Optimizing Biofuels Production in an Uncertain Decision Environment

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Abstract[1]

The question of increasing biofuels production and the development of different biofuels production technologies has become controversial. On the one hand, production of corn-based biofuels creates a 'food/feed vs. fuel' tradeoff condition, along with subsequent uncertainties for both consumers and producers (farmers). On the other, advanced biofuels (from, e.g., switchgrass, miscanthus, algae), although acknowledged as environmentally friendly, are not available yet on a large commercial scale. In addition, the resource availability for the production of biofuels feedstocks and the question of a sustainable biofuels production are major issues impacting decision making.

By using a multi-objective optimization model and fuzzy logic, the paper presents an approach of modeling sustainable biofuels production from conventional and advanced biofuels feedstocks, under the condition of limited resources and uncertainty resulting from incomplete information or missing knowledge about resource availability for biofuels production.

Key words: Biofuels, multi-criteria decision-making, linear programming (LP), fuzzy set theory, uncertainty

1 Introduction and problem setting

In recent decades, biofuels production (both ethanol and biodiesel) in the United States (US) has been continuously growing. It was triggered by several economic, environmental and political incentives, such as: extending the security of the national energy supply, reducing greenhouse gas (GHG) emissions and global warming, creating new market outlets or additional demand for agricultural products, strengthening regional development and finally stimulating economic growth.

In 2011/2012, the total ethanol production from corn in the US amounted to 13,559 million gallons and made 98.3% of the total ethanol production in the country. Cellulosic ethanol was not produced on a commercial scale in 2011/2012, but 9 million gallons of this fuel are estimated

[1] The paper provides an abbreviated version of the research topic. More details can be found in Ziolkowska (2013). Please also contact the author with any further questions.

to be supplied on the market in 2012/2013. The total biodiesel production and consumption in 2011/2012 amounted to 1,109 million gallons (FAPRI, 2012).

For many years, US policy has been actively supporting the production and consumption of biofuels with subsidies and mandates. Due to the limited production of cellulosic ethanol, in 2010, the Environmental Protection Agency waived and adjusted the envisaged mandate down to 16 billion gallons by 2022. Further adjustments in the coming years are possible. The current market situation shows a disparity between the biofuels production/consumption, on the one hand, and expectations in terms of the desired level of biofuels production/consumption, on the other. In addition, the limited resources for the production of biofuels feedstocks and the question of a sustainable biofuels production are major decision making issues.

In the process of designing a sustainable biofuels policy, multiple economic, environmental and social aspects need to be considered in policy decisions. A comprehensive methodology for such kind of an evaluation is, for instance, multi-criteria analysis. The research on multi-criteria methodology for biofuels production and policies has evolved in recent years, with studies of Dinh et al. (2009), Mohamadabadi et al. (2009), Turcksin et al. (2011), Perimenis et al. (2011), Rajagopal et al. (2011) that evaluated multiple criteria in the biofuels production chain or policies. However, none of those studies addressed the question of uncertainty resulting from missing information and accompanying each decision-making process. To fill this gap, Ziolkowska (2011) proposed a multi-criteria approach for several biofuels feedstocks, capturing uncertainties of decision making that can be used in an interactive policy design process with decision makers.

This paper goes one step further and presents a fuzzy logic multi-objective optimization model to answer the question of a sustainable biofuels production, both from conventional (corn, soybean, canola) and advanced (switchgrass and algae) biofuels feedstocks, considering uncertainties in decision-making processes. In this way, the paper extends the existing literature on biofuels evaluations that have been mainly conducted by means of probabilistic models in the past and recent years.

2 Research objectives

The paper presents a multi-objective linear programing model for analyzing sustainable biofuels production scenarios in the situation of limited resources and/or missing information on resource use. Due to limited information and statistical data on biofuels feedstocks, especially those used in advanced technologies, the paper is focused on five feedstocks only: corn, soybean, canola (representing conventional feedstocks) and switchgrass and algae (representing advanced biofuels feedstocks). As most advanced biofuels are not produced commercially yet, the model provides a tool that can be used also in mid-term perspective to analyze biofuels and their sustainability in meeting the defined objectives of the biofuels policy.

3 Methodology and data

The methodological framework, presented in this paper, consists of the following approaches:

- Fuzzy Multi-criteria Decision-Making approach PROMETHEE
- Fuzzy logic
- Expert elicitation
- Linear programming model with fuzzy resources.

The approaches will be briefly discussed in the following sections.

3.1 PROMETHEE approach and derivation of objective coefficients for the LP model

The objective coefficients for the LP model have been generated by the PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) approach. They denote the potential of the analyzed feedstocks for meeting the defined biofuels policy objectives, while the PROMETHEE decision function encompasses all biofuels policy objectives, as defined in this study. The details of constructing the PROMETHEE approach and deriving the coefficients have been described extensively in Ziolkowska (2013). Here, only a brief overview has been provided.

The analyzed biofuels feedstocks were expressed as a set of alternatives $A = \{a_1, a_2, \ldots, a_5\}$ representing corn (a_1), switchgrass (a_2), soybean (a_3), canola (a_4) and algae (a_5). One of the main steps in the PROMETHEE approach is the evaluation of the alternatives (here: biofuels feedstocks) in terms of the defined criteria (here: biofuels policy objectives).

The policy objectives $C = \{c_1, c_2, \ldots, c_{12}\}$ included in this study represent three objective groups:

1) Economic objectives - Reducing biofuels production costs (c_1), Increasing biofuels productivity/acre (c_2), Insuring national food security (c_3), Securing farmers' incomes (c_4)
2) Environmental objectives - Reducing greenhouse gas emissions (c_5), Reducing water usage (c_6), Reducing land use (c_7), Protecting biodiversity and landscapes (c_8)
3) Social objectives - Increasing consumer welfare (c_9), Supporting local communities (c_{10}), Improving health and safety issues (c_{11}), Creating new jobs (c_{12})

The PROMETHEE methodology in this study covers both tangible (measurable) variables (e.g., biofuels production costs, GHG emissions, water use, land use) and intangible (non-measurable) variables (e.g., health and safety issues, national food security, etc.). The measureable variables were derived from experiment-based publications on different biofuels feedstocks describing the degree of the respective feedstocks of meeting the defined objectives (Mata et al., 2010; Dinh et al., 2009; Pimentel and Patzek, 2005). They were included in the LP model as constraints coefficients. The intangible variables were assessed by twenty experts from the US Environmental Protection Agency (EPA), US Department of Agriculture (USDA), Food and Agricultural Policy Research Institute (FAPRI), International Food Policy Research Institute (IFPRI) and from several US universities. For this study, only experts specializing in the field of biofuels with an extensive knowledge about all analyzed biofuels technologies have been selected and their assessments were anonymous.

The experts assessed the relative importance of the defined policy objectives and the relations between the feedstocks in terms of those objectives. For the estimation of the policy objectives a numerical scale 1-10 (with 1 indicating the lowest importance and 10 representing the highest level of importance) was used. The relations between the biofuels feedstocks and the policy objectives were assessed by means of a linguistic scale (a tool of fuzzy logic introduced by

Zadeh (1965)). The linguistic scale included the following evaluation levels: 'very low' (VL), 'low' (L), 'medium' (M), 'high' (H), 'very high' (VH). The expert assessments were further translated into fuzzy number (table 1).

3.2 Fuzzy relations and membership function

In this paper, fuzzy set theory was used to address the question of uncertainties related to available resources in biofuels production.

Fuzzy set theory defines the membership of any element *x* belonging to the set $A\ (\tau_A(x))$ as either a non-member (if it takes the value of 0) or a member (if it takes a value of 1); where A is a subset of the entire set X (universe of discourse). The mapping of the function is denoted by $\tau_A: X \rightarrow \{0,1\}$. Therefore, for each element $x \in X$, it applies:

$$\tau_A(x) = \begin{cases} 1, & iff\ x \in A \\ 0, & iff\ x \notin A \end{cases}$$

For the biofuels analysis, the universe of discourse X was defined as a finite set $X = \{x_1,\ x_2, \dots, x_5\}$ with the set elements $x_1,\ x_2, \dots, x_5$ denoting the analyzed biofuels feedstocks. Each element *x* in a fuzzy set $\tilde{A}$ and in the universe X is described by means of a membership function with the numerical 'degree of membership' on the real continuous and closed interval between 0 (non-membership) and 1 (complete membership).

The fuzzy set $\tilde{A}$ in X is a set of ordered pairs $\tilde{A} = \{(x, \mu_{\tilde{A}}(x))\}, \forall\ x \in X$ with the membership function $\mu_{\tilde{A}}: X \rightarrow \Theta$, which maps all $x \in X$ into an ordered set Θ (called the 'membership set' and representing the set [0, 1]), while $\mu_{\tilde{A}}(x)$ indicates the grade of membership of x in $\tilde{A}$ for each $x \in X$ (Smithson and Verkuilen, 2006; Munda, 2008).

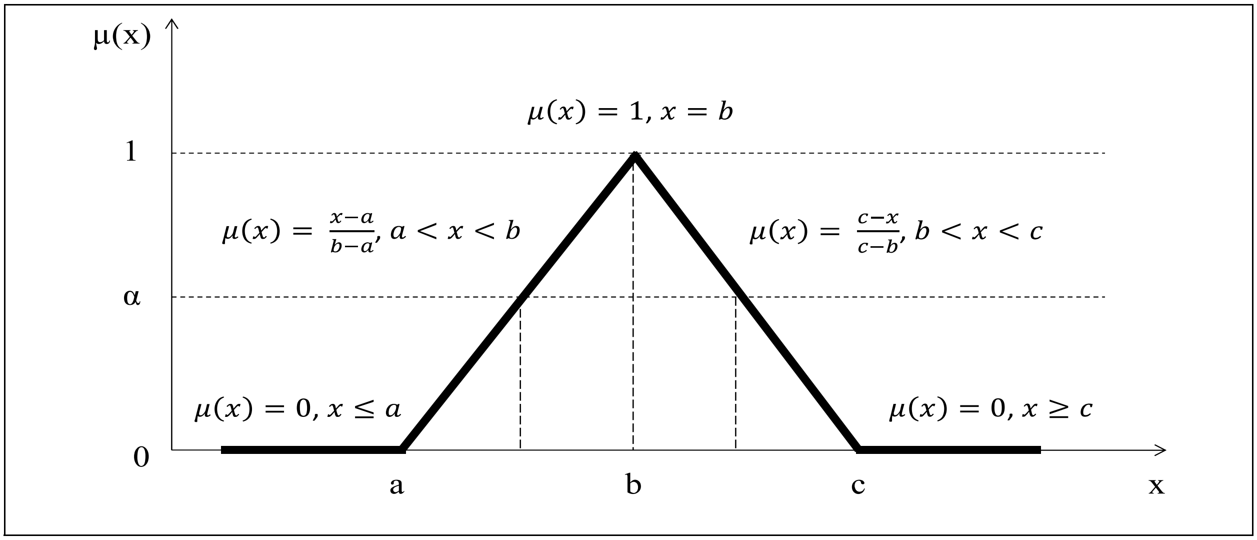
In this study for biofuels feedstocks, the fuzzy set $\tilde{A}$ in X is represented as follows:

$$\tilde{A} = \sum_{i=1}^{5} \oplus\ \mu_A(x_i)$$

where $\mu_A(x_i)$ denotes the value of the membership functions of the respective biofuels feedstocks and $\oplus$ indicates the union operator in fuzzy logic symbolic.

In this paper, the triangular membership function (figure 1) was applied, due to its simplicity in representing vagueness and uncertainty. According to the definition of the triangular membership function, an element x has the membership degree of 1 (a full membership), if and only if $x = b$, while it takes the membership value of 0 (and becomes a non-member) if and only if $x \leq a \ or \ x \geq c$. Each membership value, such that: $a < x \leq b \ and \ b < x \leq c$, assigns an intermediate degree of membership (between 0 and 1) to the element x that is called a triangular fuzzy number.

Figure 1 Triangular fuzzy number and membership function



Source: Author's construction according to Kahraman et al. (2006)

As mentioned above, the assessments given by the experts with a linguistic scale were translated into triangular fuzzy numbers (table 1) and further used for evaluating the sustainability ranking of biofuels feedstocks and ultimately as objective coefficients for the multi-criteria LP model.

Table 1 Linguistic variables and triangular fuzzy numbers

Linguistic variable	**Triangular fuzzy number**
Very low (VL)	(0.00, 0.00, 0.25)
Low (L)	(0.00, 0.25, 0.50)
Medium (M)	(0.25, 0.50, 0.75)
High (H)	(0.50, 0.75, 1.00)
Very high (VH)	(0.75, 1.00, 1.00)

Source: Authors' performance

3.3 Multi-criteria linear programming model for biofuels production

The multi-criteria LP model with fuzzy resources (fuzzy constraints) is based on the PROMETHEE approach and uses in addition data from the FAPRI data base on biofuels production from the analyzed feedstocks in 2010 ('current production'). As of 2010, no biofuels have been produced from switchgrass and algae on a commercial scale in the US. Thus, current production coefficients for biofuels from these feedstocks amount to zero.

Due to limited availability of political and scientific knowledge and of statistical data, the optimal resource use for biofuels production optimizing sustainability goals of the biofuels policy is not known precisely. Therefore, it was estimated by maximizing the defined objective function in the situation of biofuels production in 2010.

For the defined optimization problem the objective function was defined as a sum product of the objective coefficients of the respective alternatives and biofuels production level from the respective analyzed biofuels feedstocks as of 2010.

$$Max\ Z, \qquad s.t.\ Z = \sum_{i=1}^{5} z_i\, x$$

with:

Z – objective function

z_i – objective coefficients for the respective alternatives (biofuels feedstocks) for $i = 1, \ldots, 5$

x – current biofuels production from the respective feedstocks for $i = 1,\ 2,\ \ldots, 5$

$x \geq 0$ and $\mu_{\tilde{C}_i}(x), \forall i.$

In this model, the objective function covers the economic, environmental and social policy objectives cumulatively.

The objective function is subject to four constraints expressed with inequalities under the condition of fuzzy resources represented with the parameter θ. Due to missing data on the optimal resource use for biofuels production, the right-hand sides of the constraints were estimated according to the current resource use in the base-case scenario. In the base-case scenario, the parameter θ is equal to zero, thus assuming that no uncertainty in the resource availability exists. The following constraints have been defined:

(1) GHG emissions constraint: $\mu_{\tilde{C}_{GHG}}(x)$:

$$\sum_{i=1}^{5} a_{iGHG}\, x \;\leq\; b_{iGHG} + \,\theta \times b_{iGHG}^{0} \Rightarrow \sum_{i=1}^{5} a_{iGHG}\, x \;\leq 39.75 + \theta \times 10$$

with: a_{iGHG} denoting the GHG emission coefficients for the respective biofuels feedstocks (performance of the biofuels feedstocks in terms of GHG emissions),

b_{iGHG} denoting the current GHG emissions by the respective biofuels feedstocks in the base-case scenario,

b_{iGHG}^{0} representing the tolerance margin for GHG emissions set randomly and deviating by 10 units from the resource use in the base-case scenario.

The subscript i in the variable b_{iGHG} and other constraint variables refers to the lower and upper bounds of the constraints.

The right-hand side of the constraint was set as an upper bound, as a sustainable biofuels policy seeks to limit GHG emissions.

(2) Water usage constraint: $\mu_{\tilde{C}_{Water}}(x)$:

$$\sum_{i=1}^{5} a_{iWater}\, x \;\leq\; b_{iWater} + \theta \times b_{iWater}^{0} \Rightarrow \sum_{i=1}^{5} a_{iWater}\, x \;\leq 47.96 + \theta \times 10$$

with: a_{iWater} denoting the water use coefficients for the respective biofuels feedstocks,

b_{iWater} denoting the current water use for biofuels production from the respective feedstocks cumulatively,

b_{iWater}^{0} denoting the tolerance margin for water use deviating by 10 units from the resource use in the base-case scenario.

Also in this case, the right-hand side of the constraint was set as an upper bound, as according to a sustainable biofuels policy, a maximum possible yield should be reached by a minimum input of water resources.

(3) Land use constraint: $\mu_{\tilde{C}_{Land}}(x)$:

$$\sum_{i=1}^{5} a_{iLand}\, x \;\leq\; b_{iLand} + \theta \times b_{iLand}^{0} \Rightarrow \sum_{i=1}^{5} a_{iLand}\, x \;\leq 3{,}182.60 + \theta \times 10$$

with: a_{iLand} denoting the land use coefficients for the respective biofuels feedstocks,

b_{iLand} denoting the current land use for biofuels production from the respective feedstocks cumulatively,

b_{iLand}^{0} denoting the tolerance margin for land use deviating by 10 units from the resource use in the base-case scenario.

The right-hand side of the constraint was set as an upper bound, as the biofuels production cannot compete with, e.g., the agricultural production for land resources.

(4) Lower bound for the total biofuels production: $\mu_{\tilde{C}_{Prod}}(x)$:

$$\sum_{i=1}^{5} a_{iProd}\, x \;\geq\; b_{iProd} - \theta \times b_{iProd}^{0} \;\Rightarrow \sum_{i=1}^{5} a_{iProd}\, x \;\geq\; 48.92 - \theta \times 1$$

with: a_{iProd} denoting the production coefficients for the respective biofuels feedstocks, b_{iProd} denoting the current biofuels production from the respective feedstocks cumulatively, b_{iProd}^{0} denoting the tolerance margin for biofuels production deviating by 1 unit from the current production in the base-case scenario.

The right-hand side of the constraint was set as a lower bound, as the goal is to maximize biofuels production in general.

In addition, the non-negativity constraint holds, such that:

$$x \geq 0, \qquad \forall\ i = 1, 2, \ldots, 5$$

and excludes solutions with negative biofuels production levels.

The constraints are defined as 'available resources' for biofuels production. While the term of this definition is plausible for the water and land use constraint, in case of the GHG emission constraint, the term 'available resources' is defined as the permitted level of the GHG emissions related to biofuels production from the respective feedstocks.

For the constraints ‘GHG emissions’, ‘Water usage’ and ‘Land use’, b_i^0 was assumed to be equal to 10, while for the constraint ‘Biofuels production’ b_i^0 was assumed to be 1. Those assumptions are random, as no exact policy requirements exist in terms of the resource use at this point of the biofuels policy formulation. They allowed the narrowing down of the possible solution space.

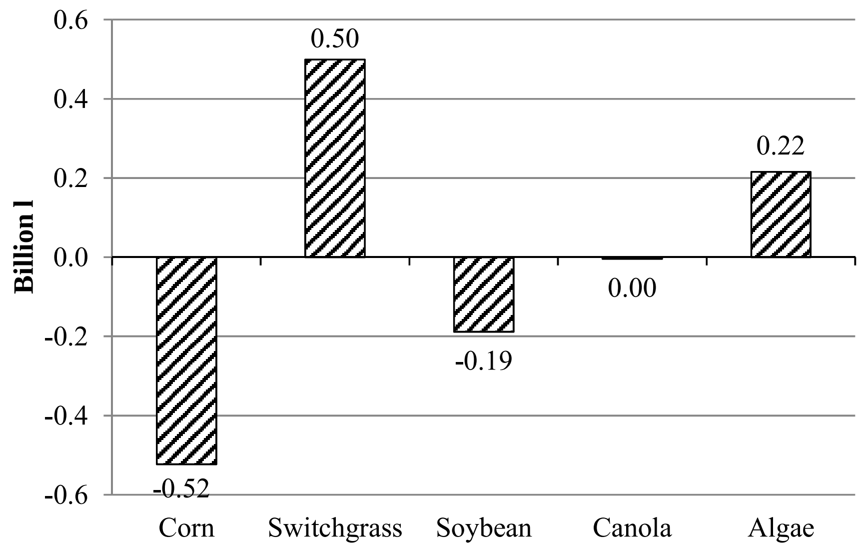
4 Results

4.1 Optimal biofuels production in base-case scenario

The results show that changes in the production levels would be necessary to maximize economic, environmental and social policy criteria subject to the given constraints, as defined in the model. As the advanced biofuels feedstocks presented in this study belong to emerging technologies, and also due to several assumptions in the presented model, the analysis should be understood as an attempt to demonstrate a tool for interactive policy-making under the condition of changing resource availability (uncertain resource availability), rather than a definite optimal policy solution.

An objective-oriented biofuels production in the base-case scenario shows that 47.44 billion l ethanol would be produced from corn, 0.50 billion l ethanol from switchgrass, 0.75 billion l biodiesel from soybean, 0.02 billion l biodiesel from canola, and 0.22 billion l biodiesel from algae. The production levels are clearly determined, among others, by the objective coefficients; and only biofuels production from switchgrass (with the second high objective coefficient) reaches the upper production bound. The production of biofuels from soybean and canola is determined by the lower bound that is binding in this case. Thus, compared with the base-case scenario and the current biofuels production from the respective feedstocks as of 2010, the optimal/objective-oriented production would require to increase ethanol production from switchgrass by 0.50 billion l and biodiesel production from algae by 0.22 billion l. Also, it would require to decrease ethanol production from corn by 0.52 billion l and biodiesel production from soybean by 0.19 billion l. Biodiesel production from canola would remain at the same level as currently given (figure 2).

Figure 2 Difference between the optimal and current biofuels production in base-case scenario



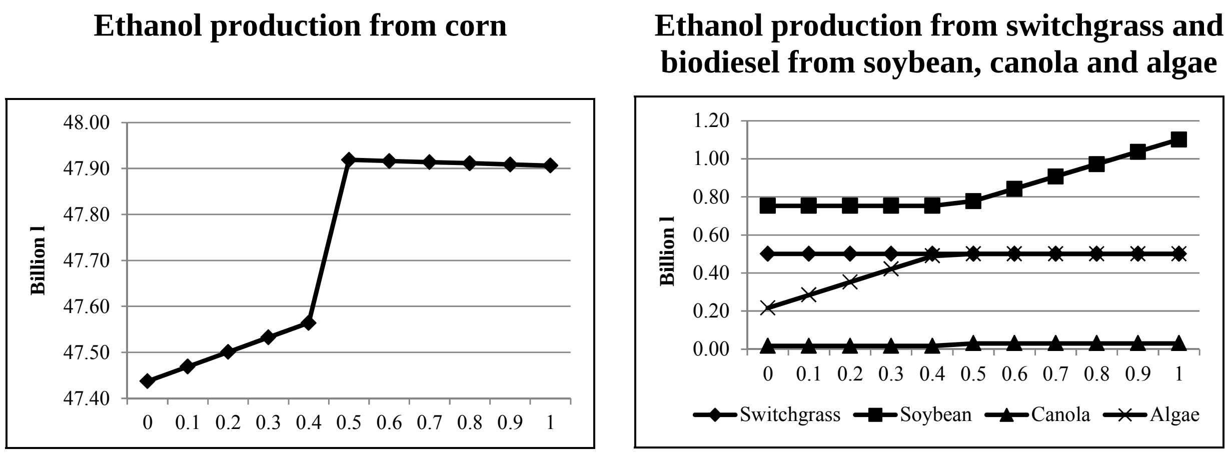
Source: Author's calculations

4.2 Sustainable biofuels production with fuzzy resources

In most decision situations and optimization problems, the amount of available resources is not always (precisely) given or known. Therefore, available resources can be specified only approximately. By converting a fuzzy decision problem to a parametric programming with fuzzy resources, the optimal solutions under changing conditions of resource availability for the biofuels production were analyzed. For this purpose, the θ parameter was stepwise parameterized between 0 and 1, subject to the defined constraints. The parameterization of the θ parameter represents a deviation from the crisp values describing the available resources (the situation with $\theta = 0$, base-case scenario) and it extends the available solution space for the right-hand of the linear constraints (resource use).

The analysis shows that increasing the resource availability (allowing higher GHG emissions, increasing water and land use) would allow extending corn ethanol production as compared to the base-case scenario. At the 40% higher level of available resources ($\theta = 0.4$) as compared to the base-case scenario, corn ethanol production increases from 47.56 to 47.92 billion l. The same increasing tendency applies to biodiesel production from soybean and canola, although the increase is less considerable than in the case of corn ethanol (figure 3). Also biodiesel production from algae increases with the growing available resources, however only up to the level where the θ parameter takes the value of 0.4. For any other amount of available resources greater than 40% of the resource availability in the base-case scenario ($\theta > 0.4$), biodiesel production from algae remains on an unchanged level of 0.50 billion l and is limited by the upper bound of the defined constraint in the LP model. Only the production of switchgrass ethanol is constant regardless of the available resources. It is determined by its high objective coefficients; it reaches the upper bound of the constraint in the base-case scenario and remains unchanged throughout the analysis.

Figure 3 Optimal biofuels production in the situation of changing available resources



Note: 0 represents the base-case scenario in terms of the available resources, while 1 indicates the maximum resource availability in the model, based on the available resources in the base-case scenario.

Source: Author's calculations

5 Conclusions and outlook

The paper presents a multi-criteria linear programming model with fuzzy resources for estimating an objective-oriented biofuels (ethanol and biodiesel) production from traditional and advanced biofuels feedstocks. It indicates practical benefits of applying this methodology in interactive decision-making processes and designing sustainable biofuels policies.

The analysis shows algae and switchgrass to be the most suitable for biofuels production in terms of maximizing the defined economic, environmental and social policy criteria simultaneously. Corn, that is currently the most important feedstock for ethanol production in the US, has the lowest sustainability potential among the analyzed feedstocks. In order to maximize the economic, environmental and social objectives of the biofuels policy, ethanol production from switchgrass would need to be extended by 0.50 billion l and biodiesel production from algae by 0.22 billion l. At the same time, ethanol production from corn would need to be limited by 0.52 billion l and biodiesel production from soybean by 0.19 billion l. Biodiesel production from canola would remain at the same level as in 2010. Also, biofuels production scenarios were analyzed for changing resource availability. A breakthrough point in biofuels production is the level of 40% increase in resource use as compared to the base-case scenario.

As the model includes switchgrass and algae that are currently not used on a commercial scale for biofuels production in the US, the analysis shows a decision situation reaching into the future. In the next decades, advanced production technologies are expected to expand on the biofuels market and provide feedstocks that will allow for minimizing production costs and resource use.

The paper provides an example of a comparative-static analysis. A possible extension could include a dynamic fuzzy linear programming model for production changes occurring over time and for predicting future biofuels production under changing resource availability. However, for this kind of analysis, a larger data set would be required that is not available at this point of time and with the current still limited knowledge, especially on advanced biofuels feedstocks costs and production trends.

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