Biomass and Bioenergy 116 (2018) 113–121

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

Optimal management of perennial energy crops by farming systems in France: A supply-side economic analysis

Nosra Ben Fradj[a,b,*], Pierre-Alain Jayet[b]

[a] Institute of Soil Science and Plant Cultivation, State Research Institute, Dept. of Bioeconomy and Systems Analysis, 24-100, Pulawy, Poland
[b] UMR Economie Publique, INRA, AgroParisTech, Université Paris-Saclay, 78850, Thiverval-Grignon, France

ARTICLE INFO

Keywords:
Perennial energy crop
Optimal management
Faustmann rule
Stochastic process
Net present value
Optimal rotation period

ABSTRACT

This paper aims at analysing the sensitivity of supply of a perennial energy crop, i.e. Miscanthus *x* Giganteus, in France, to yield and economic parameters. We use a decision-making method over natural resources, commonly applied in sustainable forest management, to evaluate the economic potential of the crop at plot level. The method allows us to determine the optimal rotation period (ORP) and the net present value (NPV) of Miscanthus in different farming system types when growth function is accounted for in a non-stochastic way as well as when it is governed by a random process. The short-term agricultural supply model, AROPAj, is used to highlight the competitiveness of Miscanthus regarding other crops within the 157 French farm groups portrayed in the model. We also detail the impact assessment regarding NPV and ORP, land use, Nitrogen (*N*) fertiliser demand and losses. We find that yields, price, renewal cycle costs and the discount rate may interact with yield randomization and significantly affect the future profitability of Miscanthus. As a result of our economic optimization, and in contrast to the common view of Miscanthus grown on marginal land, this crop could be profitable on the most productive land, generally devoted to food crops. For a price contracted at €70 tons of dry matter and fixed rotation cost given at €3000 per hectare, farming systems are predicted to grow Miscanthus on more favourable areas when its yield potential is high, thus leading to a substantial decrease in *N* input levels and losses.

1. Introduction

Changes in the world's climate and the increased interest in energy security have led to numerous studies on non-food biomass production. If we are to fuel our energy needs with biomass rather than petroleum, large-scale production of biomass is required. Moreover, greenhouse gas emissions (GHG), one of the driving factors behind climate change, can be reduced by using plant-based biofuels because the useful biomass can fix atmospheric carbon [10] and sequester carbon in the soil [4]. Based on lignocellulosic biomass, one of the benefits of second generation (2G) biofuels is that they reduce GHG emissions by up to 85% compared to conventional fuels [26] and can be produced from diverse raw materials such as wood, grasses and crop residues. It is also known that 2G feedstock is more land-use efficient than 1G crops [13] and may therefore be used to ensure bioenergy demand. In fact, growing a high-yielding crop, i.e. Miscanthus, would require 87% less land to produce the same amount of 1G biomass, given that Miscanthus yields are about 15–20 tons dry matter per hectare per year ($tdm\ ha^{-1}y^{-1}$) [17].

Miscanthus has other features that make it a sustainable source of 2G bioenergy. With an average lifespan of between 15 and 25 years, Miscanthus is a C_4 herbaceous grass suitable for a wide range of European climatic conditions [20]. Moreover, it is an environmentally-friendly crop, requiring low levels of Nitrogen (*N*) fertilisers and consequently having a lower risk of nitrate contamination of groundwater. In this study, we have chosen a natural hybrid between *Miscanthus sinensis* and *Miscanthus sacchariflorus*, i.e. Miscanthus *x* Giganteus [16], which is the most experimentally developed hybrid in France. From the economic standpoint, Miscanthus *x* Giganteus (hereafter referred to as Miscanthus) is harvested annually, thus providing farmers with a yearly income. Since it is sterile, this hybrid requires vegetative multiplication by rhizomes and therefore entails high establishment costs ranging between €2400 and €4800 ha^{-1} [8]. In addition, Miscanthus is intended to be grown on marginal land in order to circumvent the heated "Food *vs.* Fuel" debate. However, some studies have shown this crop has a high-yield potential when it is cultivated on good-quality soil [24]; [25]. Thus farmers opting to cultivate Miscanthus are faced by a major question. They have to reserve the land for a long rotation period of at least 15 years, yet want to ensure a rapid return on investment and a yearly income more or less equivalent to that of existing crops. At

* Corresponding author. Institute of Soil Science and Plant Cultivation, State Research Institute, Dept. of Bioeconomy and Systems Analysis, 24-100, Pulawy, Poland.
E-mail addresses: nosrabenfradj@iung.pulawy.pl (N. Ben Fradj), pierre-alain.jayet@inra.fr (P.-A. Jayet).

https://doi.org/10.1016/j.biombioe.2018.06.003
Received 15 September 2017; Received in revised form 25 May 2018; Accepted 1 June 2018
0961-9534/

which date, therefore, will the crop provide the highest market value? In other words, in which year should the final cutting take place, especially given that an expensive biomass resource is being cultivated and that land is needed for other production.

In the field of natural resource economics involving perennial land-consuming plants, studies have sought to answer the question of timing by applying Faustmann's rule [12], the method commonly used to address questions of optimal resource management. The rule is well applied especially when the growth function and price of trees are assumed to be known over time. Nonetheless, numerous methods have been developed to generalize the application of this rule. Focusing on optimal rotation, some studies have accounted for uncertainty. Resulting from random fluctuations in the productivity level or from random changes in natural conditions, biomass uncertainty can play a central role in forest management. Different approaches have been developed to deal with this uncertainty. Tree size is modelled through a diffusion process [22] as well as through a geometric Brownian motion [9], with a view to solving the rotation problem [27]. Considers a general stochastic differential equation model for the growth process in continuous time [6]. Models the growth process in discrete time by employing Markov decision processes.

Despite the fact that Miscanthus raises a similar question of harvest timing under biomass uncertainty, Faustmann's formula has not to our knowledge been used to analyse this issue. To manage the random yield of Miscanthus, we develop a simple stochastic model in which the yield process is based on a popular distribution, the so-called beta-distribution. Because of its versatility, this distribution has been used by Ref. [23]; among others, to model a variety of uncertainties. It is generally used for representing processes with lower and upper limits, while at the same it has the flexibility to model both positive and negative skewed data. In this study, we address the question of biomass uncertainty in continuous time for a perennial resource. By applying two Faustmann models, we derive harvesting rules to deal with the optimal rotation age and the economic value of Miscanthus when its growth function is accounted for in a non-stochastic way as well as when it is governed by a random process. Given the differences in results between these two cases, we make use of the AROPAj model to highlight them.

AROPAj is an optimization economic model of European agricultural-supply. It is a one-year period mathematical programming model, based on a micro-economic approach [2]. Covering most arable crop, grasslands, fodder and livestock farming sectors, the model describes the supply choices of individual farm groups in terms of land allocation and plant and animal production. Farms are grouped into farm groups, within each region, according to their technico-economic orientation, economic size and altitude class. Representative farm groups are assumed to maximise their total gross margin. The feasible production set is driven by modules representing farm characteristics (i.e. crop rotation, animal demography, livestock limit, animal feeding, fertiliser consumption) and different policy measures related to the Common Agricultural Policy and the application of agro-environmental instruments. Other modules describe environmental impacts such as N-losses, i.e. ammonia (NH_3), nitrous oxide (N_2O) and nitrate (NO_3). Computation of these outputs can be refined when estimated by linking AROPAj with the STICS crop model [15].

In the light of the above, we firstly identify the economic parameters that affect harvest timing and the economic value of Miscanthus, in addition to yield potential. Secondly, we show how the issues of timing and valuation alter when the farmer cannot foresee the future (the stochastic approach) compared to when he can foresee it (the non-stochastic approach). Finally, we address the question of differences between the non-stochastic and random cases, in terms of production, land use and N-losses.

2. Materials and methodological approach for economic estimates

We calculate the optimal value and rotation age of Miscanthus respectively under non stochastic and random conditions. The value of Miscanthus is determined by using the Faustmann rule, usually associated with forest that is harvested at the end of the cycle. In our case, it is applied to Miscanthus, which is harvested annually.

2.1. Non-stochastic value expectation of miscanthus

The method we used to calculate the value and optimal rotation age of Miscanthus in the non-stochastic case is explained in Refs. [5] and [3]. These papers detail the two-step procedure used to integrate perennial crops into a one-year period optimization model. First, the continuous time-yield function is correlated with a control plant yield, i.e. cereals, to deal with the lack of information on yield. Second, the optimal rotation period and value are estimated using a Faustmann dynamic approach.

Based on the Faustmann decision rule, the farmer's goal is to decide on the rotation period T that maximises the intertemporal economic value of Miscanthus. The net cumulative profit over one rotation of duration T is as follows:

$$V_m(T) = -c_0 + \sum_{t=1}^{T} M(t)\, e^{-(\delta-\alpha)t} \tag{1}$$

where c_0 is the establishment cost paid off over each T-cycle duration at $t = 0$, and δ and α are the discount and inflation rate, respectively. $M(t)$ is the annual gross margin. Commercial harvesting starts at the second year, so that $M(1) = 0$, and for t 2, $t \geq 2$, $M(t) = p_t\, y(t) \; - \; c_t$, where c_t are the annual production costs paid at any of the T years and p_t is the price of a ton dry matter of the harvested yield at t.

In opting for cultivating Miscanthus on 1 ha, the farmer is assumed to maximise its cumulative profit over infinite time denoted by $W(T)$

$$W(T) = \sum_{n=1}^{\infty} V_m(T)\, e^{-\delta n T} \tag{2}$$

The general principle of our optimization process is divided into three steps: (i) we first maximise W against T; (ii) we deduce the annual net equivalent value $V_m(T)$ and average yield over one period; and (iii) we integrate the new crop, i.e. Miscanthus, into the set of eligible activities in AROPAj in which land allocation is optimally computed.

The first step of the process is based on a yield estimation according to a growth function $y(t)$ defined for a growing cycle and expressed as follows:

$$y(t) = a\left(\frac{1}{\left(1 + e^{\frac{b-t}{c}}\right)} - \frac{1}{\left(1 + e^{\frac{b}{c}}\right)}\right)e^{-dt} \tag{3}$$

The y-parameters reflect three phases: an initial increasing phase with a possible inflexion point (b), an intermediate stabilisation phase at a maximum level (a), and lastly a decline phase described by a spreading parameter (c) and an attenuation coefficient (d).

2.2. Introduction of a random process into the faustmann modelling

In this section, we suppose that only biomass quantity is random and all the other economic factors are unchanged. The random yield process is based on a beta distribution that represents how the harvest yield expectations change during a rotation period.

The first period begins at time $t = 0$, the planting date, and continues to $t = T$, the clear-cutting date. We are interested in yield expectations at each time t. We assume that yield realizations are positive and finite, and that the distribution is restricted to values between 0 and the value given by the potential function $y(t)$. To generate a random process, each yearly expected yield is multiplied by $\varepsilon_t = E[\tilde{y}(t)]$ and each random yield $\tilde{y}$ follows a beta distribution. The standard beta probability distribution function for a random variable $\tilde{y}$