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Energy analysis of willow production for bioenergy in Sweden

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ABSTRACT

Energy from biomass, including lignocellulosic crops such as willow (*Salix* spp.), is expected to increase in importance in Sweden. This study assesses the average annual net energy yield and the ratio between gross energy yield and total primary energy input for well-managed current commercial willow production systems in Sweden subject to three levels of fertilization with mineral nitrogen (N): N-high, N-medium, and N-zero. The average annual net energy yields are estimated at 175, 133, and 86 GJ ha^{-1} yr^{-1}, and the (dimensionless) energy ratios are estimated at 19, 32, and 47, for N-high, N-medium, and N-zero, respectively. Thus, there is a trade-off between achieving a high net energy yield and achieving a high energy ratio. Since the total primary energy input amounts to ≤ 5% of the gross energy yield in all cases, and the amount of arable land is limited, productivity increases may be considered more important than energy efficiency improvements. Substantial improvements in energy performance can be achieved by increasing harvest levels and improving energy efficiency in ammonia production and biomass transportation. The results should be interpreted with caution since several input parameters, especially energy use in ammonia production, fuel consumption rates, and the yield response to fertilization, are associated with considerable uncertainties.

1. Introduction

The Swedish government has decided that Sweden should be one of the world's first fossil-free welfare nations. By 2045, no net greenhouse gas (GHG) emissions are to be emitted to the atmosphere [1], and, by 2030, the vehicle fleet is supposed to be independent of fossil fuels [2]. Bioenergy is considered critical in reaching these goals [3,4]. Currently supplying ca. 23% of the total primary energy demand [5], bioenergy is already an important part of the Swedish energy mix. Perennial lignocellulosic crops, such as willow (*Salix* spp.), are considered attractive options since their production requires less energy [6], and has less of a negative environmental impact [7–9], than production of annual crops such as sugar beets, rapeseed, and wheat.

Willow species are characterized by fast growth, large biomass production potential, limited pest problems, high genetic diversity, short breeding cycles, and high resprouting capacity, i.e., ability to produce new shoots from the same stump after harvest [10]. Willow has been grown commercially for bioenergy in Sweden since the 1990s, primarily in the southern and central parts of the country. While the cultivated area is small, ca. 10,000 ha [11], Sweden is at the forefront of commercial willow plantations for bioenergy [12]. Plantations are typically managed as short-rotation coppice, i.e., multiple harvests and regrowth from the same stump [7]. So far, willow production has provided solid fuels for heat and power generation but may in the future also provide feedstock for production of liquid and gaseous fuels meeting stringent limits on GHG emissions [13].

Previous studies on willow production for bioenergy in Sweden have analyzed the introduction and development of commercial willow plantations [14], identified the reasons for slower-than-expected expansion and lower-than-expected yields [15], developed yield models for commercial willow plantations [16], estimated yields in experimental and commercial plantations and assessed impacts on groundwater and soil organic carbon [11], quantified divergences in yield levels between experimental and commercial plantations [17], evaluated cost reduction possibilities [18], assessed climate impacts [19], and studied how weeds are best controlled [20] and how different rates of mineral nitrogen (N) fertilization affect yields [21]. Studies have also evaluated systems that provide additional functions besides biomass supply [22], e.g., phytoextraction of cadmium and other contaminants on arable land [23] and treatment of sludge and nutrient-rich

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wastewaters [24,25].

Several energy analyses of Swedish willow production systems for bioenergy have also been made [6,26–29]. However, whereas fertilization is an important management aspect that strongly influences yield [12,16,21] as well as energy performance, only one study, namely González-García et al. [28], has previously investigated how different levels of N fertilization affect the performance of Swedish willow production systems. González-García et al. [28] found that willow production without the use of mineral N was more energy efficient (i.e., had a higher energy output: input ratio) than fertilized willow production. However, despite the use of yield data from a large set of Swedish commercial plantations, lack of data about fertilization levels prevented a solid analysis of the relationship between N fertilization and yield levels. It was assumed that plantations with high yields were fertilized with N, while plantations with low yields were not fertilized [28]. However, many factors influence yields, and a high level of fertilization does not guarantee a high yield, if, e.g., soil quality is poor, weather conditions are unfavorable, or the plantation is infested with pests. Further, the energy analysis was only a minor part of the study.

Thorough studies of the effects of different levels of N fertilization on the performance of Swedish willow production systems are therefore lacking. This paper aims to fill this knowledge gap by providing a detailed and up-to-date energy analysis of willow production for bioenergy in Sweden. The average annual net energy yield (*net energy yield*, for short), and the ratio between the gross energy yield and the total primary energy input (*energy ratio*, for short), are estimated for well-managed current commercial Swedish willow production systems subject to three levels of fertilization with mineral N. The study also aims at contributing to the debate about sustainable bioenergy production systems.

2. Materials and methods

The method consists of four steps: 1) definition of the willow production systems (Section 2.1); 2) inventory analysis of management operations and material inputs in the studied production systems (Section 2.2); 3) energy analysis (Sections 2.3); and 4) assessment of performance (Section 2.4). The assessment is based on a detailed and thorough review of management operations and energy use. Predominantly empirical data, collected from a wide range of published sources as well as experts, are used in the assessment.

2.1. Willow production systems and system boundaries

Willow production with three different levels of fertilization with mineral N are studied (Table 1): no N fertilization (N-zero), a medium level of N fertilization (N-medium), and a high level of N fertilization (N-high). Detailed information about fertilization practices in Swedish willow plantations is not available. Therefore, it is not known how these fertilization levels compare to current actual practice. The different levels are, however, all considered realistic and practically feasible. The medium level, with 160 kg ha^{-1} of mineral N applied per cutting cycle, is fairly close to the most recent fertilization recommendation for willow production in Sweden: 220 kg ha^{-1} of mineral N applied per cutting cycle [21].

Table 1
Definitions of the production systems studied here.

Case	Definition
N-high	High level of N fertilization: 480 kg ha^{-1} of mineral nitrogen (N) applied in each cutting cycle: 160 kg N ha^{-1} yr^{-1} for 3 years after each harvest (except the last), corresponding to, on average, 140 kg N ha^{-1} yr^{-1} over the plantation life cycle.
N-medium	Medium level of N fertilization: 160 kg ha^{-1} of mineral N applied in the first year after each harvest (except the last), corresponding to, on average, 40 kg N ha^{-1} yr^{-1} over the plantation life cycle.
N-zero	No N fertilization (0 kg N ha^{-1} yr^{-1}).

Other than the level of fertilization, the three cases are subject to the same management operations (but the number of harvests differ, see Section 2.2.1). Production in southern/central Sweden is considered, but the analysis is not specific to any particular site or type of soil. The production systems are managed as short-rotation coppice according to available management recommendations and considered representative of current and commercial plantations.

The system boundaries include the primary production of energy carriers and material inputs, field management operations and transportation of wood chips to the bioenergy-conversion site (heat plant or combined heat-and-power plant), see Fig. 1. The energy embodied in agricultural machines and implements (plows, harrows, etc.) is also included. The energy use is fully allocated to the studied production systems. Human labor, infrastructure for transportation, and biomass conversion to secondary energy carriers (heat/electricity) are not included.

2.2. Inventory of management operations

The management operations and material inputs of the production systems were determined based on information from practitioners and managers of willow plantations, information from the literature, and assumptions based on our own experience, see Table 2, which also specifies the time (year) of performance.

Willow cultivation is assumed to be well established, implying that specialized machinery is available and employed to a large extent on a yearly basis. The choice of machinery and management operations is based on a number of assumptions: 1) willow plantations are established on existing cropland previously cultivated with annual crops; 2) plantations are established on private commercial farms that have access to their own or hired machinery; 3) the soil has an average production potential; 4) management operations are not hindered by any physical conditions of the fields, such as size, shape, and drainage; 5) good agricultural practice, regarding, e.g., soil preparation, planting, and weed control, is applied at all stages; 6) no irrigation is applied; and 7) all plantations are terminated after 24 years. More information about the management operations is available in the Supplementary material, Section S1.

2.2.1. Data on fertilization and yields

Data on yields, and on the relationship between yield and level of N fertilization, were obtained from fertilization trials by Aronsson et al. [21]. The trials were conducted between 2008 and 2010 at five sites with commercial willow plantations in central Sweden (Högsta, Åsby, Lindberg, Djurby, and Hjulsta), using modern willow varieties in a randomized block design with four replicates. Mineral N was applied at four different rates: 1) no fertilization ("Control"); 2) 160 kg N ha^{-1} in a single dose after harvest ("Economy"); 3) 60, 100, and 60 kg N ha^{-1} in the first, second, and third year after harvest, respectively ("Normal"), and 4) 160 kg N ha^{-1} in the first, second, and third year after harvest ("Intensive"). The fertilization levels for N-high, N-medium, and N-zero correspond to the "Intensive," "Economy," and "Control" treatments in Aronsson et al. [21], respectively.

Yields from Aronsson et al. [21] represent estimates of the average standing crop biomass in the five sites after three years, calculated using data from annual field measurements of shoot diameters and site-specific allometric equations describing the relationship between shoot diameter and dry mass. To better represent the plantations considered here, the yield data from Aronsson et al. [21] were adjusted by applying a correction factor of 0.9 in order to account for losses associated with harvest (Table 3). Further, the lengths of the cutting cycles were adjusted, and the yields were adjusted accordingly. Yield levels were assumed to be the same for all harvests, except for the first and the last. The yield of the first harvest was assumed to be 37.5% lower than that