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Nitrogen and energy balance of a short-rotation poplar forest system

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Summary

The mean annual dry matter production of a short-rotation poplar forest was 14.4 tonnes ha^{-1} during a 5-year growing period. A nitrogen balance was made to estimate the need for nitrogen of the system. During the growing period trees took up 542 kg N ha^{-1} of which 64 % is in bole and branches. In the 5th year denitrification was measured in undisturbed columns in the field by the acetylene-inhibition technique. An annual denitrification rate of 18 kg N ha^{-1} was estimated on the basis of the observed N_2O profile. The system needed an annual input of 122 kg N ha^{-1} to balance the nitrogen budget. The energy balance showed that at the present dry matter production the system had a net output of 54 GJ ha^{-1} $year^{-1}$.

An increase of the dry matter production to a maximum of 25 tonnes ha^{-1} $year^{-1}$, which seems possible when the trees are planted at higher density, would raise the net energy output up to 97 GJ ha^{-1} $year^{-1}$ in spite of higher energy inputs associated with fertilizer applications. Although this study shows that, at the present level of dry matter production, short-rotation forestry is an energy-producing system, both the dry matter production and the energy prices have to increase considerably to make the system economically feasible.

Introduction

The recent energy crisis prompted a renewed study of biomass production for fuel purposes. One of the potential fuel sources is wood produced in short-rotation forestry.

Short-rotation forestry has considerable advantages over conventional forestry such as higher yields per land unit and increased labour productivity (Gib-

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son, 1978). The costs per unit of land for establishment and management, however, are higher in short-rotation forestry.

Van Boven & de Hoop (1979) calculated that, at prevailing price levels, energy from poplar fuelwood was not or hardly economic in the Netherlands. Sooner of later, the expected rise in the costs of fossile energy, however, could make this kind of energy farming economically attractive under Dutch and comparable conditions.

Nitrogen is one of the major limiting nutrients in agricultural production in Northwestern Europe. Therefore the nitrogen economy of a short-rotation poplar ecosystem may have a great impact on its economic and energetic performance. On the one hand the availability of nitrogen to the trees should be high enough to sustain optimal growth while, on the other hand, the industrial production of nitrogen fertilizers might have a negative effect on the energy balance and the economic feasibility of short-rotation forestry (Frissel et al., 1978).

For this reason we have collected data to assess the nitrogen balance in a short-rotation poplar forest. Special attention was given to the determination of N uptake by the trees and of N losses by denitrification. On the basis of this nitrogen balance we have made a rough estimation of the energy balance of a short-rotation forest. These experiments were carried out in close cooperation with the Stichting Industrie Hout (Institute for the Promotion of Industrial Wood Production) and the Dorschkamp Institute for Forestry and Landscape Planning, both in Wageningen.

Materials and methods

Description of the experimental field

The experimental field in Hummelo, Netherlands, was established in 1974 by the Stichting Industrie Hout, as a pilot field for the production of industrial poplar wood and presents the first short-rotation forestry field in the Netherlands. The data on plant weight, plant and soil composition and denitrification are all from the same plot of 40 m x 30 m.

Soil

The soil type is a clay loam (Dutch classification: sandy hydroearth, according to de Bakker & Schelling, 1966) used as pasture land before the poplars were planted. The soil is moderately well to somewhat poorly drained. Mean lowest water-table in summer is 1.2 m below the soil surface.

Ten sequential layers, each of 10 cm, were sampled; ten samples were taken from each of the layers. Subsamples for chemical analysis were taken after mixing, air-drying and sieving (2 mm) of the samples. The pH was measured in aqueous extracts. Total soil organic carbon and total N were determined by the Laboratory for Soil and Crop Testing at Oosterbeek. Concentrations of NH_4^+ and NO_3^- in 2*N* KCl extracts of the soil samples were determined with a Cenco autoanalyser. Ammonium was assayed with a Nessler procedure (van Ginkel & Sinnaeve, 1980) and nitrate with the hydrazine-reduction method.

Plant material and fertilization
Poplar cuttings of the clone RAP (a hybrid of *Populus deltoides* and *Populus trichocarpa*) were planted to a depth of 0.6 m in the spring of 1974, at 2 m × 2 m (2500 trees ha^{-1}).

The rootless cuttings were one year old with an average length of 2.5 m. The field was ploughed to a depth of 0.3 m in the tree rows prior to planting. After planting the herbicide gramoxone (5 litres ha^{-1}) was sprayed in the tree rows with a band width of about 1 m.

Nitrogen was supplied as calcium-ammonium nitrate (23 % N) at a rate of 100 g $tree^{-1}$ in the first and 200 g $tree^{-1}$ in the second year. The total N amendment thus corresponds to 172 kg N ha^{-1}. After 2 years potassium fertilizer was given as 'K-40' at a rate of 400 kg ha^{-1}, corresponding to 133 kg K ha^{-1}.

Harvest and plant analysis
Two trees of average size were selected and lifted after 5 growing seasons in April 1979. The average size of the trees was determined by measuring the diameter at breast height of 170 trees. At harvest time the trees were bare. The soil cover, mainly consisting of decomposing poplar leaves and some twigs and herbs, was collected in a circle with a radius of 1 m around the stem of the 2 harvested trees. Root systems were dug out as good as possible with a spade (estimated yield > 90 %), the branches were cut off with an axe and the bole was divided into 1 m sections. For root trunk and bole segments the following procedure was followed. A 1-cm thick disc was sawn from the middle of each section and the discs were subsequently coarsely desintegrated with an axe. These pieces of wood, the branches, the lateral roots and the soil cover were further processed in a wood-chopper, dried at 70 °C and then finely ground in a routine laboratory plant mill. The powder was digested in a sulphuric acid-salicylic acid mixture with addition of hydrogen peroxide in the final stage of digestion, according to standard Kjeldahl procedures. Total N in the digests was assayed with a Cenco autoanalyser following the Nessler procedure (van Ginkel & Sinnaeve, 1980).

Denitrification
Denitrification, i.e. transformation of NO_3^- into N_2O and $N_2$was measured by the acetylene-blockage technique (Smith et al., 1978). Acetylene is known to inhibit the transformation of N_2 into N_2O (Yoshinari & Knowles, 1976; Balderston et al., 1976). Four perspex columns (∅ 12 cm, length 1.1 m) were pushed hydraulically into the soil of the experimental site. Acetylene was applied to two columns by flushing the column with a mixture of air and acetylene (10 %, v/v) at a rate of 1.8 litres h^{-1}. The two other columns were not flushed and served as blank. The air-acetylene mixture entered the columns, which were covered by airtight caps, approximately 2 cm below the soil surface. After overnight flushing caps were removed and 10-cm^3 gas samples were taken at 40, 60 and 80 cm depth, via copper tubes buried in the soil.

Gas samples were taken daily during a period of three weeks. Samples were stored and transported from the field in bottles, which were vacuumized in advance and closed with silicone septa.

N_2O and acetylene concentrations in the samples were measured by gas chromatography with a Pye Unicam GCV gaschromatograph fitted with a Poropaque Q column (length 5 m, ∅ 2 mm) and ^{63}Ni- Electron Capture Detector. Temperature of injector, column and detector were 50, 70 and 300 °C, respectively.

Results and discussion

Wood production

The trees grew vigorously and healthy and the mean annual length increment exceeded 3 m after the first year (van den Burg & Kolster, 1977). After 5 growing seasons the trees were about 13 m high and the total tree weight per hectare was about 82 tonnes dry weight (= Total production minus soil cover; Table 1). Assuming a negligible initial mass of the cutting and ignoring litter production, this figure corresponds to a mean annual dry matter production of 16.4 tonnes ha^{-1}. When leaves and roots are not used as fuel, the mean production rate would be 14.4 tonnes dry wood ha^{-1} $year^{-1}$.

Besides improvements of yields through the application of new, faster growing clones that may be developed in future the yield could have been higher by increasing the number of trees per hectare. As compared to the yields at the present spacing of 2 m × 2 m, a 1.5 m × 1.5 m spacing (4440 ha^{-1}) would increase the yield by 78 % and 1 m × 1.5 m (6670 ha^{-1}) by 167 %.

Considering the observed minimal competition for rooting space, sunlight and the sufficiency of water higher densities seem possible. The experiments of Frison (1968), who used plant densities up to 9050 trees ha^{-1}, support this assumption.

Nitrogen in trees

Highest N contents were found in the dry matter of fallen leaves (soil cover) and in lateral roots, whereas bole dry matter showed lowest N concentration (Table 2). Measurements in August 1975 and 1976 showed that the dry matter of leaves

Table 1. Dry weight of composing plant parts of 5-year old poplar trees. Mean data of two trees.

Plant part	Dry weight		
	kg ha^{-1}	% of total	
Root trunk	5141	5.8	11.3
Lateral root	4924	5.5	
Bole	63786	71.6	80.7
Branches	8110	9.1	
Soil cover	7099	8.0	
Total	89060	100.0	

Table 2. Nitrogen content and amounts of nitrogen in composing plant parts of 5-year old poplar trees. Mean data of two trees.

Plant part	% N in DM	N in plant parts	
		kg ha^{-1}	% of total N
Root trunk	0.60	31	6
Lateral roots	1.04	51	9
Bole	0.43	274	51
Branches	0.85	69	13
Soil cover	1.65	117	22
Total		542	101

of the same trees had N contents of 2.9 and 2.4 %, respectively (van den Burg & Kolster, 1977) indicating that part of the N has disappeared from the leaves prior to or after abscission.

Most of the N in the trees is contained by the bole and the branches. The root system contains only 15 % of the total nitrogen of the trees. It is conceivable that in the growing season the proportion of the total N in the leaf fraction is much higher. Moreover, the soil cover is an underestimate of the dry matter in leaves from a growing plant. Harvest of fuel wood would remove 64 % of the plant N. This corresponds to a removal of 343 kg N ha^{-1} or a mean annual removal rate of 69 kg ha^{-1}.

Soil analysis and denitrification measurements

The pH of the soil seems to have a significant effect on the fate of N. The data of Table 3 clearly indicate a linear relationship between pH and NO_3^- concentration and an inverse relation between pH and NH_4^+ concentration. This can be explained from the well-known, inhibitory effect of soil acidity on nitrification (e.g. Dommergues & Mangenot, 1970).

Table 3. The concentration of total organic C, total N and of NH_4^+ and NO_3^- and pH at various depths of a soil used for short-rotation forestry with poplars.

Depth (cm)	pH	Total organic C (%)	Total N (kg N ha^{-1})	NH_4^+ (kg N ha^{-1})	NO_3^- (kg N ha^{-1})
0- 10	5.1	3.0	3770	12.0	5.5
10- 20	5.0	2.7	3510	4.9	4.8
20- 30	5.0	2.1	2860	3.4	4.8
30- 40	5.0	1.2	1560	5.8	4.5
40- 50	5.4	0.5	650	7.6	5.2
50- 60	5.4	0.4	390	4.8	5.8
60- 70	5.6	0.3	260	2.5	7.1
70- 80	8.1	0.2	260	3.7	9.4
80- 90	8.2	0.2	260	1.8	13.6
90-100	8.2	2.0	260	3.2	15.9

Table 4. Average values of N_2O concentrations (mg/kg) in soil-atmosphere samples at various depths with and without acetylene application; for a three weeks period (daily measurements). The range of the observed concentrations is given in parentheses.

Depth (cm)	N_2O (mg/kg)	
	+ acetylene	– acetylene
40	2.3 (0.3- 8.3)	2.1 (0.3-11.2)
60	8.0 (0.4-13.4)	7.9 (0.3-13.4)
80	10.2 (1.1-16.7)	6.1 (0.3-19.7)

Denitrification was measured for three weeks in spring. The N_2O concentration in the soil atmosphere fluctuated very much with the weather conditions (Table 4). The lowest values given in Table 4 were all obtained at the same day, which was dry and sunny. Most of the highest values were observed at a relatively warm day (maximum temperature 20 °C), which followed after several days of intensive rainfall. Although the conditions in spring are relatively favourable for denitrification, the data may give a fair indication of the mean annual denitrification rate in the present soil regarding the temperate, humid Dutch climate.

Acetylene, though present at concentrations far above the minimum of 0.1 % (v/v) required to block the $N_2O \rightarrow N_2$ conversion (Ryden et al. 1979), did not increase the N_2O concentration significantly. This might be, because at the prevailing pH mainly N_2O is produced as end product of denitrification (Nömmilk, 1956). Another explanation could be a reduced production of NO_3^- owing to an inhibition of nitrification by acetylene (Hynes & Knowles, 1980). In the latter case the N_2O production could remain constant after acetylene application, whereas the total production of gaseous N compounds due to denitrification is reduced.

From the observed mean N_2O concentration profile the annual denitrification rate was estimated. The change in N_2O concentration of a particular soil layer due to diffusion and production by denitrification is given by

$$\frac{dN_2O}{dt} = D_{N_2O} \cdot \frac{d^2N_2O}{dx^2} + S_{N_2O} \qquad (1)$$

where D_{N_2O} = apparent diffusion coefficient of N_2O ($cm^2\ day^{-1}$)
S_{N_2O} = production rate of N_2O
x = distance between the centres of two adjacent layers (cm).

Eq. 1 was solved numerically by using a computer simulation model, which considered a soil column of 1 m length divided into ten layers of 10 cm each. The atmospheric N_2O concentration was set to $3 \times 10^{-7} cm^3\ cm^{-3}$. By trial and error we fit the calculated concentration profile to the observed one. The observed profile (acetylene treatment) was calculated assuming a production of about $4 \times 10^{-6}\ cm^3$ N_2O per cm^3 soil per day, which approximates an annual denitrification rate of 18 kg N ha^{-1}. This value should be considered as a first approximation. The number of available data is too limited to draw hard conclusions. Moreover, the calculations are highly affected by the value of the diffusion coefficient which varies enormously and the air-filled fraction of soil, which are interrelated. Based on the soil type and the experimental conditions the diffusion coefficient was estimated to be 300 cm^2 day^{-1} at an air-filled fraction of 15 % (Rolston et al., 1976).

Nitrogen balance

To estimate the need for fertilizer nitrogen at a given level of wood production a nitrogen balance was made for the system (Fig. 1). The balance was obtained from the following data and estimates.

– The soil-N concent was calculated from the data of Table 3 assuming a root zone of 1 m.

– The tree N content was derived from data of Table 2.

– A fixed litter production and a litter decomposition rate constant of 0.2 per year was assumed (Lousier & Parkinson, 1976). The annual litter N production is calculated using Jenny's (1941) equation.

$$\frac{dN}{dt} = -k\,N + A \qquad (2)$$

where N = litter-N (kg N ha^{-1})
k = decomposition rate constant ($year^{-1}$)
A = production rate (kg N ha^{-1} $year^{-1}$).

Integration of Eq. 2 gives:

$$N = N_0 e^{-kt} + A\,(1-e^{-kt}) / k \qquad (3)$$

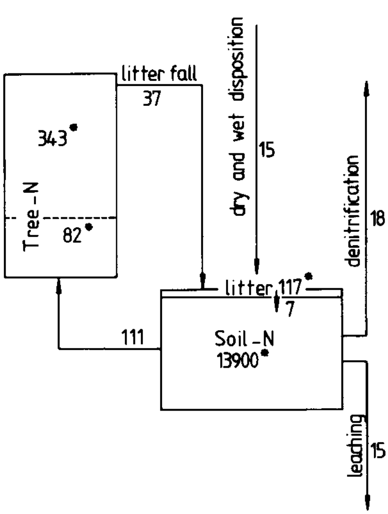

Fig 1. Schematic presentation of the nitrogen cycle in a short-rotation poplar forest. The figures indicated with an asterisk are amounts of N (kg N ha^{-1}), that are measured at the time of harvest after a growing period of 5 years). Other figures refer to annual fluxes (kg N ha^{-1} $year^{-1}$).

If it is assumed that the initial amount of litter, N_o, is zero. A is 37 kg N ha^{-1} year^{-1} for N = 117 kg N ha^{-1} (Table 2), k = 0.2 year^{-1} and t = 5 years.

The rate of nitrogen mineralization from litter is then 7 kg N ha^{-1} year^{-1}.

– Annual input due to dry and wet deposition is estimated at 15 kg N ha^{-1}. For Dutch conditions an annual input of 14 kg N ha^{-1} was estimated for arable land (Frissel, 1978). In the same study an input of 5 to 30 kg N ha^{-1} year^{-1} for deciduous and coniferous forests on acid soils of the northern hemisphere was mentioned. Input due to N_2 fixation is negligible under the present conditions.

– Output due to leaching and denitrification is estimated to be 15 and 18 kg N ha^{-1} year^{-1} respectively under the present conditions. The figure for leaching losses is derived from the aforementioned studies of Frissel (1978). Ammonia volatilization can be neglected because of the low pH of the top soil.

– From the N content of the trees after a 5 years-growing period and the calculated litter production the annual uptake of N by the tree is calculated to be 122 kg N ha^{-1}, including root development. Without new root development during the second and following regrowth periods the annual N uptake would be 106 kg N ha^{-1}. If replantation is considered after 15 years with a harvest every 5 years the average N uptake during this period of 15 years would be 111 kg N ha^{-1} year^{-1}.

Based on this balance the system needs an annual inorganic N input of 122 kg N ha^{-1} under the present conditions. If a net mineralization rate of soil-N of 2 % per year is assumed, the soil-N supply is sufficient, even for a higher wood production. However, in our opinion it would be incorrect to make a N balance on long-term base that includes a continuous net mineralization of soil organic nitrogen. As soon as the soil system has come to a steady-state, mineralization and immobilization will be equal resulting in a zero N supply, and fertilization to a rate of approx. 120 kg N ha^{-1} year^{-1} will be necessary. Moreover, delivery of nitrogen by mineralization is, in general, not in phase with the N demand during a growing season. Apparently, supply of N due to mineralization of soil organic matter is sufficient in the present case because the fertilizer input during the first and second year (172 kg N ha^{-1}) cannot account for the total output during the past growing period, i.e. N uptake by the trees and losses due to leaching and denitrification.

The dry matter production has to increase significantly to obtain an economically feasible production level even when energy prices will rise (Frissel et al., 1978). It seems worthwhile to consider a higher production by means of a higher tree density. A spacing of 1.5 m x 1.5 m would increase the yield with 78 % at equal tree growth. At this spacing the annual rate of photosynthate accumulation would approach its maximum theoretical value under Dutch conditions (Wareing & Cooper, 1971). This production level requires about 265 kg fertilizer N ha^{-1} year^{-1}. This figure includes a higher loss of N due to leaching and denitrification up to twice the values given in Fig. 1. Frissel (1978) clearly showed that output of N from agroecosystems due to leaching and denitrification depends on the N input level and approximates 25 % of the input rate for inputs of 150 kg N ha^{-1} $year^{-1}$ or higher in the Netherlands.

Energy balance

The nitrogen budget mentioned enabled us to make a rough estimation of the energy balance of a short-rotation forestry system (Table 5). The main assumptions to calculate the data presented in Table 5 are:

– the energy requirement to produce 200 kg fertilizer nitrogen is 10 GJ (gigajoules);

– the costs to transport wood to the power plant are 500 MJ per tonne;

– the energy output due to heat of combustion is 5.6 MJ per kg dry matter (efficiency = 35 %); and

– irrigation is needed at high production levels to meet the water requirements of the trees (Frissel et al., 1978).

Although Table 5 is a rough estimation of the energy inputs and outputs, it shows that despite high energy inputs for the transport of wood and the production of fertilizers short-rotation forestry is energetically feasible. Furthermore, high fertilizer application appears to be a means to gain energy.

With respect to the economics of short rotation forestry it must be pointed out, that Frissel et al. (1978) calculated that even a production of 25 tonnes dry matter per hectare per year, which is, theoretically, the maximum production in the Netherlands, is not economically feasible at present energy prices. Only if the inflation-corrected energy price would double, the net annual results of short-rotation poplar forests might become attractive for production levels of 20 tonnes or more.

The many guesses and estimates that had to be made, cause that conclusions and recommendations based on this study, have to be made with great care. Ne-

Table 5. Energy balance of a short-rotation forest system at two production levels (kg dry matter ha^{-1} $year^{-1}$)

	14 000 kg ha^{-1} $year^{-1}$	25 000 kg ha^{-1} $year^{-1}$
Inputs (MJ)		
Fuel, electricity	3 000	5 500
Fertilizers, chemicals	6 000	13 300
Depreciation	6 000	8 000
Other costs (incl. irrigation)	2 000	4 000
Transport	7 000	12 500
Total	24 000	43 300
Output (MJ)		
Combustion	78 400	140 000
Net output (MJ)	**54 400**	**96 700**

vertheless this study shows that the nitrogen cycle is an important factor in establishing the economical and energetical feasibility of this kind of energy farming.

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