data on willow plantations was obtained in the United Kingdom, and there may be differences in species behaviour between the British and continental populations. Furthermore, the presence of a species in a willow plantation is not a real guarantee that it will use this land for migration. It may, for example, only use it for foraging or resting, while staying in the same habitat.

6.2. *Financial competitiveness*

There is no specific national financial instrument for the establishment and management of ecological corridors in The Netherlands. Some provinces have allocated own funding for this purpose, but in general subsidy regulations for nature conservation or desiccation abatement are applied for [47]. And in order to find financial resources, the ecological corridor land use is often combined with other, e.g. recreational or infrastructural land-use types [37,40]. As a consequence, potential financial benefits from the implementation of willow SRC as an ecological corridor alone are still unclear, and a break-even price for willow SRC in

Table 6
Guide species for terrestrial ecological corridors with woody or shrubby elements, and their possible occurrence in willow plantations

Species group	Total guide species[a]	Occurring in willow[b]		Examples of shared species
		Surely[c]	+Potentially[c]	
Songbirds	24	2	11	Marsh warbler (*Acrocephalus palustris*) Whitethroat (*Sylvia communis*)
Butterflies	29	9	12	Speckled wood (*Pararge aegeria*) Ringlet (*Aphantopus hyperantus*)
Mammals	57	19	36	Badger (*Meles meles*) Roe deer (*Capreolus capreolus*)
Of which Mice	12	5	10	Bank vole (*Clethrionomys glareolus*) Common shrew (*Sorex araneus*)
Of which Bats	21	3	3	Noctule (*Nyctalus noctula*) Serotine (*Eptesicus serotinus*)
Total	110	30 (27%)	59 (54%)	

[a]Guide species for terrestrial corridors with woody or shrubby elements. From 8 policy documents on provincial ecological corridors [37–43].

[b]Based on field surveys. For songbirds: see [46]; for butterflies: [44]; for mammals: [45]. Species that have been found in more than one provincial document were counted for every mention.

[c]Category 'surely' includes species that have been found regularly, category '+Potentially' includes these plus species that have been found irregularly, or whose presence also depends on other (external) circumstances such as soil moisture content.

ecological corridors cannot be calculated. However, an allocation of tasks in which a willow cultivator leases a corridor plantation free of charge, complying to specific corridor management rules in return, is well conceivable.

6.3. Potential area

The recent national target area for ecological corridors amounts ca. 50, 000 ha of wet and dry ecological corridor [36]. Much of this area, e.g. the wet corridors, or corridors of marshes or open vegetations, will beforehand be unfit for willow SRC. Based on eight provincial documents, a rough estimation of 2000 ha could be made of the total area of terrestrial ecological corridors in The Netherlands containing woody or shrubby area or elements. This is a maximum estimate for willow SRC in ecological corridors: some corridors will need small-scale, patchy woodland, or will consist of a linking zone of less than 5 m. Such dimensions will hardly be interesting for rational energy farming with willow.

In this context however, it is worth noting that there is persistent discussion on functioning and dimensions of ecological corridors [42,48–50]. Especially ecological scientists argue that the currently designed ecological corridors will often be inadequate and that larger corridors will be necessary; some extended, 'robust' corridors have been announced in the latest national policy document on nature conservation [36]. These developments may also increase the potential area for willow SRC in these areas.

7. Discussion and conclusions

7.1. On the results

In Table 7, the characteristics of the explored combinations are summarised, in terms of their biophysical feasibility, cost savings, and potential area.

Regarding the existence of biophysically feasible multiple land-use combinations with willow SRC, this study shows that several options do exist. In fact, almost all options studied are biophysically feasible.

Regarding the second criterion, that multiple land use should decrease break-even prices (and thereby production costs) for willow SRC, the option in groundwater extraction areas (with winter wheat as a competing crop) and the modernised coppicing on traditional coppice lands meet this criterion. However, for the option in traditional coppice, innovations

Table 7
The proposed land-use types to be combined with willow farming, their biophysical and financial feasibility and the potential land area

	Biophysical feasibility	Certainty	Effect on financial competitiveness	Certainty	Potential area (ha)	Certainty
Groundwater protection areas	Yes	+	Negligible	+	77,000	+
Groundwater extraction areas	Yes	+	25%[a]	−	5000	+
Traditional willow coppice case 1	Yes	+	Negligible	+	1000	+
Traditional willow coppice case 2	No	+	> 50%	−		
Ecological corridors	Yes	−	Unknown	−	2000	−

[a]With organic wheat as a competing crop.

in harvesting technology are required to make the option biophysically feasible. Biophysical feasibility is therefore not a guarantee for improved financial performance of multiple land-use options versus single land use.

The multiple land-use options with significant financial benefits amount to 6.000 ha, or less than 0.1% of Dutch domestic energy demand. Studies concentrating on the demand for biomass energy estimate that a contribution of between 20,000 and 100,000 ha of energy crops will be required to meet the 10% renewable energy target in the year 2020 [51,52]. Therefore, the biophysically feasible multiple land-use options with significantly decreased break-even prices for willow SRC may be significant to these targets, but their contribution to the overall domestic energy demand is negligible.

Given the results for the studied options, multiple land use appears to be biophysically feasible in many cases. Options that enhance energy crop introduction by improved financial competitiveness are much scarcer, and their potential area is limited and uncertain. It appears that multiple land use is a useful strategy for energy crop introduction, but it will not be a panacea for large-scale introduction of energy crops. However, if more multiple land-use options should be studied, financially interesting options may be found and the overall potential area may increase.

7.2. *On the applied method*

The methods introduced in Section 2 had to be adapted in most option explorations. Regarding biophysical feasibility, only in the groundwater protection and extraction options the combined land-use type could be clearly translated into land-use requirements. In the traditional coppice and ecological corridor options, clear requirements were not available, and an evaluation was done on extrapolated information (e.g. on the presence of corridor guide species in surveyed willow SRC). In the financial analyses, many data were also lacking. Therefore, some results should only be considered indicative. For example, of the competing land-use types in groundwater extraction areas, only management costs were available, and no possible benefits. In general, it still needs a considerable research effort in order to elaborate land-use types related to nature and biodiversity on the same level of detail as land-use types related to physical production, such as agriculture or willow SRC.

These methodical limitations make that the conclusions from this study should be applied with prudence. The proposed rapid appraisal method, however, provides a clear and systematic framework for a qualitative or semi-quantitative indication of combination feasibility and financial competitiveness. Per combination, some creativity may be required to adapt the method to the available data.

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