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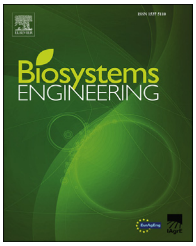

Research Paper

Dynamic modelling of cut-and-store systems for year-round deliveries of short rotation coppice willow

Daniel Nilsson [a,*], *Anders Larsolle* [a], *Nils-Erik Nordh* [b], *Per-Anders Hansson* [a]

[a] *Swedish University of Agricultural Sciences, Department of Energy and Technology, P.O. Box 7032, S-75007 Uppsala, Sweden*

[b] *Swedish University of Agricultural Sciences, Department of Crop Production Ecology, P.O. Box 7043, S-75007 Uppsala, Sweden*

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Short rotation coppice willow (SRCW) is a high-yielding energy crop that can be used to produce solid, liquid or gaseous biofuels. The crop is harvested during the winter, when the leaves have dropped. For economic reasons, however, most fuel processing plants require continuous year-round delivery of raw material. Thus, SRCW should be harvested as stems or in larger pieces in order to be storable, and not chipped directly at harvest for immediate use in large-scale heating plants, which is common practice at present. The aim of the project within which this study was conducted is to find cost-effective whole-stem harvesting and handling systems for year-round deliveries of natural-dried SRCW. A discrete event simulation model for such systems was developed in this study, taking weather, soil trafficability, geographical conditions, natural drying of the material and storage losses into account. The model was applied to a fictitious processing plant in Uppsala, Sweden. Machine performance and costs for a system with one stem harvester and up to three in-field shuttles, together with one chipper truck for chipping and transport, were investigated. The simulations showed that field trafficability had a crucial impact on total quantity harvested. The total cost was € 40 t^{-1} dry matter. Yield of SRCW and harvest productivity were important factors regarding costs. The model can be used to design cost-effective harvesting and handling systems for year-round deliveries of SRCW.

1. Introduction

Short rotation coppice willow (SRCW) (*Salix* spp.) is a fast growing and high yielding energy crop with several environmental benefits. For example, when SRCW replaces coal for the production of district heating, the net reduction in global warming potential (GWP_{100}) in a Swedish context is 0.1–0.2 kg CO_2-eq. MJ^{-1} (Hammar, Ericsson, Sundberg, & Hansson, 2014). The sequestration of soil carbon by SRCW corresponds to about 2 t CO_2 ha^{-1} yr^{-1}, on average, during a simulated period

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* *Corresponding author.*
E-mail address: daniel.nilsson@slu.se (D. Nilsson).

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Nomenclature

A_f	Area of an agricultural field (m^2)
C	Concentration in water (kg m^{-3})
C_c	Annual capital costs (€ yr^{-1})
D	Daily drainage (mm)
D_{eff}	Effective diffusivity of water (m^2 s^{-1})
E_a	Daily actual evapotranspiration (mm)
h	Depth of soil profile (mm)
I	Investment cost (€)
I_m	Antecedent soil moisture index (mm)
k	Mass transfer coefficient (m s^{-1})
K_{fc}	Hydraulic conductivity at field capacity (mm day^{-1})
K_{sat}	Hydraulic conductivity at saturation (mm day^{-1})
l	Length of a rectangular field (m)
l_r	Length of a row (m)
n	Depreciation time (yr)
n_p	Number of passes (or rows)
P	Daily precipitation (mm)
r	Radial distance from centre (m)
r_i	Interest rate (decimal)
R	Daily runoff (mm)
R	Radius of stem (m)
SL	Storage losses (decimal)
t	Time (s)
v	Operating speed of harvester (km h^{-1})
w	Width of a rectangular field (m)
w_a	Actual soil water content (mm)
w_p	Soil water content on previous day (mm)
w_{pwp}	Soil water content at permanent wilting point (mm)
w_{sat}	Soil water content at saturation (mm)
x	Number of days from 1st March
Y_a	Annual yield for harvest no a (tonnes dry matter (t DM) ha^{-1} yr^{-1})
α	Drainage rate exponent
$\rho_{a,i}$	Air water concentration at stem surface (kg m^{-3})
$\rho_{a,b}$	Air water concentration within stem (kg m^{-3})

of 100 years (Hammar et al., 2014). Several other studies confirm that short rotation coppice crops in general are beneficial regarding emissions of greenhouse gases (GHG) when replacing fossil fuels (see e.g. Cherubini et al., 2009; Gabrielle, Nguyen The, Maupu, & Vial, 2013; Schweier, Schnitzler, & Becker, 2016).

Several studies have also shown that the energy ratio for SRCW, expressed as energy output in relation to total primary energy input, is favourable; at least 20:1 according to Börjesson (2006) and SOU (2007) (including all processes from cultivation to delivery at heating plant). For example, Ericsson et al. (2013) report an energy ratio of 24:1 when using willow for the production of district heating (combustion included). Furthermore, when planted on fallow or surplus agricultural land, the cultivation of SRCW does not occupy land needed for the production of food. Cultivation of *Salix* spp. is also beneficial regarding the disposal of municipal wastewater and sludge, as these wastes can be used as fertilisers in SRCW plantations (Dimitriou & Rosenqvist, 2011). SRCW also performs phytoremediation by removing heavy metals from soils (Berndes, Fredrikson, & Börjesson, 2004; Mleczek et al., 2010), and increases biodiversity (Verheyen et al., 2014).

The cultivated area of SRCW in Europe is modest with Sweden (10 000 ha) and Denmark (5000) as leading countries (Dimitriou & Mola-Yudego, 2017). The present acreage in Sweden is far from the acreage of 100 000 ha predicted when the crop was introduced some decades ago (SOU, 2007). Important reasons for the reluctance of farmers to grow SRCW are the long rotation period (approximately 20 years), the need for specialist machinery for planting and harvesting and the visual impact on the landscape (Ostwald, Jonsson, Wibeck, & Asplund, 2013; Paulrud & Laitila, 2010). In a study by Paulrud, Rönnbäck, Gunnarsson, and Olsson (2010), 29 commercial growers of *Salix* and four harvesting contractors in Sweden were interviewed to map their experiences and attitudes to cultivation of this crop. Most farmers reported being dissatisfied, citing low economic profitability, “problems with harvesting systems” and “ineffective organisation to take care of the harvest and to sell the *Salix* chips” as their main difficulties (Paulrud et al., 2010).

The costs of harvesting and transport of SRCW may constitute up to half the total production costs (Hauk, Knoke, & Wittkopf, 2014). However, there is reported to be major potential for cost reductions in harvesting of SRCW (Rosenqvist, Berndes, & Börjesson, 2013). According to those authors, in a future time perspective of 15–20 years, the harvesting costs could be reduced by 50%, partly by economies of scale (25%) and partly by learning effects and technological development (25%). Regarding economies of scale, manufacture of machines in larger series, expanded cultivation area, shorter transit distances between fields and increased competition among harvesting contractors are potentially important cost reduction measures. At present, SRCW harvesting machines are used on only about 400 ha per year in Sweden (Rosenqvist et al., 2013).

SRCW is harvested every third or fourth year during the winter, when the leaves have dropped. There are two main methods for harvesting: cut-and-chip and cut-and-store (Danfors & Nordén, 1995a; Hollsten, Arkelöv, & Ingelman, 2013; Mitchell, Stevens, & Watters, 1999; Vanbeveren, Schweier, Berhongaray, & Ceulemans, 2015). The cut-and-chip method is a one-step operation in which the stems are chipped directly by the harvester and immediately blown into a trailer for transport to storage. This method has a high productivity (typically 15 tonnes dry matter (t DM) per scheduled machine hour (i.e. work time incl. delays) (sm h^{-1})) and low costs (typically 17 € t DM^{-1}) (Spinelli, Magagnotti, Picchi, Lombardini, & Nati, 2011; Spinelli, Nati, & Magagnotti, 2009; Vanbeveren et al., 2015). However, the chips have a moisture content of about 50% (wet-basis, w.b.) at harvest and are not storable for long periods as a result of rapid microbiological degradation (Jonsson, 2009). Thus, these SRCW chips are used shortly after harvest during only a few months per year. An alternative to chips are billets, which can be stored for longer than direct-chipped SRCW, depending on billet length and purity (O'Sullivan, 2006).

The cut-and-store system is a two-step operation in which the stems are cut and then stored loose or bundled for natural