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Consequential life cycle assessment of the environmental impacts of an increased rapemethylester (RME) production in Switzerland

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ABSTRACT

Arable land is a constrained production factor – particular in Switzerland. Merely 45% of the consumed crops are produced domestically. Hence, the additional cultivation of rape for producing methyl ester is assumed to substitute crops used for food production. Consequently, Switzerland has to face the decision either to use the arable land for food production and import fuels or to produce fuel from rape and import the displaced food. Using Consequential Life Cycle Assessment (CLCA), the environmental consequences have been assessed if rape for energetic utilization substitutes rape used as edible oil or barley used as animal fodder. The study shows, that displacing food production by RME production in Switzerland can reduce total GHG emissions, when GHG-intense soy meal from Brazil is substituted by rape and sunflower meal, which is a co-product of the vegetable oil production. On the other hand, an increased production of vegetable oils increases various other environmental factors, because agricultural production of edible oil is associated with higher environmental impacts than the production and use of fossil fuels. In summary, the environmental impacts of an increased RME production in Switzerland rather depend on the environmental scores of the marginal replacement products on the world market, than on local production factors.

1. Introduction

Driven by scarcity of fossil fuels and climate change the idea of using renewable energy is attracting interest both in the Swiss public eye and in the industry. Fuels made from biomass – so-called biofuels – are currently the most important form of renewable energy in road transportation and are supposed to play a role in reducing greenhouse gas emissions (GHG) and decreasing our dependency on fossil fuels at least over the short to medium term [1,2]. Despite the potential of biofuels on reducing GHG emissions, the environmental impacts of producing biofuels are manifold ranging from nutrient outwash to biodiversity loss [3]. These direct environmental impacts have been investigated extensively in various Life Cycle Assessment (LCA) studies [4–6]. Because the production of biofuels is land intensive, the environmental impacts of biofuels are strongly intertwined with other uses of land like nature conservation [7], supply of food [8] and production of biomaterials [9]. For a sound assessment of the total environmental impacts of producing biofuels, it is therefore necessary to address also indirect impacts, which take place outside of the value chain of biofuels.

The goal of this study is to assess the direct and indirect environmental impacts when Switzerland substitutes one percent of its annual diesel consumption by the domestic production of RME. We used consequential LCA (CLCA) to quantify the direct and indirect environmental impacts resulting from an increased production of RME in Switzerland.

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2. Methodology

2.1. Consequential LCA

LCA is a method for analyzing and assessing environmental impacts of a material, product or service along its entire life cycle [10]. Two main approaches are distinguished: the attributional and the consequential approach. The approaches differ with respect to system delimitation and the use of average versus marginal data.

Attributional LCA (ALCA) is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems [11]. Within an ALCA, the system investigated is limited to a single full life cycle from cradle to grave. Hence, co-production has to be treated by applying allocation factors. Furthermore, the attributional approach uses average data in order to attribute the average environmental burdens for producing a unit of the product in the system [11].

Consequential LCA (CLCA) is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions [11]. In contrast to ALCA, the system within a CLCA is not limited to one life cycle. The consequential approach uses system enlargement to include the life cycles of the products affected by a change of the physical flows in the central life cycle. Hence, allocation is avoided. According to this, marginal instead of average data is used within the consequential approach. Marginal data is represented by the product, resource, supplier or technology, which is the most sensitive to changes in demand. Economic value criteria are used to identify the marginal products.

2.2. System enlargement for assessing consequences

In addition to the changes in the main life cycle, this paper distinguishes two stages of consequences that are both handled by system enlargement: consequences (A) driven by the usage of constrained production factors and (B) driven by the changed outputs of multifunctional processes.

(A) An increase/decrease use of a resource will cause a change in the availability of the respective resource for other life cycles [11]. For example, a shift of rape oil from edible oil-consumption to RME production in Switzerland could decrease the availability of edible oil domestically. Since the overall demand for the oil is assumed to be stable, the lack of edible rape oil in Switzerland will be compensated for by additional imports of the marginal oil on the world market.

(B) The consequences driven by co-products stemming from multifunctional processes are considered as well. Ekvall and Weidema have defined rules for system enlargement driven by multifunctional processes [11]. Furthermore, Weidema determined how to handle the environmental burdens of additional or avoided production processes [12]. For example, the increasing production of rape oil for energetic use will lead to a corresponding growth of rape meal, which is a co-output of rape oil production. Given that the primary function of rape meal is feeding animals, it is likely that the increasing amount will substitute the marginal animal fodder on the world market which is most sensitive to changes in demand. In this study, soybean meal from Brazil is used as the most sensitive animal fodder. Consequently, the additional amount of rape meal is assumed to reduce the import and production of soybean meal in Brazil. In this case, the system is enlarged to the soybean production affected.

2.3. Assessing land use changes

The increase/decrease in the availability of agricultural products induces changes on the agricultural level. Corresponding effects to an increased demand for a specific crop are expansion, displacement and intensification [13].

Expansion is defined by the transformation of a specific land type like natural area or fallow land into arable land. In order to assess the effects of expansion, the marginal land, i.e. the land which will be transformed first, has to be identified.

Intensification increases the yield per hectare. Hence, no additional land is transformed. However, the increase in yield is caused by an increase of inputs per hectare, e.g. of water, energy and nutrients, which again can increase the environmental burdens of a given area.

Displacement substitutes one crop with another and is primarily assumed to occur in countries which face physical and also regulatory constraints [13].

As long as crops are displaced, the effect of displacement trickles through the overall global agricultural system until it is balanced by intensification and expansion. In theory, all displacement, intensification and expansion steps must be taken into account in order to ascribe the consequences of an increased cultivation to the energy crop of interest. In practice this is simply not possible. Based on this insight, different approaches have been used to simplify the assessment of consequences. For instance Kløverpris [13] uses a dynamic-economical model based on the Global Trade Analysis Project (GTAP) to determine the possible consequences on the agricultural stage. Another approach developed by Schmidt [14] is to cut off short and mid term changes and instead focus on the long term marginal supplier of a specific crop. In an increasing market the long term marginal supplier is the unconstrained supplier with the highest increase in production and lowest long term marginal production cost [12].

3. Scope

3.1. Goal and functional unit

The goal of this study is to assess the direct and indirect environmental impacts when Switzerland substitute one percent of its annual diesel consumption by the domestic production of RME. Using the method of consequential LCA, two future systems are analysed and compared: one where the current developments unfolds, i.e. Diesel is further imported, one where RME is increasingly produced.

In order to compare both scenarios, the functional unit is defined as "one MJ fuel given at regional storage in Switzerland (CH)". Consequently, both scenarios must fulfill these functions.

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3.2. Scenarios analysed

According to Steenblik [15], the production of rape methyl ester (RME) in Switzerland depends on subsidies from the government. Subsidies in the past, however, have been devoted to the cultivation of oil seeds and not the production of RME [15]. As a consequence, the approx. 180 km^2 are cultivated with rape seed are mainly used for edible oil production, whereas RME is only produced on a small scale in pilot plants with an annual production of <5 kt [15]. Recently, however, the Swiss government has implemented mineral oil tax exemption for all agro biofuels that do not exceed given environmental and social thresholds. On the other hand, a moratorium of the import of all foreign agro-related biofuels has gained attention and is currently discussed in the parliament. Currently, the impact of both on the domestic production of RME is unknown.

Therefore, what-if-scenarios [16] have been developed in cooperation with experts from the Federal Office for Agriculture in Switzerland (FOAG). According to the FOAG, expansion and intensification of arable land are not expected to happen in Switzerland since physical and regulatory restrictions determine these possibilities. Hence, the additional amount of rape for energetic utilization in Switzerland could only be met by increased energetic use of the available rape oil or by displacing other crops. In detail, the FAOG expects that the additional production of RME would replace edible rape oil (Table. 1, scenario 1) or barley (Table. 1, scenario 2). For both cases it is assumed that the displaced product will be compensated for by increasing imports of a functionally equivalent product from foreign countries. These biofuel scenarios will be compared with the reference scenario of using the respective amount of fossil fuels (Table. 1, scenario 0). As a further benchmark, we show the results for attributional delimited scenario for RME production where co-products are handled by allocation and indirect effects are excluded (Table. 1, scenario 3).

The knowledge of the experts from FAOG is primarily related to Switzerland. Thus, we used statistics from FAO and literature data to complement the insights for the identification of marginal suppliers of the crops displaced domestically.

In scenario 1, the displaced amount of edible rape oil is expected to be compensated by imports of a) rape oil or b) sunflower oil from Europe (RER) or c) palm oil from Malaysia (MY). It must be taken into account that the analysed systems refer to two different periods. The additional production of rape and sunflower oil in Europe is rather a short-term response to the lack of rape oil in Switzerland. Given that the overall agricultural area in Europe is slightly decreasing [17], it appears not likely that Europe is the long-term marginal supplier of edible oil for the global market. In the long term, palm oil from Malaysia/Indonesia should be seen as the relevant marginal given that it has (and is predicted to have) the lowest production costs and the highest increase in production compared with other important vegetable oils.

In scenario 2, the FOAG expects that the displaced amount of barley is covered by imports of a) barley from Canada (CAN) and b) barley from Europe (RER). In general, the production of barley in the EU is slightly increasing with the strongest increase in the eastern part of Europe (Poland, Czech Republic and Ukraine) [17]. However, according to Schmidt [18], Canada is predicted to face the highest increase in production until 2015. Based on that, it must be considered that Europe rather reflects the short-term marginal supplier of barley, whereas Canada is most likely the long term marginal supplier of barley.

3.3. System enlargement to co-products

In addition to the system enlargements caused by displacement, the system must include the consequences induced by co-products.

In scenario 1, the increased production of vegetable oils in foreign countries causes an indirect availability of press cake (meal) on the global market.

As regards scenario 2, the additional production of RME in Switzerland will cause a direct increase of rape meal and

Table 1 – Analyzed scenarios. In order to evaluate the burdens inherent to a specific consequence, each branch of consequence represents one scenario analysed down the line (source: our own depiction).

Scenario	System delimitation	Increased RME production in CH is met	Consequences in CH	Substituted amount is compensated for by	Corresponding country B	Increased demand in country B is met by	Scenario-label
(0): Diesel is imported	Attributional	–	–	–	–	–	REF
(3): Rape-ME production	Attributional	(Excluding consequences)	–	–	–	–	RME_ATT
(1): Rape-ME production at the expense of the available rape oil	Consequential	Utilization of the available rape oil	-Less rape oil for edible oil production	-Import rape oil	Europe (RER)	Expansion area	RME_OIL_R
				-Import sunflower oil	Europe (RER)	Expansion area	RME_OIL_S
				-Import palm oil	Malaysia (MY)	Expansion area	RME_OIL_P
(2): Rape-ME production at the expense of the available rape oil	Consequential	Displacement of barley production	-Less barley -Less straw	-Import barley -Import straw	Europe (RER)	Expansion area	RME_BEXP_RER
					Europe (RER)	Intensification	RME_BINT_RER
					Canada (CAN)	Expansion area	RME_BEXP_CAN

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glycerine. According to the FOAG, the additional glycerine is exported to Europe, where it is assumed to reduce industrial glycerine production. This is regarded as a good proxy for the effects that are taking place.

The direct (scenario 2) or indirect (scenario 1) increase in rape, sunflower or palm (kernel) meal is expected to diminish the import and production of soybean meal in Brazil (BR). Weidema [12] and Schmidt [18] determined soybean meal as the marginal meal on the global market and Brazil as its long-term marginal supplier. The reduction in the amount of soybean meal induces a decrease in the production of the co-produced soybean oil. The corresponding increase in the production of palm oil in Malaysia leads to an additional amount of palm kernel meal and again, the production of soybean meal in Brazil is affected. This loop iterates till the flows trend against zero. Fig. 1 shows as an example the applied system enlargement caused by the additional production of one MJ RME in Switzerland within the RME_OIL_P scenario.

In total, the RME production in CH is attributed with the burdens inherent to the additional production of palm oil and credited with the environmental burdens stemming from avoided soybean meal production.

It is worth noting, that the fatty acid composition of rape seed, sunflower, soybean and palm oil are not the same. However, according to Schmidt and Weidema [19], they are substitutable within the most important applications (frying oil/fat, margarine, shortenings and possibly salad oils) and hence, they are treated here as equivalent. Since no price elasticity's were taken into account, the substitution of one kg edible oil in Switzerland is assumed to be compensated for by an additional import, production and cultivation of 1 kg edible oil in the corresponding country.

The substitution between edible oils is assumed to take place in a one to one relation, whereas the reduction in soybean meal is calculated by means of the difference in protein content, although not merely the protein content, but also other influence factors such as fatty acid compositions and the energy contents determine the application of a specific meal. However, according to the FOAG, no general fodder unit is defined for Switzerland and since each animal transforms a different part of the energy only the protein content was taken into account. Table. 2 shows the protein contents which were taken for the calculations.

3.4. *Considered changes on the agricultural level*

Finally, all of the consequences are assumed to be compensated on the agricultural level in foreign countries by expansion or intensification. Potential displacement effects occurring in foreign countries are not considered. With focus to the short-term marginal supplier, this can be justified since the changes we focus on are rather small in the context of global markets. The long-term marginal supplier, in turn, is only assumed to correspond with expansion or intensification [20].

If an increased demand for a specific crop is met by expansion, the system must be enlarged to include (i) the avoided

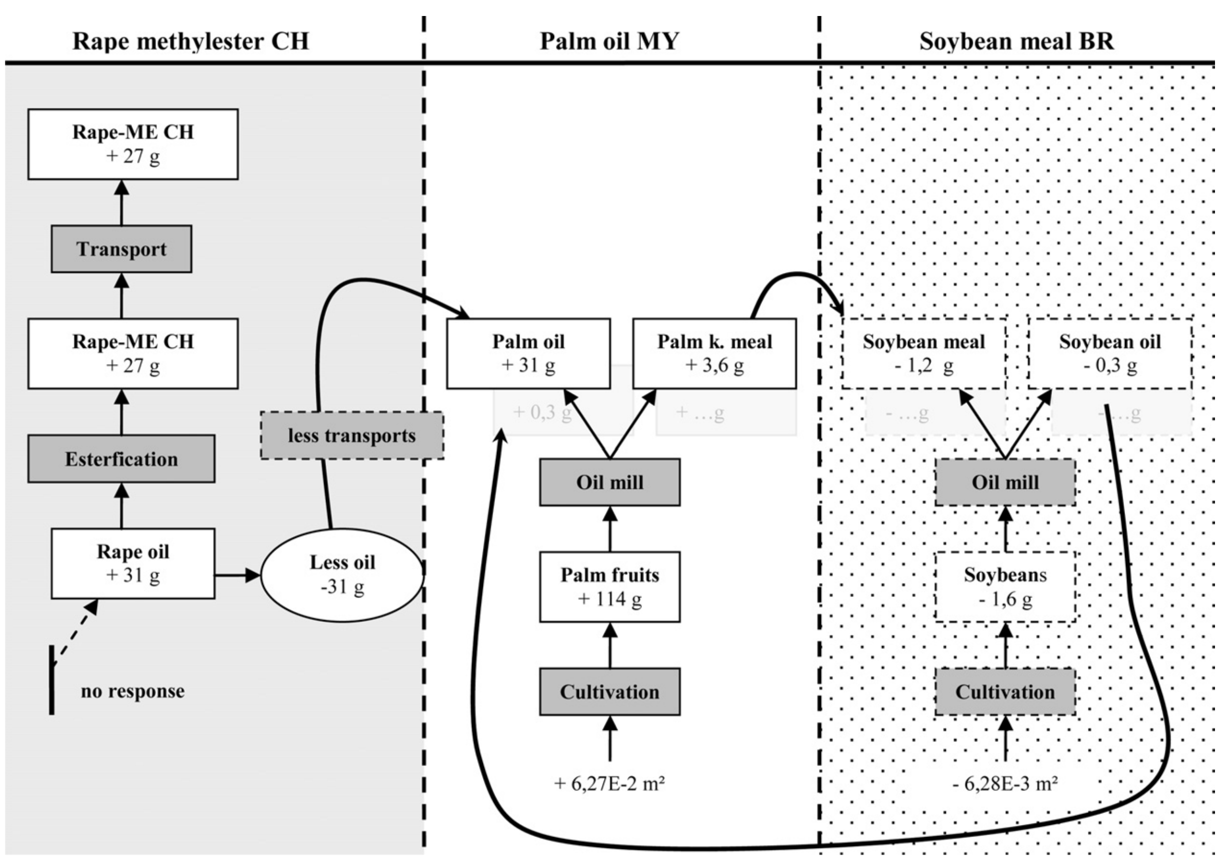

Fig. 1 – Palm oil–soybean meal loop driven by the additional production of RME in Switzerland. The shaded boxes represent the start of the second loop (source: modified from [31]).

Table 2 – Protein content of specific meals in dependence of their dry matter (source: °FOAG, *[31]).

	Rape meal°	Soybean meal°	Palm kernel meal*	Sunflower meal°
Dry matter (DM), %	89	87.5	92	87
Energy content				
Protein, % of DM	37,08	50,71	16,2	34,48
Protein, g kg^{-1} (including moisture after processing)	330	440	149	300

interventions inherent to the land use prevailing before the change, i.e. commonly land under natural vegetation and (ii) the emissions related to the land use change (LUC) [14]. In this study (i) is not included since sensitivity analysis proved their influence to be insignificant [20]. In order to take account of the additional or avoided land use, the marginal land types must be identified. Table. 3 illustrates the marginal land types assumed to be affected in the relevant regions and the CO_2 emissions related to the LUC taking account of the change in above ground biomass, dead organic matter (DOM) and soil organic carbon. The emissions are related to a time horizon of 20 years.

The increase in rape oil production in Europe is assumed to affect set aside areas [18]. According to Grieg-Gran et al. [21], the increase in oil palm production is expected to occur at the expense of 1/3 grassland and 2/3 rainforest. Currently, approx. half of the deforested rain forest in Malaysia is rain forest on peat land [22]. Peat lands cover 3% of the Earth's land area but store approx. one-third of global soil carbon and to 70 times the current annual global emissions from fossil fuel burning [22]. Consistent with Flaskerud [23], the decrease in soybean meal production in Brazil is expected to avoid the transformation of savannah, grassland and rainforest. In order to relate the emissions from LUC to the functional unit of the consequential scenarios, a choice has to be made with respect to the time scale the emissions are attributed to. Following default assumption of the IPCC [24] we applied 20 years as a baseline. In addition a sensitivity analysis describing the relevant scenarios was used to evaluate the importance of emissions resulting from land use change. The reason for our taking this approach is the difficulty of discounting the emissions resulting from land transformation on a definite time scale.

Kløverpris [13] identified two basic possibilities of intensification: a) optimization of production and b) technological development. The first includes the increasing application of fertilizer and pesticide, increasing irrigation and cropping intensity. Intensification by technological development is driven by the improvement of mechanical aids, crop strains and agricultural practices. In summary, numerous possibilities exists for intensification but only some of them are applied as a consequence of a change in demand for crops [13].

In this study, intensification is modeled by calculating the difference between extensive and intensive barley production on the basis of Swiss LCI data from the Ecoinvent database (Fig. 2)

Hence, intensification is not merely driven by applying an additional amount of fertilizer but by the whole difference in the cultivation practice between extensive and intensive production. However, this approach indicates a linear increase in yields meaning that the increase in yields realized in the past is projected in the future. This is a simplification of reality, since the yield diminishes with increasing inputs [13].

3.5. *Used life cycle inventory data*

The applied life cycle inventory data were primarily taken from ecoinvent [25,26]and thus follow the determined quality guidelines. For example, emissions on the field such like N_2O are calculated in accordance with Nemecek [26].

However, in order to model the determined scenarios additional LCIs were required or simplifications necessary. In the following we briefly explain the most important adaptations and simplifications.

No LCI data for barley cultivation in Canada and for barley production in Poland, Czech Republic or Ukraine (the expected short term marginal suppliers) was/were available. For barley production in Canada, we used the LCI data from Schmidt [20]. In order to model the increased production of barley in Europe we use the LCI of barley cultivation in France from the

Table 3 – Scenario related CO_2-emissions from land transformation. Only CO_2-emissions are mentioned. Emissions from fire and organic digestion are not taken into account.

Region	Europe[a]		Malaysia[b]			Brazil[c]			Canada[d]
Transformation from	100%	100%	33%	33%	33%	42%	51%	7%	100%
	Grassland	Set-aside	Rain forest on peat land	Rain forest	Grassland	Savannah	Grassland	Rain forest	Grassland
Transformation to	Barley	Rape seed, Sunflower	Oil palm	Oil palm	Oil palm	Soybean	Soybean	Soybean	Barley
GWP (100a) (CO^2equivalent) tonne	90	99	2′208	488	−33	303	125	679	90

a Emissions based on our own calculation according to [24] (tier 1 methodology).
b The applied shares are based on [18]. The emissions were calculated according to (i) [32] for peat land, (ii) [24] for rain forest (tier 1 methodology), (iii) [20] for grassland.
c The applied shares base on [23]. The emissions were calculated according to (i) [20] for savannah and (ii) [24] for grassland and rain forest (tier 1 methodology).
d Emissions based on data from Schmidt [20].

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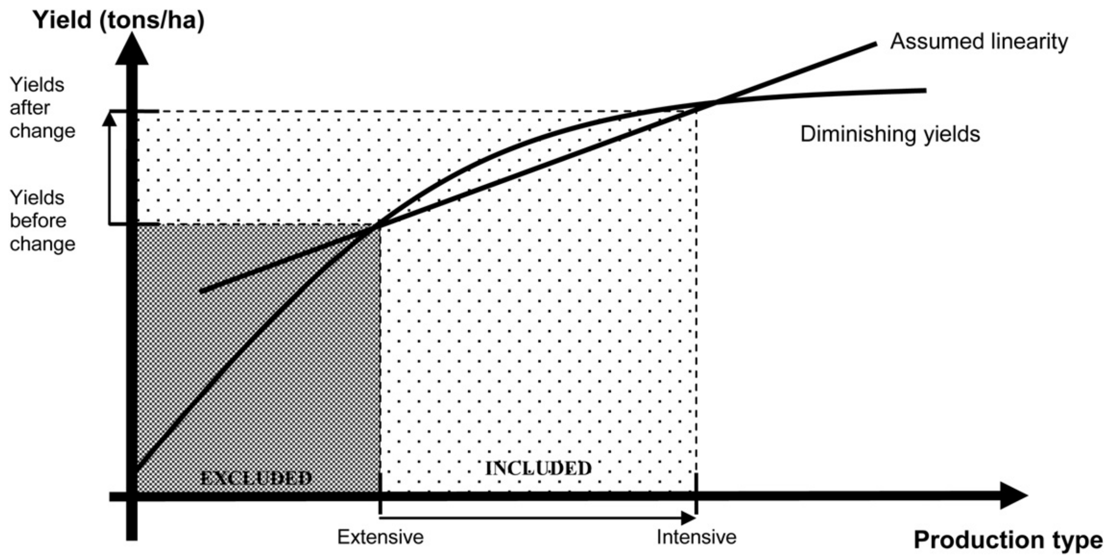

Fig. 2 – How the LCI for intensification is derived for a specific crop (source: our own depiction).

Ecoinvent database [25]. Together with Germany, France is currently one of the main importers of barley to Switzerland and the only country in the west and south EU with a positive trend in barley production [17] (2000–2007).

The point of substitution between the displaced and the marginal oil is refined/transesterified oil. Since no LCI data for the refining of crude vegetable oil was available, we omitted the refining stage. Using data from Schmidt [20], we found that this simplification is not important for the gained results.

3.6. *Impact assessment*

The environmental burdens of the analysed scenarios are compared by means of chosen CML [27] indicators, land use and the Swiss method of ecological scarcity (Environmental Impact Points, UBP 06,) [28]. The first method was primarily used to evaluate the GHG emissions but also other environmental effects like ecotoxicity and acidification on the midpoint level. Midpoint methods refer to the classical impact assessment and are characterized by stopping quantitative modelling before the end of the impact pathways [29]. The Swiss method of ecological scarcity (UBP 06), in turn, is an endpoint method, which base on the distance to target principle. The total environmental damage is assessed by weighing the calculated LCI flows by means of legal limits determined by the Swiss law. Endpoint methods model the full cause-effect chain up to the environmental damages [29]. The Swiss method of ecological scarcity was applied in order to reflect the total effects to the environment within the Swiss perspective on environmentally relevant flows.

4. Results

4.1. *RME production substitutes edible rape oil*

This scenario analyzes the consequences if the increased production of RME substitutes rape oil, i.e. already available rape oil is used for RME production. The functional unit is defined as "1 MJ fuel given at regional storage in CH". Fig. 3 shows the GHG emissions of the analysed scenarios.

Within the REF scenario, the main impacts are caused by the combustion of diesel (74 g CO_2 equiv.) whereas the extraction and import turned out to be less important (15 g CO_2 equiv.). We have not considered the biogenic CO_2 uptake of the biofuels. Thus, we did not take account of its release but rather added the combustion of diesel in the baseline scenario in order to account for the full differences in the emissions of the analysed systems.

The attributional delimited scenario shows less GHG emissions than the fossil reference (62 compared to 89 g CO_2 equiv.). Most of the GHG emissions stem from the cultivation of rape seed (55 g CO_2 equiv.). As regards the consequential scenarios, GHG emissions related to the domestic production of edible oil in Switzerland are not important (6 g CO_2 equiv.). The reason for this is that the cultivation of rape and its conversion to edible oil is not included in the scenarios since it is not affected. Regarding the GHG emissions of the cultivation, conversion and the import of edible oil from foreign countries, the additional production of palm oil in Malaysia causes the highest emissions (345 g CO_2 equiv.) primarily due to the considered land use changes which cause approx. 90% of these emissions. It appears that palm oil drives less substitution effects, since the volume and also protein content of the co-produced palm kernel meal is much lower compared to the rape or sunflower meal. The net GHG emissions of the palm oil scenario are significantly higher than from rape or sunflower oil (329 compared to 58 and 74 g CO_2 equiv., respectively). The additional production of rape and sunflower oil in Europe are dominated by the considered land use changes (114 and 124 g CO_2 equiv., respectively) and in addition by the emissions stemming from production (115 and 110 g CO_2 equiv. respectively). The cultivation accounts for approx. 80% of the GHG emissions related to production. The main impacts stem from dinitrogen monoxide emissions on the field and the emissions related to fertilizer production. Both scenarios are significantly

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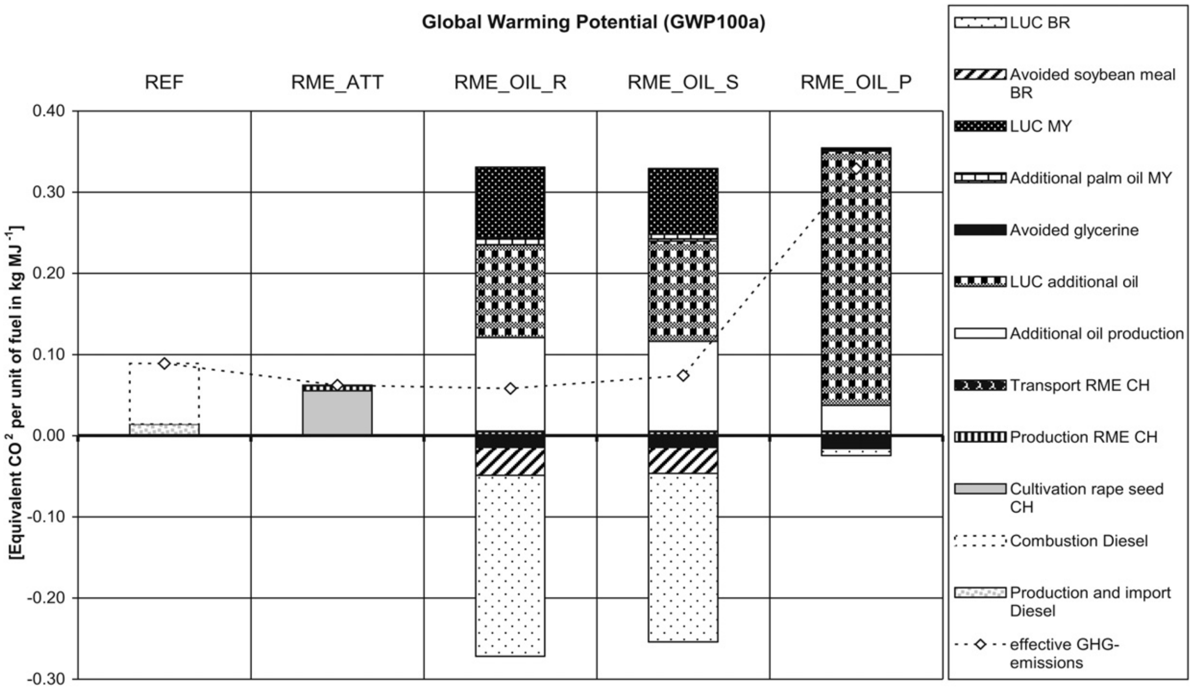

Fig. 3 – Process contribution to global warming of a) diesel, low in sulphur, b) RME attributional, c) RME at the expense of the available rape oil (source: our own depiction).

affected by the reduction in soybean meal production in Brazil. In particular the related land use change results in a significant decrease of the net GHG emissions (−223 and −207 g CO_2 equiv., respectively). On the other hand, the feedback loop to palm oil production adds additional GHG emissions (95 and 89 g, respectively) but mainly due to the higher yields of oil palms the iterating soybean meal – palm oil loop is dominated by the avoided production of soybean meal.

Table. 4 shows various environmental indicators for the examined scenarios.

The results do not show a clear pattern. The REF scenario exhibits lowest values for acidification, eutrophication, human toxicity, terrestrial ecotoxicity and land use but causes the highest impacts for abiotic and ozone depletion. In general, the highest impacts for most categories are caused by the RME_OIL_RAPE scenario followed by the RME_OIL_SUN and RME_OIL_PALM scenario. With regard to the rape oil and sunflower scenario, the results for ozone depletion, photochemical oxidation and land use are dominated by the avoided production of soybeans. As mentioned prior, for the palm oil scenario the influence of the applied system enlargements to soybean meal is less significant. For example, although the yield of oil palm is much higher than of rape oil, the overall land use of the rape oil scenario is lower due to the avoided production of soybean meal. When each impact category is assumed to be equally important none of the consequential scenarios does better than the REF system.

A comparable picture is drawn by the Swiss method of ecological scarcity (Environmental impact points, UBP) (Fig. 4). Both the attributional and the consequential scenario(s) cause more net UBP than the REF scenario (214, 307, 410 and 192 UBP compared to 88 UBP respectively).

The consequential scenario is primarily dominated by the additional production of vegetable oils in foreign countries (447, 536 and 111 UBP, respectively) and the related land use change (35, 38 and 97 UBP, respectively). Most of the impacts related to production result from the additional cultivation of the vegetable oils (97% for rape and sunflower oil and 87.5% for palm oil, respectively). In detail, approx. 50% of the impacts of rape oil cultivation in Europe stem from cypermethrin, nitrate and phosphate emissions. The result for the cultivation of sunflower is dominated by nitrate, the cultivation of oil palm in Malaysia by nitrate and cypermethrin emissions. The impacts of the domestic transesterification of RME (6 UBP) and the avoided glycerine production (−15 UBP) are less important. As regards the RME_OIL_RAPE and -_SUN scenario, the net UBP impact is diminished due to the avoided production of soybean in Brazil (−154 and −143 UBP, respectively) and the related land use change (−69 and −64 UBP, respectively). Both overcompensate the impacts added by the corresponding increase in palm oil production (58 and 54 UBP, respectively).

4.2. *RME production substitutes feed barley*

This scenario analyzes the consequences if the increased production of RME substitutes barley.Fig. 5 shows the results for GHG emissions.

It appears that the only differences between the consequential scenarios are the impacts caused by the additional production of barley and the related land use change. All other system enlargements are identical. As regards the consequences induced by co-products, the avoided production of soybean meal overcompensate the GHG emissions caused by

Table 4 – Characterized midpoint indicators of a) diesel, low in sulphur (REF), b) RME attributional and c) RME at the expense of the available rape oil. With respect to a and c, the lowest results are shaded (source: our own depiction).

System/Impact category based on fuel output	Unit	REF	RME_ATT	RME_OIL_R	RME_OIL_S	RME_OIL_P
Abiotic depletion SB equivalent	mg MJ^{-1}	566	235	295	189	115
Acidification SO_2 equivalent	mg MJ^{-1}	226	488	483	227	272
Eutrophication PO_4 equivalent	mg MJ^{-1}	41	361	272	1119	167
GWP 100 CO_2 equivalent	g MJ^{-1}	89	62	58	74	329
Ozone depletion CFC-11 equivalent	mg MJ^{-1}	1.3E-02	3.5E-03	−6.6E-03	−7.8E-03	−9.5E-03
Human toxicity 1,4–DB equivalent	g MJ^{-1}	9	19	40	17	14
Terrestrial ecotoxicity 1,4–DB equivalent	mg MJ^{-1}	84	46645	184851	11953	46103
Photochemical oxidation C2H4 equivalent	mg MJ^{-1}	14	5	11	10	45
Land use	dm^2 MJ^{-1}	0.0035	17	5	48	6

the related additional production of palm oil (−277 compared to 103 g CO_2 equiv., respectively). The main fraction of the GHG emissions are caused by the related land use changes (240 and 93 g CO_2 equiv.). The avoided production of glycerine is less important (−15 g CO_2 equiv.). The displacement of barley production in Switzerland causes more negative GHG emissions than the displacing RME production (−101 compared to 79 g CO_2 equiv., respectively). The GHG emissions of both are dominated by the cultivation step which accounts for 88% and 87%, respectively. With focus to the additional production of barley, the production in Europe by expansion adds 226 g CO_2 equiv.; 117 g are caused by land use change and 109 g by production. The additional production by intensification causes significant lower GHG emissions (28 g CO_2 equiv.) primarily because no land use changes occur and the LCI only includes the additional inputs necessary to intensify production. From all alternatives, the barley production in Canada causes the highest GHG emissions because of the lower yields and the corresponding land use change (401 g CO_2 equiv., i.e. 256 g by land use change and 145 g by production). To provide the barley substituted in Switzerland more than twice the area must be cultivated in Canada and even though the emissions are lower per hectare, in summary, more GHG emissions occur.

Table. 5 shows the results for chosen CML midpoint indicators and land use.

Comparing across the consequential scenarios, the alternative appropriation of RME_BRER_INT falls out to be most preferable within the most impact categories, followed by RME_BRER_EXP and RME_BCAN_EXP. The results for the RME_BRER_EXP and RME_BCAN_EXP scenario are dominated by the system enlargements to the avoided production of soybean meal in Brazil and barley in Switzerland. The results for global warming, ozone depletion and photochemical oxidation are mainly affected by the avoided production of soybean meal, whereas the results for eutrophication are dominated by the avoided production of barley. Except for the RME_BCAN_EXP scenario, both overcompensate the impacts added by the additional production of barley in foreign countries. The REF scenario shows lowest environmental impacts for acidification, human toxicity and land use.

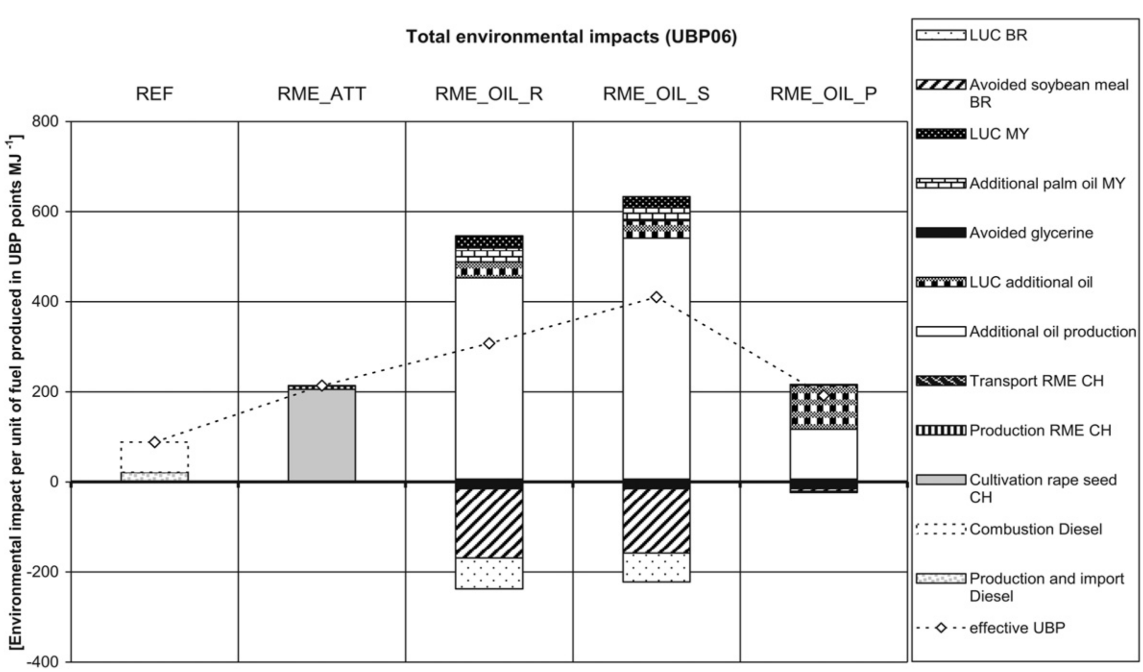

Fig. 4 – Process contribution to UBP06 of a) diesel, low in sulphur, b) RME attributional, c) RME at the expense of the available rape oil (source: our own depiction).

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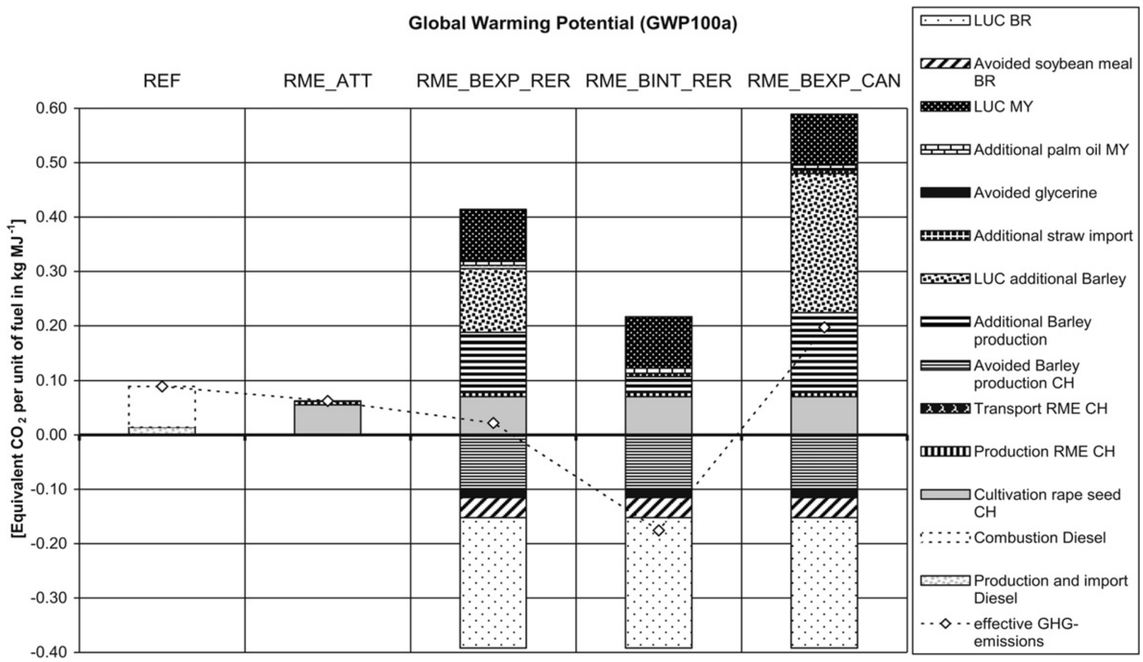

Fig. 5 – Process contribution to global warming of a) diesel, low in sulphur, b) RME attributional, c) RME at the expense of barley CH (source: our own depiction).

Using the Swiss method of ecological scarcity (UBP), the general pattern for the consequential scenarios remains (Fig. 6).

In general, the scenarios are dominated by the avoided production of barley in Switzerland which contribute negative with −566 UBP and the avoided production of soybean meal (−239 UBP, i.e. 165 UBP caused by production and 74 UBP by land use change). The results for avoided barley production are mainly caused by emissions into ground water (Nitrate) and emissions into air (N_2O and CO_2). Likewise, the impacts of avoided soybean meal production are basically influenced by nitrate and phosphorus emissions into water and 2,4-D emissions into soil.

Comparing across the scenarios, the RME_BEXP_RER scenario cause higher net UBP than the REF scenario (310 compared to 88 UBP), whereas the RME_BINT_RER and RME_BEXP_CAN scenario results in lower net UBP impacts (−151 and −83 UBP, respectively). The reason for the higher net UBP for the RME_BEXP_RER scenario, base on nitrate and heavy metal emissions.

5. Discussion

Fig. 7 shows the results for both GHG emissions and total environmental impact (UBP06) for all analysed scenarios in relation to the fossil reference.

In sum the study shows different trends in environmental impacts, when the Swiss production of RME is increased.

With focus to the results for scenario 1, the increased use of rape oil for RME production causes an additional production of vegetable oils on the world market. This has a negative influence on many environmental impact factors and also on

Table 5 – Characterized midpoint indicators of a) diesel, low in sulphur (REF), b) RME attributional and c) RME at the expense of barley cultivation in CH. With respect to a and c, the lowest results are shaded (source: our own depiction).

System/impact category based on fuel output	Unit	REF	RME_ATT	RME_BEXP_RER	RME_BINT_RER	RME_BEXP_CAN
Abiotic depletion SB equivalent	mg MJ^{-1}	566	235	217	78	454
Acidification SO_2 equivalent	mg MJ^{-1}	226	488	879	241	1353
Eutrophication PO_4 equivalent	mg MJ^{-1}	41	361	−209	−1669	−649
GWP 100 CO_2 equivalent	g MJ^{-1}	89	62	23	−175	197
Ozone depletion CFC-11 equivalent	mg MJ^{-1}	0.0134	0.0035	−0.0076	−0.0099	−0.0034
Human toxicity 1,4 −DB equivalent	g MJ^{-1}	9	19	13	37	23
Terrestrial ecotoxicity 1,4 -DB equivalent	mg MJ^{-1}	84	46645	95791	84820	85281
Photochemical oxidation C2H4 equivalent	mg MJ^{-1}	14	5	−37	−41	−25
Land use	dm^2 MJ^{-1}	0.0035	17	4	−20	38

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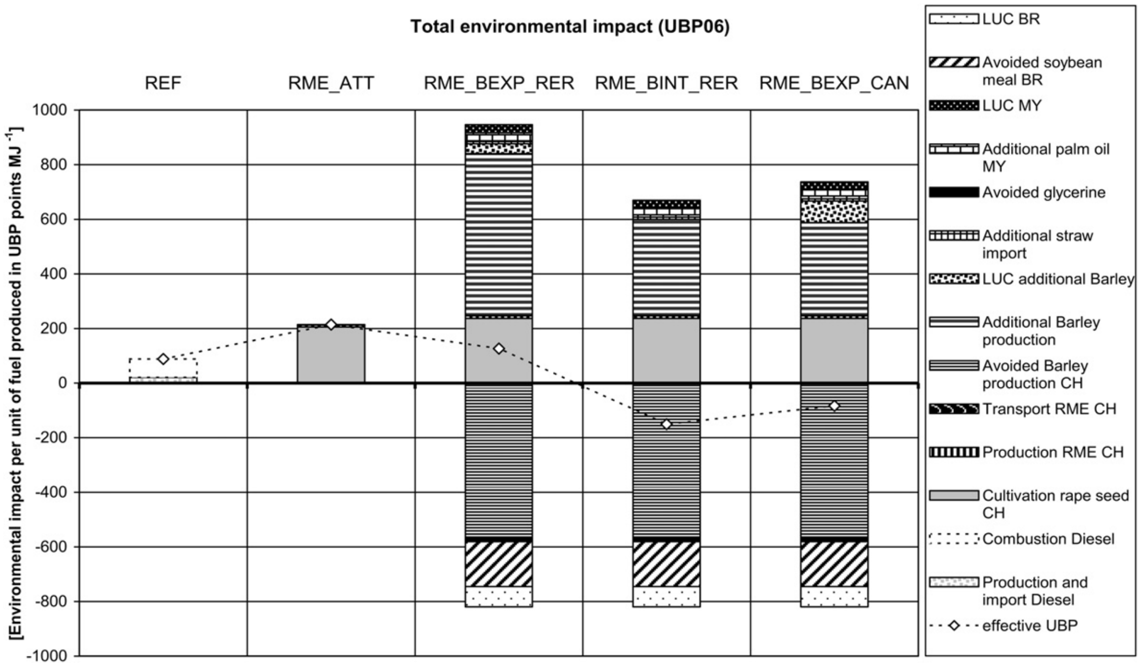

Fig. 6 – Process contribution to UBP06 of a) diesel, low in sulphur, b) RME attributional, c) RME at the expense of barley CH (source: our own depiction).

the aggregated environmental impacts within all possibilities analysed. As regards rape and sunflower oil, the main impacts stem from the agricultural production itself. With respect to palm oil, the CO_2 emissions from LUC dominate the results, i.e. in particular the devastation of rain forest on peat land. If those emissions are excluded, as might be realistic for plantations grown on marginal land, the net impacts related to palm oil production would decrease significantly. In sum, all systems of scenario 1 are associated with higher environmental impacts than the production and use of fossil fuels.

The results for scenario 2 are dominated by the domestic replacement option, i.e. barley production in CH, and the alternative provision of the barley displaced from foreign countries. For example, the higher the impacts of the domestic barley production displaced the lower the net environmental impacts of RME production in Switzerland. If the additional barley is produced by expansion, it is in particular the relative yield, i.e. the yield of avoided domestic production in comparison to the additional marginal production, and the related release of CO_2 which determine the outcomes for GHG emissions. The compensation of the increased agricultural production by intensification leads to much lower environmental impacts than expansion of the agricultural area. This might be explained by the fact, that (i) only the additional environmental impacts caused by the intensification have been accounted for and (ii) a linear increase in yields has been applied. Given that the increase in yield is already diminishing [30] the environmental impacts related to intensification are possibly underestimated.

Within both scenarios, an increased production of RME in Switzerland increases the availability of press cake on the global market, i.e. direct (scenario 2) or indirect (scenario 1). This decreases the demand for Brazilian soybean meal, which is the marginal protein meal on the global market [12,18]. The decreased demand for soybean meal significantly decreases the total GHG emissions mainly due to the avoided transformation of rain forest.

Fig. 8 illustrates the 95% confidence interval of each scenario calculated with Monte Carlo analysis (1000 runs). It is worth noting that the uncertainties related to the CO_2 emissions from land use change are not included in the Monte Carlo analysis. Given that the emissions of land use change are the most important factor for the outcomes, the results would have been distorted. Due to their importance, they are treated separate within the applied analysis of the parameter sensitivity.

When considering the uncertainties related to the input data the general patterns remains, i.e. except for RME_BINT_RER all other scenarios show higher trends than the fossil reference scenario as regards either GHG emissions or UBP. However, both scenarios include uncertainties related to the applied system delimitation, i.e. the related choices, which are not included in the Monte Carlo analysis.

In this context it must be stressed, that the analysed scenarios refer to different periods; namely short-term and long-term. This means, in particular the scenarios considering Europe as the marginal supplier of the crop/oil displaced, rather reflect the environmental impacts of the short-term response. This enhances the probability that the increase in production is met by displacement of other crops. Thus, the more accurate scenarios are RME_BEXP_CAN and RME_OIL_P since both focus on the long-term marginal suppliers and thus minimize the risk that the additional production of the crop/oil occurs at the expense of other crops. Fig. 8 depicts the sensitivity of both scenarios.

The allocation of the CO_2 emissions from land use change to 10 (GHG/UBP 0.5) and 30 years (GHG/UBP 1.5) changes the results of both scenarios significantly. This issue is remarkable, as this

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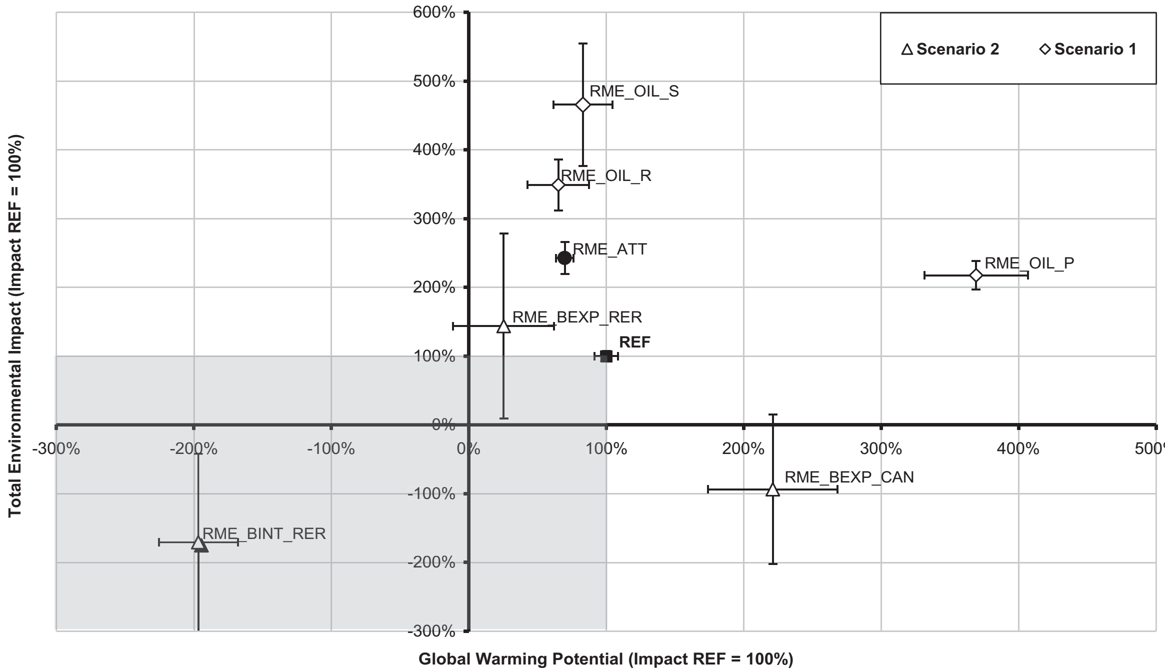

Fig. 7 – Two-dimensional representation of GHG emissions and total environmental impact including the uncertainties evaluated with Monte Carlo analysis. Values are relative to the baseline scenario (REF). Scenarios in the grey area show better evaluation results than the REF scenario in respect of both criteria meaning lower GHG emissions and lower overall environmental impacts (source: our own depiction).

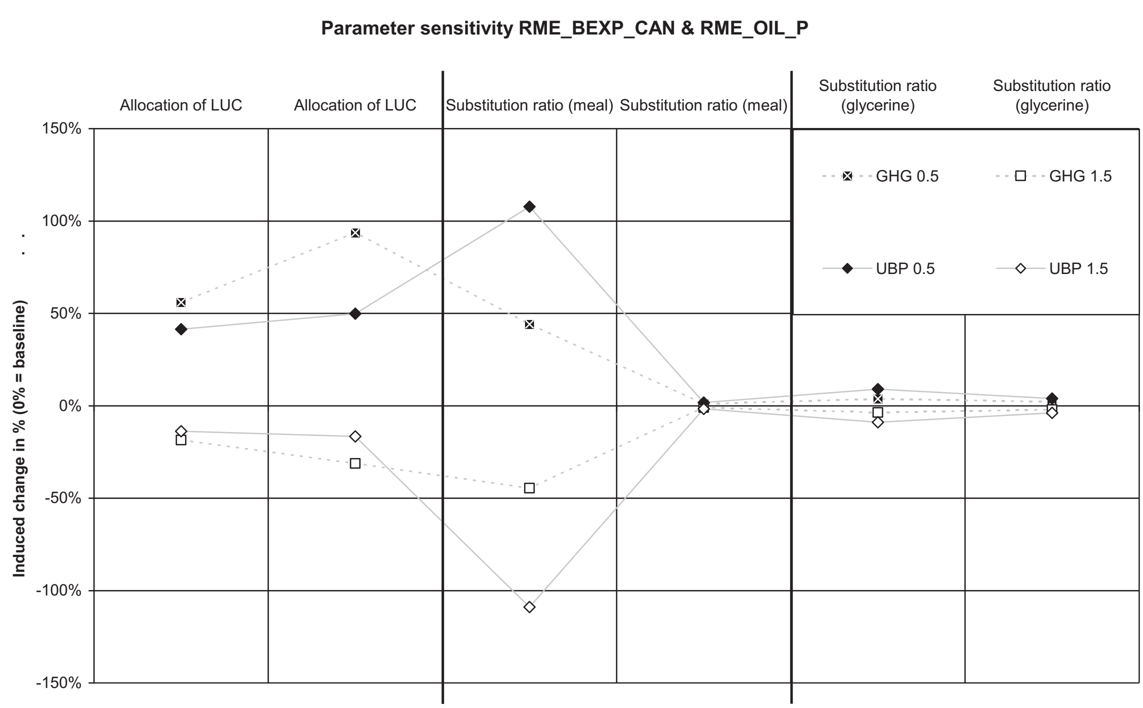

Fig. 8 – Parameter sensitivity of the RME_EXP_P and RME_OIL_P scenario. The graph shows the sensitivity if parameters such like the substitution ratio between the marginal products is (i) decreased by a factor of 0.5 or (ii) increased by a factor of 1.5. Values are relative to the baseline results of the respective scenario (source: our own depiction).

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is also highly relevant for all other agro-biofuels. The RME_-BEXP_CAN scenario appears less sensitive than the RME_OI_P scenario. The reason is that the avoided emissions from land use change of soybean meal production increase likewise with the emissions from additional palm oil and barley production.

Regarding the substitution ratio between rape meal and soybean meal (RME_BEXP_CAN), the sole application of the protein content is possibly a simplification. For example, in addition to the protein content, Schmidt [18] used Scandinavian Feed Units and the energy content to calculate the substitution between rape and soybean meal. This result in an overall substitution ratio of 0.76 compared to our ratio of approx. 1 (both including the feed back loop). As shown by Fig. 8, when half the amount of soybean meal would be substituted, in particular the results of the RME_BEXP_CAN scenario would increase remarkably (108% for UBP and 44% GHG emissions). Without the significant benefit from avoided soybean meal production, the results are dominated by the additional production of barley in foreign countries. The RME_OIL_P scenario, in turn, might underestimate the benefit from avoided soybean meal production since the energy content of palm kernel meal is not taken into account. If 1.5× the amount of soybean meal would be replaced per unit palm kernel meal produced, the results for the RME_OIL_P scenario would merely decrease by 2% for GHG emissions and 1% for UBP.

Likewise, a change in the amount of industrial glycerine production replaced per unit of co-produced glycerine shows less influence on the results of both scenarios.

6. Conclusion

In sum this study shows the strong dependence of the results on the global replacement options. If, for example, the marginal product on the world market for protein meal is switching from soybean meal to rape meal, the net GHG emissions of most of the analysed scenarios would increase remarkable. From a long-term environmental perspective it seems to be therefore wise, to focus the production of biofuels on feedstock's, that are decoupled from the global food and feed markets. Examples are biogenic waste or non-edible energy crops that grow specifically on degraded land.

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