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Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach

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Abstract

The quantities and use efficiencies of nitrogen (N) fertilizer and energy input are seen as important indicators for the environmental impact of the production of energy crops. On the other hand, the high targets set in Europe for the production of biofuels will require high energy yields and efficient use of available agricultural land. The aim of this study is to describe the N, energy and land use efficiencies in relation to the N supply, for the energy crops triticale (*Triticosecale* Wittmack) – harvested as whole crop – reed canary grass (*Phalaris arundinacea* L.) and miscanthus (*Miscanthus* × *giganteus*). Field trials in Southwest Germany (48–49°N latitude) were performed to measure the biomass and bioenergy yields at different N fertilizer levels. The nitrogen use efficiency (NUE), defined as the ratio of biomass yield to N supply (sum of soil NO_3^-–N and N fertilized) and the energy use efficiency (EUE) (net energy yield/energy input), were derived from data on biomass and bioenergy yields by the boundary line approach. For all three crops, NUE and EUE decreased with increasing N fertilizer rates. NUE and EUE were at all N and energy inputs highest for miscanthus and lowest for reed canary grass. At an N supply of 100 kg ha^{-1} a^{-1}, the NUEs of miscanthus, triticale and reed canary grass were 0.35, 0.14 and 0.11 t dry biomass/kg N, respectively. At an energy input of 10 GJ ha^{-1}, the EUEs for miscanthus, triticale and reed canary grass were 54, 26 and 13 GJ bioenergy per GJ energy input, respectively. The highest net energy yields (here used as indicator for the land use efficiency) of triticale and reed canary grass were harvested at the highest N fertilizer level of 140 kg N, with maximum values of 281 and 129 GJ ha^{-1} a^{-1}, respectively. These results show that for triticale and reed canary grass, the maximization of NUE, EUE and land use efficiency are conflicting. Only for miscanthus, the N, energy and land use efficiencies were simultaneously highest at the lowest N supply level. A maximum net energy yield of 590 GJ ha^{-1} a^{-1} was harvested from miscanthus. It was concluded that the best way to maximize resource use efficiency in biomass production is to choose for the production of the perennial C4 crop miscanthus, at those locations that are suitable for miscanthus production.

Keywords: Nitrogen; Energy; Use efficiency; Herbaceous biomass

1. Introduction

Different policy papers of the EU (see the so-called ‘White Paper’ of 1997, ‘Green Paper’ of 2000 and the Biofuel Directive of 2003 (CEC, 1997, 2000, 2003)) project that in 2010, about 5700 PJ energy in Europe should come from biomass and that additionally in 2010, 5.75% of the fuel consumed by the automotive fled in Europe will be produced from biomass. Because residues from forestry and agriculture cannot provide all biomass needed to fulfill these targets, it is expected that at least 10 million ha of agricultural land in Europe will have to be dedicated to the production of energy crops, unless the biofuels are imported from non-EU countries (Monti and Venturi, 2003; Van den Broek et al., 2004).

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A sustainable production of energy crops will have to fulfill several targets simultaneously. In the context of sustainability, the environmental benign production of biomass and the potential positive ecological impact of biomass crops are generally mentioned in first place (Biewinga and van der Bijl, 1996; Haber et al., 1997; Struik and Bonciarelli, 1997). Important environmental aspects are, amongst others, the impact on biodiversity, the demand for nitrogen (N) fertilizer, erosion, pesticide use and the demand for fossil energy. From these ecological indicators, the demand for N fertilizer and energy were here chosen for further analysis for reasons described below.

The use of N fertilizer is seen as an indicator for many environmentally relevant impacts like groundwater pollution by nitrate leaching or ozone depletion by emissions of nitrous oxides (Schmidt et al., 2000; Kutra and Aksomaitiene, 2003; De Paz and Ramos, 2004). Additionally, the production of N fertilizer contributes to a high share of fossil energy consumption in crop production (Boerjesson, 1996; Kaltschmitt and Reinhardt, 1997; Lewandowski et al., 2000a; Heller et al., 2003). Therefore, an environmentally benign production of biomass is supported by a low N fertilizer input. Nitrogen use efficiency (NUE), respectively, a high use efficiency of N fertilizer, is desirable given the high costs for the fertilizer and the above described environmental impacts of fertilizer application (Schulte auf'm Erley et al., 2005).

The consumption of fossil energy contributes to the emission of carbon dioxide (CO_2), which leads, together with methane (CH_4) and nitrous oxide (N_2O), to the so-called greenhouse effect (increase of global temperature and ozone depletion). A low demand for fossil fuels is therefore desirable to minimize or mitigate the emissions of greenhouse gases. When biomass is used energetically, only the amount of CO_2 is emitted that previously was fixed in the process of photosynthesis. However, the production of biomass requires energy input as fuels (e.g. for the tractor to plow the land) and in the pre-chains (e.g. for N fertilizer production) and therefore leads to emissions of greenhouse gases. Previous studies have shown that the amount of energy needed for biomass production depends on the kind of biofuel being produced, the kind of crop being grown and the intensity of production (especially amount of N fertilizer). About 5–20% of the amount of energy that is contained in the harvested biomass is necessary as input to the production of biomass being produced for combustion (solid fuel) (Lewandowski et al., 1995; Boerjesson, 1996; Kaltschmitt and Reinhardt, 1997; Scholz and Ellerbrock, 2002). The lower the demand for energy in biomass production, the more fossil energy can be replaced and the more greenhouse gas emissions can be avoided.

The energy use efficiency (EUE) in agriculture has been analyzed for agricultural food production since the 1970s (Pimental et al., 1973; Lünzer, 1979; Oheimb et al., 1987). Compared to other sectors, agriculture does not only consume fossil energy but can also produce energy by fixing sun energy chemically in biomass. By using external energy, for example, for soil cultivation and the production of N fertilizer, the use efficiency of the sun energy can be enhanced (Oheimb et al., 1987).

Only crops that yield significantly more energy than is required to grow them are suitable energy crops, and their potentials increase the higher the net energy yields (i.e. harvested energy yield minus energy input for production) are. Energy balances have been performed for different energy crops (see, e.g. Leible and Wintzer, 1993; Kaltschmitt and Reinhardt, 1997; Scholz, 1997; Heller et al., 2003). However, a direct comparison of these results is often hampered by the lack of a standard balance methodology. Differences can, amongst others, be found for the determination of system borders, the energy streams being considered, the algorithms used, coefficients used and the data basis (Kalk and Hülsbergen, 1996). Therefore, we here want to compare different crops by using the same methodology and data basis.

In this study, we do not want to focus on the energy and N fertilizer demand only, but discuss the findings against the area demand for biomass production by different crops. Because of the high future demand for biomass in Europe, it is expected that (good quality) agricultural land can become scarce and biomass for energy production may compete with food production, with the production of biomass for material uses or other land uses, for example, nature areas. Under this aspect, high land use efficiency, i.e. high biomass yields, appears desirable. On the other hand, high biomass yields may require intensive production with high inputs of N fertilizer and energy, probably also on the expense of the energy and N use efficiency (Lewandowski et al., 2000a; Heller et al., 2003). This raises the question for the optimal production intensity.

The aim of this study is to describe the N, energy and land use efficiency in dependence of the N supply for different important energy crops. For this purpose, field trials at different locations in Baden-Württemberg (Southern Germany) with varied N supply levels were performed. To perform these experiments, the three energy crops miscanthus (*Miscanthus × giganteus*), reed canary grass (*Phalaris arundinacea* L.) and triticale (*Triticosecale* Wittmack) were chosen for two reasons: (a) because of previous experiments and literature information, we expected these herbaceous crops to be able to build high biomass yields under given climatic–ecological conditions and (b) the performance of the crops allows for quality management with regard to combustion quality.

Miscanthus is a perennial C4[1] crop, originated from subtropical regions of East Asia. Previous field trials have shown the high biomass yield potential and a good combustion quality of miscanthus biomass in comparison

[1] The terms C4 and C3 crops are derived form the chemistry of the photosynthetic pathways. The first product of phytosynthesis in C4 crops is C_4 dicarbonic acid, which contains four carbon atoms. C3 crops first build phosphoglycerate, containing three carbon atoms.

to other herbaceous crops (Clifton-Brown and Jones, 1996; Jørgensen, 1997; Lewandowski et al., 2000b). The strongly lignified stems of miscanthus are generally harvested in early spring, i.e. after winter, which allows for low ash, N, chloride, potassium and water contents (Lewandowski et al., 2003a,b).

Reed canary grass is grown on several thousand hectares in Sweden and Finland for the production of pulp and paper and for energetic use. It is a perennial C3 grass adapted to various soil conditions in Northern Europe. Because of strongly lignified stems, it can be harvested in one cycle per year, which allows for a late, quality oriented harvest in early spring. The late harvest leads to a reduction in moisture, ash, potassium and chloride content of the biomass (Landström et al., 1996; Hadders and Olsson, 1997).

Amongst all cereals, triticale is most suitable for the production of solid fuels because it combines a high whole-crop biomass yield with the option of late, quality directed harvest (Vetter et al., 1995). Triticale is characterized by a firm grain seat (Albrecht, 1996). Therefore, no grain loss occurs when the biomass is harvested late at low contents of moisture, chloride, ash and potassium. Triticale is an annual crop and therefore allows more flexibility in planning for the farmer than the above described perennial grasses.

2. Materials and methods

2.1. Description of the locations

The field trials were performed in 1997–2000 on four locations in Southwest Germany (48–49°N latitude, 8–10°E longitude) that range from comparatively cool and humid to warm and dry conditions (see Table 1).

2.2. Field trials

Table 2 shows in which years trials were performed with miscanthus, reed canary grass and triticale. Table 3 contains a description of the field trial performance.

2.2.1. Miscanthus field trials

At all sites, the genotype *Miscanthus × giganteus* was planted in four replications. Only in DUR and IHO, irrigation was applied during the first year of establishment. The establishment and overwintering rate was 95–98%. Fifty kilograms of nitrogen per hectare was given in a single dose at the time of sprouting. Another 50 or 100 kg N ha^{-1} was given in the end of May on those plots, which received more than 50 kg N ha^{-1} a^{-1}. Because of high amounts of mineralized N present in the soil in early spring, no additional N fertilizer was applied in GUT. Basic dressing was given uniformly (except K0 and K322 plots in GUT) to all plots at 166 kg K (as K_2SO_4) and 22 kg P (as Superphosphate) ha^{-1} annually in April. In all trials, the biomass was harvested yearly in February. Yield was assessed from 1 m^2 by cutting manually shoots at a height of 5 cm above ground level. Here, we use yield results from the second ratoon onwards because miscanthus yields are low in the first year of establishment.

Table 2
Overview on the performance of field trials on different locations in different years

Crops	Locations			
	DUR	IHO	HOH	GUT
Miscanthus	1992–1996	1992–1996	1994–1996	1993–1996
Reed canary grass	1996–1997	1996–1997		1996–1997
Triticale		1996, 1997	1996, 1997	1996, 1997

2.2.2. Reed canary grass field trials

Reed canary grass (variety 'Palaton') was sown as a trial with fully randomized block design in four replications. The N fertilizer doses applied were 0, 70 (30/40) and 140 (50/50/40) kg N ha^{-1} a^{-1}. P and K fertilizers were given before sowing and after the harvest in 1996. For yield measurement, 1 m^2 per plot was harvested. The stems were cut 5 cm above ground in mid of December in 1996 and 1997. The yield is here shown for the whole above ground biomass (stems, leaves and panicles) for the year 1997 only. Yields in 1996 were low because the plants had to establish.

2.2.3. Triticale field trials

Triticale (variety 'Trimaran') was grown in trials together with wheat and rye. The trials had a split–split–plot design with the main factor 'cereal species' and the sub factor 'N fertilizer' in four replications. The details on trial

Table 1
Description of experimental sites

Location: abbreviation	Soil	Texture	Soil N_t [%]	Soil C_t [%]	Long-term average temperature [°C]	Long-term average precipitation [mm]
Durmersheim: DUR (Upper Rhine Valley)	Haplic luvisol	Loamy sand	0.15	0.96	9.8	780
Ihinger Hof: IHO (Southwest of Stuttgart)	Haplic luvisol	Silty clay	0.19	1.84	8.0	691
Hohenheim: HOH (near Stuttgart)	Haplic luvisol	Silty loam	0.11	1.09	8.8	697
Gutenzell: GUT (Upper Swabia)	Gleysol	Loamy sand	0.73	9.60	7.5	850

Table 3
Field trial parameter

Crop	Miscanthus	Reed canary grass	Triticale
Genotype/variety	*Miscanthus* × *giganteus*	Palaton	Trimaran
Establishment	Planting	Sowing	Sowing
Planting density	2 plants m^{-2}	26 kg seeds ha^{-1}	125 kg seeds ha^{-1} (320 grains m^{-2})
Planting/sowing time	15 May–5 June	23–25 April	8–30 October
N fertilizer (kg N ha^{-1} a^{-1}) as NO_3NH_4	0, 70 (40/30), 140 (90/50)	0, 50, 100, 150	0, 70 (40/30), 140 (90/50)
P fertilizer (kg P ha^{-1} a^{-1}) as Superphosphate	20	22	26
K fertilizer (kg K ha^{-1} a^{-1})	100 as KCl	166 as K_2SO_4	100 as KCl
Crop protection	Mechanical weed control 1st and 2nd year	Mechanical weed control 1st year	Mechanical weed control
Harvesting time	February	December	Stage of 'dead ripening' at 15–23% water contents
Plot size	3 m × 4 m	4 m × 4 m	2 m × 6 m

performance are described in Lewandowski and Kauter (2003). The N fertilizer (as NO_3NH_4) was applied at 0, 70 (40/30) and 140 (90/50) kg N ha^{-1} a^{-1}, no late topdressing was applied. P and K fertilizers were applied as basic dressing annually in autumn.

For yield measurement, 1 m^2 per plot was harvested. The straw was cut 5 cm above ground. Harvest was performed in the stage of 'dead ripening' at water contents of about 15–23% (whole crop). Yields are here shown for the whole crop, including straw and grain.

2.2.4. Chemical analysis and determination of N supply

Soil samples for analysis of mineralized N (Nmin) were taken in spring at the beginning of the vegetation period. The analysis was performed according to the method of Wehrmann and Scharpf (1979).

The N supply was calculated as the sum of mineralized N, measured as NO_3^-–N in April before sprouting of new shoots, and the amount of added N fertilizer.

2.3. Nitrogen use efficiency

We define NUE according to López-Bellido and López-Bellido (2001), where NUE is the ratio of yield (in t dry matter ha^{-1} a^{-1}) to N supply, and N supply is the sum of soil NO_3^-–N and N fertilized.

2.4. Energy balance and energy use efficiency

The energy use efficiency was calculated in GJ GJ^{-1} as the output:input ratio of the primary net energy yield and the energy consumption.

The primary energy yield was calculated as product from the fresh biomass yield and the lower heating value of the fresh biomass. The lower heating value was calculated by the DIN 51900 (DIN, 1988) formula and by using values of 19,896, 19,823 and 19,415 kJ kg^{-1} for the water and ash free upper heating value for miscanthus, reed canary grass and triticale, respectively. The hydrogen (H) concentration of the biomass used here was 6.00, 6.24 and 5.88% for miscanthus, reed canary grass and triticale, respectively (Lewandowski and Kicherer, 1997; Siegle, 1998).

For calculating the primary net energy yield, the energy consumption was subtracted from the primary energy yield. The higher the net energy yields, the more efficiently the land is used. Therefore, we here use the net energy yield to describe the land use efficiency.

The energy consumption was assessed according to methods described in Kaltschmitt and Reinhardt (1997) and on the basis of the following assumptions:

- The average field size is 5 ha (316 m × 156 m) and the distance to the farm is 2 km. Instead of experimental equipment, we assumed here the use of agricultural machines as described in Kaltschmitt and Reinhardt (1997) for an average field size of 5 ha.
- Miscanthus plants are micro-propagated and are grown in the greenhouse before planting. For the calculation of the energy input into plant propagation, transport and planting, see Lewandowski et al. (1995).
- The production periods of the miscanthus and reed canary grass plantations are 15 and 10 years (including year of establishment), respectively.
- According to Kongshaug (1998), the cumulative primary energy use for the production of fertilizer are 50 MJ kg^{-1} N, 17 MJ kg^{-1} P_2O_5, 10 MJ kg^{-1} K_2O and 1.3 MJ kg^{-1} CaO.
- We here calculated for weed control the energy consumption of a six row-hoeing machine (working width 4.5 m) which was pulled by a tractor with a power of 40–70 kW.
- In the field trials harvest of samples was done manually. For the energy balance, we assumed the following harvesting procedures. Miscanthus harvest takes place with a self-driven machine by Class. Reed canary grass is cut by a row independent cutter of Keuper (developed for maize) and baled by a self-driven quader baler (Deutz, 6 m

width). Triticale is cut by a swath mower. The swaths are left in the field for 1–2 days before they are baled. The bales are picked up by a tractor with special device and stapled on a trailer. On this trailer, the bales are transported over 2 km distance to the storage where they are stapled.

2.5. Assessment of efficiencies by the boundary line approach

2.5.1. Theory of the boundary line approach

For the boundary line approach (BLA), scatter plots are drawn between the dependent and independent variables. The BLA is based on the hypothesis that the line connecting the data points (boundary line) at the outer rim of the data body depicts the functional dependency of these variables. On this line, the independent variable is supposed to be the only factor limiting the dependent variable, whereas in the situations portrayed by points below this line another factor is limiting. The principle of the boundary line approach was first described by Webb (1972) and later applied to describe the relationship between soil nutrient concentrations and yields (Evanylo and Sumner, 1987; Evanylo, 1990).

2.5.2. Constructing boundary lines

Scatter grams were plotted between the dependent variables biomass yields and energy yields and each of the two independent variables (N availability and energy input). Each scatter gram for miscanthus contains 110 observations (data sets), for reed canary grass 24 and for triticale 18 observations. For reed canary grass, only data from the second ratoon were included because yields are lower in the establishment phase of the first year. For miscanthus, only results from the second ratoon onwards were included, too.

The normal distribution of the data was checked by the test according to Wilk and Shapiro (1968); in order to identify outliers, the method of Pearson and Hartley (1954) was used.

Data points (boundary points) which were located on the outer rim of the data body were chosen, which were more or less equidistant in respect to the *X*-axis. If possible, six data points were chosen. Polynomial functions or, if appropriate, straight lines were fitted to these boundary points, giving the boundary line. The function of the boundary line and the goodness of fit were calculated for all three relationships.

3. Results

3.1. Biomass yields and N use efficiencies

Miscanthus biomass yields varied between 8 and 38 t dry matter (DM) at the different locations (see Fig. 1a). The lowest yield level was measured at the location DUR (8–15 t DM), the highest at IHO. The yields at GUT reached 13–23 t DM. The boundary line, which describes the biomass yield in dependence of the N supply, increases to an N supply level of about 110 kg N ha^{-1} and then slowly decreases (see Fig. 1a). The N use efficiency, deducted from the biomass yield at different N supply levels, decreases continuously over increasing N supply (see Fig. 1d).

Reed canary grass yields in the second year of growth varied from 2 to 12 t DM. DUR was the location with the lowest yields (up to maximal 8 t DM). The highest yields of 7–12 t DM were measured at the location IHO. The boundary line shows a continuous increase of biomass yields with increasing N supply (see Fig. 1b). The N use efficiency decreases with increasing N supply (see Fig. 1d).

The whole crop (grain and straw) yields of triticale were strongly influenced by the N fertilizer level and were 3 t DM (without N fertilizer) to 12 t DM (140 kg N ha^{-1} fertilized) at the location GUT. The yields at the locations IHO and HOH were 8–15 and 7–18 t DM, respectively, for the different N fertilizer levels. The influence of N fertilizer level is reflected by the linear increase of the boundary line that describes the biomass yield in dependence of the N supply (Fig. 1c). Like for miscanthus and reed canary grass, the N use efficiency of triticale decreases with increasing N supply (see Fig. 1d).

The functions for the boundary lines of all parameter of Fig. 1 are shown in Table 4. The data used for the determination of these functions were normally distributed and no outliers were found.

3.2. Energy and land use efficiency

A high share (3.6 GJ ha^{-1} a^{-1}) of the energy input to miscanthus is due to the energy intensive production of plantlets in the greenhouse (see Fig. 2). If N fertilizer is applied, about 2.1 GJ ha^{-1} is expended per 50 kg N. Irrigation of miscanthus was applied in the first year of crop establishment and consumed 0.34 GJ ha^{-1} a^{-1}. The energy demands for plantlets and irrigation that came up in the first year were here divided over the whole production period of 15 years. The energy use efficiency of miscanthus biomass production ranges between 8 and 51 GJ biomass energy output per GJ fossil energy input (Fig. 3d). The land use efficiency, expressed as the net energy yield, is 115–590 GJ ha^{-1} a^{-1} (see Fig. 3a). Both, energy use efficiency and net energy yield, decrease with increasing energy input in miscanthus production (Fig. 3a and d).

Depending on the N fertilizer level, the energy input to reed canary grass production ranged from 2 to 8 GJ ha^{-1} a^{-1}. The share of energy input for N fertilizer was 61–76% at levels of 70 and 140 kg N ha^{-1} a^{-1}, respectively (see Fig. 2). Reed canary grass production reaches energy use efficiencies of 2–36 GJ GJ^{-1} (Fig. 3d) and net energy yields of 2–129 GJ ha^{-1} a^{-1} (Fig. 3b). While the boundary line for the energy use efficiency describes a strong decline of the efficiency with increasing energy input (Fig. 3d), the net energy yield shows the reverse trend, i.e. an increase with increasing energy input (Fig. 3b).

For the production of triticale whole crop, the energy input was 3.4–11.6 GJ ha^{-1} a^{-1}, with 3 and 6 GJ ha^{-1} a^{-1}

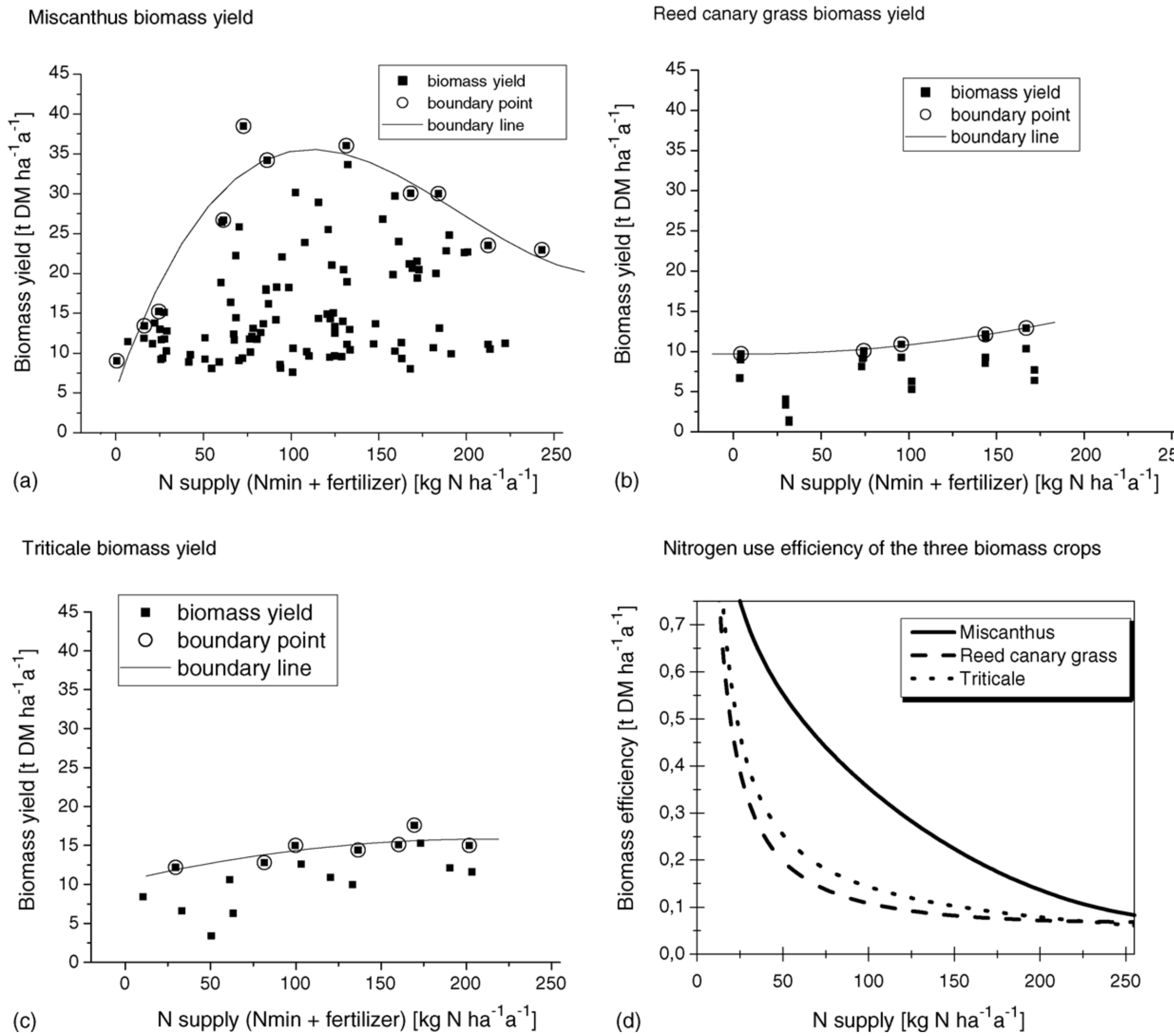

Fig. 1. Biomass yield and N use efficiency in dependence of the N supply (mineralized soil N in spring plus fertilizer N): (a) miscanthus biomass yield; (b) reed canary grass biomass yield; (c) triticale biomass yield; (d) nitrogen use efficiency of the three biomass crops.

energy demand for N fertilizer at levels of 70 and 140 kg N, respectively (see Fig. 2). Energy use efficiencies of 17–39 GJ GJ^{-1} were assessed (Fig. 3d). The highest net energy yield of 280 GJ ha^{-1} a^{-1} was calculated for the highest N fertilizer (140 kg ha^{-1}) level at the location HOH. The lowest net energy yield of 54 GJ ha^{-1} a^{-1} was measured at the variant without N fertilization at the location GUT. The boundary lines describe a decrease of energy use efficiency and a linear increase of net energy yields with increasing energy input for triticale (Fig. 3c and d).

Table 4
Quantification of the relationships between N supply and the biomass yield (Y) and N use efficiency (NUE) of miscanthus, reed canary grass and triticale; calculated by BLA

Factor	Independent factor (x): N supply level	
	r^2	Equation
Miscanthus		
Biomass yields (Y)	0.91	$Y = 5.59406 + 0.61933x - 0.0039x^2 + 6.63\ e^{-5}\ x^3$
N use efficiency (NUE)		$NUE = (5.594 + 0.61933x - 0.0039x^2 + 6.63\ e^{-6}\ x^3)/x$
Reed canary grass		
Biomass yields (Y)	0.99	$Y = 9.656 - 4.83e^{-4}x + 1.21\ e^{-4}\ x^2$
N use efficiency (NUE)		$NUE = (9.656 - 4.83e^{-4}x + 1.21\ e^{-4}\ x^2)/x$
Triticale		
Biomass yields (Y)	0.63	$Y = 10.5016 + 0.05022x - 1.19\ e^{-4}\ x^2$
N use efficiency (NUE)		$NUE = (10.5016 + 0.05022x - 1.19\ e^{-4}\ x^2)/x$

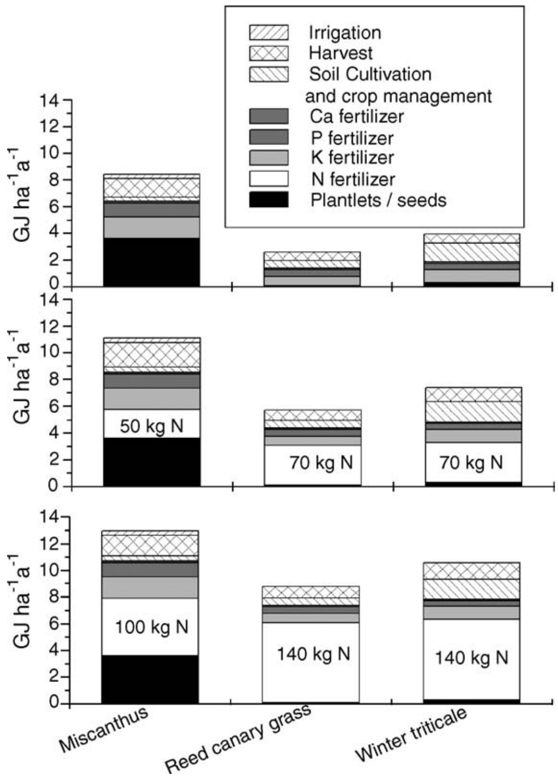

Fig. 2. Energy input for the production of miscanthus, reed canary grass and winter triticale (whole crop) at different N fertilizer levels; shown for the location IHO in 1997.

The functions, which describe the boundary line for all parameter in dependence of the energy input as shown in Fig. 3, are listed in Table 5.

4. Discussion

In crop science, linear regression analysis (LRA) is often used to quantify the relationship between two variables (see, e.g. Van der Werf et al., 1993; Clifton-Brown and Jones, 1996; Vleeshouwers, 1998, using LRA for depicting miscanthus yield). LRA is based on the assumption that the relationship between the two variables depicted is linear (Sachs, 1991). In nature, however, those relationships are rarely linear. Therefore, functions must not be chosen without knowledge of functional dependencies. This fact is taken into account by the boundary line approach. The BLA is based on the hypothesis that the line connecting the data points (boundary line) at the outer rim of the data body depicts the functional dependency of variables (Fraser and Eaton, 1983; Walworth et al., 1986). On this line, the independent variable is supposed to be the only factor limiting the dependent variable, whereas in the situations portrayed by points below this line one other factor or several other factors are limiting. Using BLA for deriving functions in many cases is therefore more appropriate than using LRA because empirical data usually scatter strongly; this was also shown in several studies in the field of soil sciences (for example, Evanylo and Sumner, 1987; Schmidt et al., 2000).

The following discussion will focus on: (a) the trends of the functions that were found for yield and efficiencies in dependence of nitrogen and energy supply, (b) the relative performance of the energy crops studied and (c) the general environmental performance of energy crops.

4.1. Yield functions depicted by BLA

For the relationship between the supply of mineral nutrients and yield increases, Mitscherlich (1954) formulated the ‘law of diminishing yield increment’. According to this law, the yield response curves are asymptotic, when the supply of one mineral nutrient is increased and other factors (e.g. genetic potential of crop, water supply, etc.) become limiting factors. When there is an abundant supply of nutrients, a point of inversion is obtained, which is caused by factors such as toxicity of the nutrient or other indirect effects such as infection with diseases (Marschner, 1986a).

The functions found for miscanthus and triticale biomass yield go along with the theoretically expected course. At an N supply level of 200 kg ha^{-1} a^{-1}, the yields of triticale are still increasing with an increase in N supply and an inversion point was not yet reached. For miscanthus, the function shows an inversion point at 114 kg N ha^{-1} a^{-1}, indicating that N supply beyond that level is harmful for miscanthus at the locations tested here. This hypothesis is supported by the observation that under drought conditions, miscanthus plants on plots being fertilized with 100 kg N kg ha^{-1} a^{-1} and more became brown and stayed smaller than those plants receiving less N fertilizer. At a low N supply level, the curve for miscanthus is very steep because here the function is dominated by values from the one location DUR where lowest yields and lowest N supply levels occurred simultaneously. A possible conclusion from this finding is that miscanthus strongly reacts on N supply at low levels of 0–50 kg N ha^{-1} a^{-1}.

In contrast, yields of reed canary grass increased with increasing N supply over the whole range of N supplies. At a level of 163 kg N ha^{-1} a^{-1}, yields of reed canary grass still increased, showing benefits from higher N supply. The point of inversion could not be determined.

At rather low N supply levels of about 4 kg N ha^{-1}, measured as mineral N in the soil, as for miscanthus as for reed canary grass, high biomass yields of up to 10 t DM ha^{-1} a^{-1} were recorded. Measurements of mineral N in the test soils were made in spring once a year, so additional N mineralized during the vegetation period was not considered. This leads us to the assumption that once N mineralization and N losses over the whole vegetation period are measured or modeled, boundary lines will lead through the zero point.

Net energy yield and energy input are aggregated values derived from energy balances and thus the boundary lines drawn for their relation are not functional. An interpretation

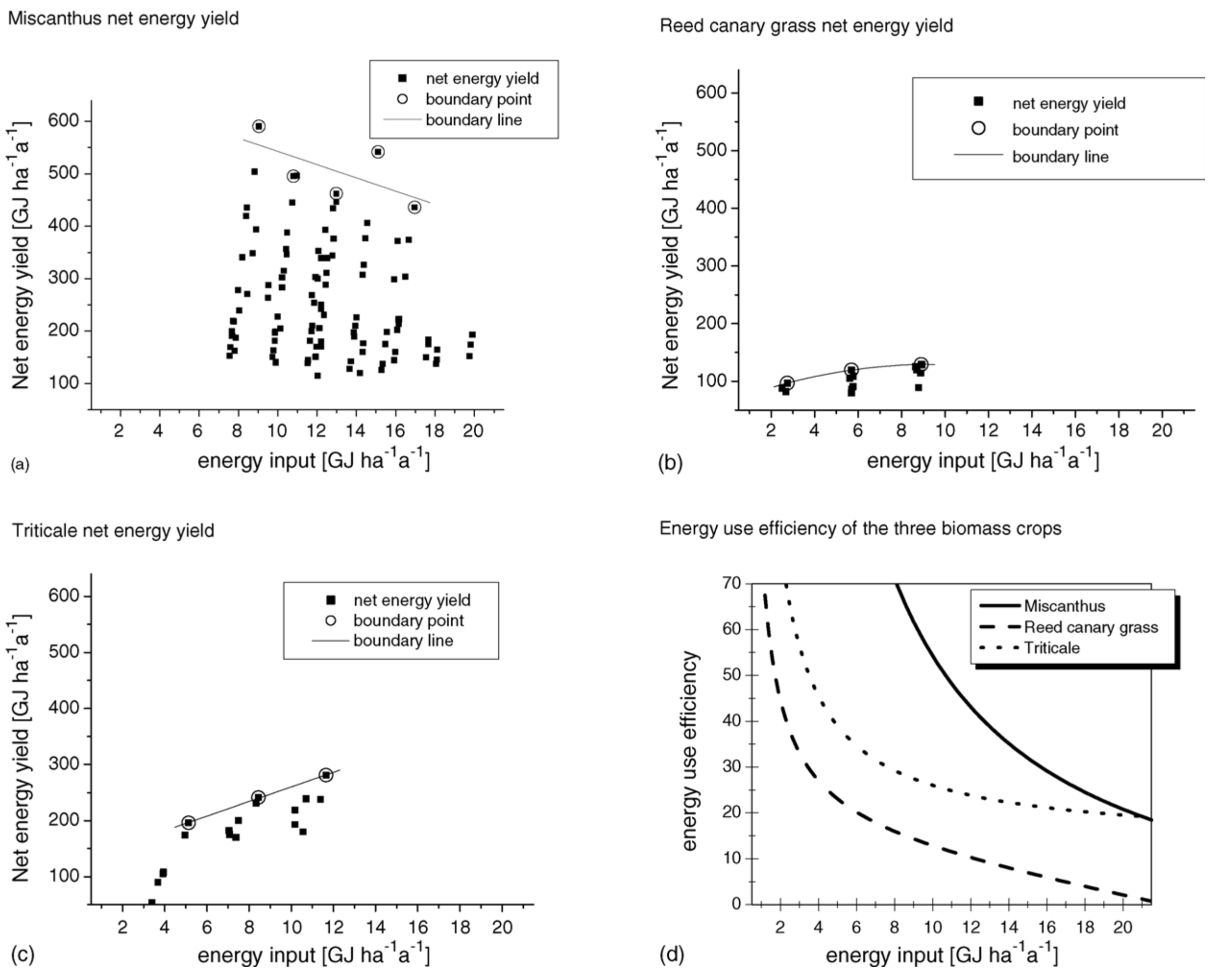

Fig. 3. Net energy yield (energy content of harvested biomass minus energy input to biomass production) and energy use efficiency in dependence of the energy input: (a) miscanthus net energy yield; (b) reed canary grass net energy yield; (c) triticale net energy yield; (d) energy use efficiency of the three biomass crops.

of the boundary lines derived here has to take into consideration that the increase in energy input is totally dominated by the input level of N fertilizers. From the functions shown in Fig. 3, it can be concluded that an increase in N fertilizer input leads to increased net energy gains for those crops that strongly react with yield increases on N fertilization (triticale and reed canary grass). For miscanthus, the highest net energy yield is measured at the lowest energy input level because at the location IHO, no N fertilization was necessary to produce maximum yields due to a soil N supply of 50 kg N ha^{-1} a^{-1}. At the location DUR, with little soil N supply, however, highest net energy yields from miscanthus were measured at an N fertilizer rate of 50 kg N ha^{-1} a^{-1}.

Table 5
Quantification of the relationships between the energy input and the energy use efficiency (EUE) and net energy yield (energy content of harvested biomass minus energy input to biomass production) of miscanthus, reed canary grass and triticale; calculated by BLA

Factor	Independent factor (x): energy input	
	r^2	Equation
Miscanthus		
Energy yields (E)	0.42	$E = 669.0991 - 12.6363x$
Energy use efficiency (EUE)		$\mathrm{EUE} = (669.0991 - 12.6363x)/x$
Reed canary grass		
Energy yields (E)	1	$E = 63.8443 + 14.074x - 0.7575x^2$
Energy use efficiency (EUE)		$\mathrm{EUE} = (63.8443 + 14.074x - 0.7575x^2)/x$
Triticale		
Energy yields (E)	0.99	$E = 129.7642 + 13.03567x$
Energy use efficiency (EUE)		$\mathrm{EUE} = (129.7642 + 13.03567x)/x$

4.2. EUE and NUE of different biomass crops

It is generally agreed that N and energy use efficiencies decrease with increasing N fertilizer or energy input (see, e.g. Delogu et al., 1998; López-Bellido and López-Bellido, 2001; Monti and Venturi, 2003 for NUE of cereals and Heller et al., 2003; Angelini et al., 2005 for EUE of willow and *Arundo donax*). Generally, the highest NUE was calculated when only soil N was available and no N fertilizer was applied. The parallel development of NUE and EUE over the N rate application is explained by the fact that an increase in energy input is mainly due to the energy consumed for the production of N fertilizer.

Similar to our results, Scholz and Ellerbrock (2002) showed that perennial crops sometimes react with yield increases on N fertilization, but at lower N supply levels than annual crops. This effect of N supply on yields of different crops also influences NUE and EUE. So, at rather low levels of N supply with increasing N supply, NUE and EUE of reed canary grass and triticale show a stronger decrease than miscanthus, but vice versa at N supply levels above 70 kg N ha^{-1} a^{-1} (see Figs. 1d and 3d). This is due to positive yield responses of reed canary grass and triticale above this N supply level in contrast to miscanthus. However, it must be mentioned that for miscanthus, absolute values were higher for the whole range of N supply or energy inputs maintained in this study than for the other crops. That means, compared to reed canary grass and triticale, miscanthus has the highest nitrogen, energy and land use efficiencies at all N fertilizer and energy input levels. The main reason for this has to be seen in the C4 photosynthetic pathway of miscanthus, combined with its perennial growth. Because of their specific physiology, C4 crops use water and N more efficiently than C3 crops (Long, 1983; Marschner, 1986b). A water use efficiency of about 300 (grams transpired water per gram dry matter produced) in C4 species compared to more than 600 in C3 species (Woolhouse, 1978) is seen as a major reason why the dry matter yields of C4 crops are higher compared to the yields of C3 crops. Because N fertilizer input holds for a high share of the energy input to crop production, those crops that need little N fertilization per tonne biomass have both, a high N and energy use efficiency. Perennial crops like miscanthus and willow have low N fertilizer demands because they internally recycle N. Miscanthus translocates N from the above ground biomass to the rhizomes in autumn, where it is stored and translocated to new emerging shoots in spring (Beale and Long, 1997). The only crop for which comparative high EUE were reported as measured for miscanthus here is *Arundo donax*, which is also a perennial grass grown as biomass crop in Southern Europe, and short rotation coppice of willow and poplar (Heller et al., 2003; Angelini et al., 2005). In a comparison of different annual and perennial energy crops in Sweden, the perennial crop willow reached the highest EUE of 21, followed by reed canary grass with 11; wheat whole crop only reached an EUE of 7 (Boerjesson, 1996). The high EUE of willow was due to the combination of the comparatively highest net energy yields (170 GJ ha^{-1} a^{-1}) with the lowest N fertilizer rate (81 kg N ha^{-1} a^{-1}) and consequently lowest total energy inputs (8.4 GJ ha^{-1} a^{-1}).

Reed canary grass is a perennial grass, too, but showed here, with respect to N, a different behavior compared to miscanthus. When water supply is sufficient, reed canary grass reacts with significant yield increases on the N fertilizer (Landström and Olsson, 1997) and seems therefore to react more strongly on N fertilizer supply than miscanthus. A possible reason could be a lower sink and storage capacity of the rhizomes. Compared to miscanthus, which has very compact and large rhizomes, the rhizomes of reed canary grass are much finer and thinner (up to 1 cm). There are, however, no investigations on the internal nutrient cycle of reed canary grass available that could support this hypothesis.

Compared to Swedish results (see Boerjesson, 1996), the energy use efficiency of reed canary grass in our field experiments is comparatively low. The variety 'Palaton' used here was bred in Sweden (by Svaloef Weibull) and is therefore adapted to Swedish site conditions. Reed canary grass has a dual photoperiodic induction requirement for flowering and genotypes react different on day length. Therefore, some genotypes that were transferred from Northern to Southern Sweden did not flower (Lewandowski et al., 2003b). Day length conditions in Southern Germany differ from the conditions in Sweden, which may explain the comparatively poor performance of reed canary grass on Southern German sites. It is to be expected that a better adaptation of reed canary grass varieties to German site conditions can improve the performance of the crop in terms of yield and resource use efficiency.

4.3. General environmental performance of energy crops

To maximize the EUE, NUE and land use efficiency, the production of those perennial crops that are best adapted to the specific eco-physiological site conditions is most favorable. But the overall environmental performance of biomass production is also depending on other features of which the demand for pesticides, soil erosion and biodiversity, are important ones. Also, with respect to these environmental indicators, perennial crops can perform better than the conventional annual energy crops (like rape seed, sugar beet, cereals, etc.) because:

- So far, no pests and diseases that require chemical control are reported from biomass grasses of short rotation coppice (see, e.g. Lewandowski et al., 2003b). Problems with rust disease in willow (*Salix* ssp.) can be overcome by choosing resistant varieties (McCracken et al., 2001). Hope and Johnson (2003) report that the avoidance of pesticides in the production of short rotation coppice supports the abundance of invertebrates.
- In perennial crop production, soil cultivation only has to be done once in a production period of 15–25 years. Soil

erosion only occurs in the year of establishment and can be overcome by under seed if water supply is sufficient. From the second year on, the established cops and their rooting systems prevent erosion (Kort et al., 1998). In annual crops, the cycle of soil cultivation and establishment is repeated yearly and therefore the susceptibility of fields with annual crops to soil erosion is higher than for perennial crops. Long-term soil rest also improves the living conditions for soil inhabitants like earthworms and rodents (Hope and Johnson, 2003).

- High stands, also in winter, a late harvest, a harvest cycle of 4 years (for trees) and the general low frequency of machine operations in perennial crops lead to an increased abundance of mammal species like rabbits, deer, foxes, rodents and bats and of nesting woodland, scrub and ruderal vegetation birds (Tolbert, 2002; Hope and Johnson, 2003).

This leads to the conclusion that plantations of perennial crops can, especially in landscapes which are poor in structural elements and forests, enhance biodiversity and enhance the environmental performance of agricultural production, also in comparison to the production of the annual food crops.

The concept of using agricultural area in Europe for the production of biomass instead of food and feed production, however, raises questions whether the high standard ecological performance of European agriculture is paid by ecological drawbacks in the agricultural production of food and feed stuff that is imported from, e.g. Latin American countries. Experiences with the introduction of cash crops for export, for example, soybean in Bolivia, showed negative ecological impacts like deforestation to gain agricultural land (Kaimowitz and Thiele, 1999) and generally questions the acceptability of food and feed imports. In terms of energy use efficiency, however, biomass production with high yielding perennial crops can perform better than the production of the replaced (and then imported) food and feed products. This is because the additional energy consumed for the transport of food and feedstuff is relatively low with about 0.2 MJ t^{-1} km^{-1} (Breugham et al., 2004). This means that even with a transport distance as far as from Latin America to Europe, energy consumption for transportation sums up to an amount of about 9% of the energy value of the transported biomass (Hamelinck et al., 2005). From the point of energy efficiency, an energy yield surplus of 10%, which is easily achieved by miscanthus production (see comparison of net energy yield of miscanthus and the annual triticale whole crop in Fig. 3), would justify the energy consumption for the import of other products.

5. Conclusions

The boundary line approach is suitable for the comparison of the N, energy and land use efficiencies of different crops grown under similar site conditions. However, more data from field trials performed under comparable conditions will be needed to strengthen the quantitative power of functional dependencies found here.

For the production of energy crops, low-input agricultural systems cannot generally be recommended because this can imply shortcomings through inefficient use of agricultural land. All energy crops tested in this study were most efficient in the use of energy and nitrogen at the lowest N supply level. To maximize net energy yield and land use efficiency for triticale and reed canary grass, however, the highest N fertilizer level of 140 kg has to be recommended. Only for miscanthus, low N fertilizer rates can be recommended to maximize N, energy and land use efficiency simultaneously.

From these results, it can be concluded that the best mean to simultaneously improve the N, energy and land use efficiencies is the choice of a crop, which efficiently transforms the growth factors into harvestable energy. Depending on the site conditions given, either the production of the perennial C4 grass miscanthus or, on cooler sites, the production of short rotation trees will lead to the most efficient use of resources. Growing perennial biomass crops additionally contributes to other environmental benefits, like a reduction of pesticide and erosion and an increase in biodiversity.

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