DEVELOPMENT OF A MONITORING CONCEPT FOR THE EVALUATION OF ILUC

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FINAL REPORT

Project No. 529/211

Sponsered by

Union zur Förderung von Oel- und Proteinpflanzen e. V. (UFOP)

Gießen 2022

1 Introduction and objective of the project

The Renewable Energy Directive (RED II, 2018/2001) sets the framework for new EU energy policies for 2021-2030. For plant-based biofuels, such as biodiesel, RED II allows existing investments in this energy sector to continue by letting member states to keep their energy consumption to remain at 2020 levels (plus 1%) up to the maximum cap of 7%. With the idea of breaking the link between plant-based biofuels and deforestation in vegetable oil producing countries, the issue of Indirect Land Use Change (ILUC) has been subjected to a new approach. The use of energy feedstocks with a high ILUC risk (i.e., plant bioenergy feedstocks grown on land with a high carbon stock) is to be restricted in EU member states and phased out completely by 2030. An exception to these restrictions is provided for feedstocks with a low ILUC deforestation risk. This is the case if the increased production of raw materials takes place through productivity advances in existing crops or if the cultivation is carried out on defined areas of use and certification is available for this. The conditions for when a raw material belongs to the products with low ILUC risk are defined in Delegated Regulation 2019/807. In the March 2019 regulation, the EU Commission assigned the highest ILUC risk to the use of palm oil for the bioenergy sector, followed by soybean oil use.

Despite the conditions formulated in the legal acts for the use of certain raw materials for bioenergy production, a number of uncertainties remain. These relate to the actual extent of the use of palm oil for bioenergy production and the extent of the expansion of palm oil production in sensitive areas, as well as in the measurement of the extent of indirect land use effects triggered by consumption. The main contributors to these uncertainties are the different methods of recording and calculating the extent of deforestation (deforestation) in the respective producer countries. These lead to considerable room for interpretation, as the current data situation and also the quality of the collected land data often provide insufficient evidence of possible change effects. For these reasons, continuous monitoring of cultivation changes for the future is indicated in order to observe and evaluate the further development of land use changes on a scientific basis. Against this background, the task of the study was to continuously monitor the further development of the data situation and scientific findings on the basis of the Directive.

This study examines current land use change trends for the three major oil crops, palm, soybean, and canola, with the following focus:

(1) The basis for the coverage of current indirect land use changes (ILUC) triggered by biofuels, whose feedstocks are soybeans, oil palm and rapeseed (SOR), are exclusively scientific studies on the topic complex of land use changes. The prerequisite for a qualified assessment of the development is the consideration of currently published scientific studies that have appeared in relevant qualified scientific journals (peer-reviewed

journals). The years 2018 to 2022 were defined as the current observation period. This period was chosen to directly follow the inventory conducted by the EU Commission (see COM(2019) 142 final of 13.3.2019 on the status of the expansion of global production of relevant food and feed crops; cf. EU Commission, 2019) and to update it with the current development.

(2) Continuous and systematic monitoring and assessment of the latest scientific findings on land use changes and their ecological effects for the crops concerned (soy, palm oil, rapeseed) should be ensured via a literature database to be compiled. The importance and development of peatland areas, as formulated in the RED II Directive, should also be the subject of the study. For the economic evaluation of the trigger effects for an indirect land use change in the context of monitoring, it was intended to continue the calculation model (Article 3, Delegated Regulation (EU) 2019/807) developed by the EU Commission for the verification of land use changes.

(3) Different evaluation methods are used in the studies for a valid recording of land use changes. All methods attempt to identify possible cause-and-effect relationships between additional feedstock demand (especially palm and soybean oil) as a result of EU biofuel policies and their contributions to the decline of high-carbon virgin forest areas. Here, the informative value of the different methodological approaches for recording land use changes should be evaluated.

(4) Similarly, an attempt should be made to account for the production and climate benefits of canola production. This is intended to effectively address potential misinterpretations regarding direct and indirect land use effects.

For the study period of 2018 - 2022, the review results of the qualified literature used for the analysis were summarized in different document lists. Each individual topic concludes with a review summarizing the literature. In addition to the project report, all relevant scientific contributions to the study were recorded chronologically and in terms of content in a database supporting the monitoring concept on the basis of an Excel file. This form of documentation ensures a constant updating and continuation of the scientific study situation.

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2 EU legal framework on the importance of ILUC

The European Commission's revised Renewable Energy Directive (RED II) drastically limits the use of biofuels derived from food crops, including palm oil, after 2020 (Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 OJ L 328/82 - RED -). The Directive maintains a limit on the consumption of biofuels and biomass fuels derived from food and feed crops in the transport sector. At the same time, the introduction of specific national limits on the total contribution of these fuels further consolidates the target for energy from renewable sources that the Union aims to achieve by 2030. Similarly, it is envisaged that Member States may set a lower limit for the contribution of biofuels from oil crops, taking into account indirect land use change (ILUC).

As part of the debate on the directive, the European Parliament has taken a stand against the use of palm oil as a biodiesel feedstock, noting that the consumption of palm oil and processed products derived from it play an important role in the impact of EU consumption on global deforestation and calling on the European Commission to phase out the use of vegetable oils that drive deforestation, including palm oil, as a component of biofuels.

The European Union (EU) Renewable Energy Directive (RED II), which came into force in December 2018, sets a national implementation deadline of June 30, 2021. It introduces new renewable energy targets (at least 32% by 2030 and fuel suppliers' obligation for 14% minimum share of renewable energy in the transport sector) and targeted measures for bioenergy to ensure [greenhouse gas (GHG)] emission savings and minimize unintended environmental impacts. Member states also have the option of phasing out early, before 2030, the use of crop feedstocks that lead to critical indirect land use changes (these are primarily palm oil and soy). One element of RED II is the cap on biofuel use in the transport sector that an EU member state can take into account when assessing target achievement, and related to this, the targeting of emissions from so-called indirect land use changes (ILUC) (European Commission, Memo 19/1656, 2019).

Under RED II, indirect land use change (ILUC) occurs when land is converted for biofuel production, shifting agricultural production to land with high-carbon stocks such as forests or wetlands. RED II is about minimizing the resulting release of CO2. The EU has thus expressed its concern that ILUC-related emissions could offset greenhouse gas savings from biofuel use (European Commission, COM 142, 2019, 3 - 4). RED II limits the ability of EU members to include so-called "high ILUC risk fuels" in their calculations of renewable energy use in the transport sector. According to Article 26 (2), the share of biofuels derived from food and feed crops with a high ILUC risk shall not exceed the 2019 consumption of such fuels recorded in the Member State concerned, unless they are certified biofuels with a low ILUC risk. From December 31, 2023, this limit will gradually decrease to 0%, until December 31, 2030 at the latest.

Indonesia and Malaysia - the two largest palm oil producers - have raised concerns about RED II before the WTO's Committee on Technical Barriers to Trade. On December 16, 2019, Indonesia requested dispute settlement consultations with the EU on this and other related measures (WTO Doc WT/DS593/1, 2019).

RED II provides for a binding EU target of 32% renewable energy by 2030. The individual EU member states are to set national contributions to achieve the overall binding Union target. This Union-level target is intended to provide more flexibility for Member States to achieve their greenhouse gas emission reduction targets in the most cost-effective way, according to their specific circumstances, energy mix and renewable energy production capacities. However, Article 25 is also interesting in this context. There, Member States are required to set the minimum share of renewable energy in final energy consumption in the transport sector at 14% by 2030. Each Member State shall ensure that fuel suppliers consider this minimum share as a target value.

Article 4 of RED II provides that in order to meet or exceed this target (as well as each Member State's individual target), Member States may take measures to incentivize the "integration of electricity from renewable energy sources into the electricity market in a market-oriented and market-driven manner, avoiding unnecessary distortions of electricity markets." As a consequence, this option would mean that if the 14% obligation is lowered, the share of biofuels from cultivated biomass would have to be reduced. If this scenario were to be pursued, member states would have to add more renewables (possibly electricity) to the energy mix elsewhere to meet the national target.

In addition, the percentage of energy from renewable sources (as measured by gross final energy consumption) of the Members shall not fall below certain minimum levels after January 1, 2021. The calculation of this percentage is based on the sum of (i) the gross final energy consumption of electricity from renewable sources, (ii) the gross final energy consumption of energy from renewable sources in the heating and cooling sector, and (iii) the final energy consumption of energy from renewable sources in the transport sector (see RED II, Article 7 (1)).

Similarly, when calculating the gross final energy consumption of energy from renewable sources in a Member State, the share of biofuels, bioliquids or biomass fuels associated with a high risk of indirect land use change (ILUC) and produced from food and feed crops for which a significant expansion of production area on high carbon stock land is observed must be lower than the consumption of such fuels in that Member State in 2019 (unless these fuels are certified as "low ILUC risk" fuels). This consumption must be reduced to 0% from the end of 2023 until the end of 2030.

RED II defines "biofuels, bioliquids and fuels from biomass with low ILUC risk" as.

- Biofuels and fuels whose feedstocks were produced under schemes that avoid displacement effects of food- and feed-based biofuels,
- Biofuels and combustibles whose feedstocks were produced under schemes that avoid displacement effects of food and feed crop-based biofuels and bioliquids and biomass

fuels through improved agricultural practices and by growing crops on land not previously used for crops; and

- produced in accordance with certain sustainability criteria set forth in Article 29 of RED II for biofuels, bioliquids and biomass fuels.

Among these many criteria is the requirement that greenhouse gas emission savings from the use of biofuels, bioliquids, and biomass fuels be either 50%, 60%, or 65%, depending on the age of the facility where the fuel is produced. Additional criteria are explained elsewhere in this article; however, all criteria must be met before energy from biofuels, bioliquids, or biomass can be counted as contributing to the EU's or a Member State's renewable energy target.

ILUC-Regulation (Delegated Regulation 2019/807)

The ILUC Regulation supplements RED II, and “lays down the criteria for determining the high ILUC-risk feedstock for which a significant expansion of the production area into land with high carbon stock is observed, and for certifying low ILUC-risk biofuels, bioliquids and biomass fuels” (EU Commission 2019).

The ILUC Regulation sets out the methodology for this purpose. The cumulative criteria are that:

- the average annual expansion of the global production area of the feedstock since 2008 is higher than 1% and affects more than 100,000 hectares; and
- the share of such expansion into land with high-carbon stock is higher than 10%, following a formula specified in the ILUC Regulation:

$$x_{hcs} = \frac{x_f + 2.6x_p}{PF}$$

Where:

x_{hcs} = share of expansion into land with high-carbon stock;

x_f = share of expansion into continuously forested areas, and areas with certain designated tree coverage, as defined in RED II (see RED II, arts 29(4)(b) and 29(4)(c));

x_p = share of expansion into wetlands as defined in Article 29(4)(a) of RED II;

PF = productivity factor, which is designated 1.7 for maize, 2.5 for palm oil, 3.2 for sugar beet, 2.2 for sugar cane and 1 for all other crops.

The ILUC Regulation also sets out the criteria for certification of low ILUC-risk biofuels, bioliquids and biomass fuels. These criteria are that such fuels comply with the GHG and sustainability criteria elaborated in Article 29 of RED II, that they have been produced through the use of “additionality measures“, and that evidence of this can be provided.

“Additionality measures” are defined in RED II as “any improvement of agricultural practices leading, in a sustainable manner, to an increase in yields of food and feed crops on land that is already used for the cultivation of food and feed crops; and any action that enables the cultivation of food and feed crops on unused land, including abandoned land, for the production of biofuels, bioliquids and biomass fuels”. Moreover, whether a biofuels can be certified as a low ILUC-risk fuel requires that the additionality measures meet certain criteria. The additionality measures must be taken “no longer than 10 years before the certification of the biofuels, bioliquids and biomass fuels as low indirect land-use change-risk fuels”, and require that a financial barrier was overcome, or the land was abandoned or severally degraded, or the crop was cultivated by a small farmer (see RED II, arts 2 and 5, respectively).

There are currently conflicts between proponents of the lucrative palm oil industry and those promoting environmental conservation; there is also international criticism due to deforestation and carbon emissions. However, plausible policy scenarios to reconcile oil palm development and forest conservation do exist.

3 Review of scientific literature on Indirect Land Use Effects

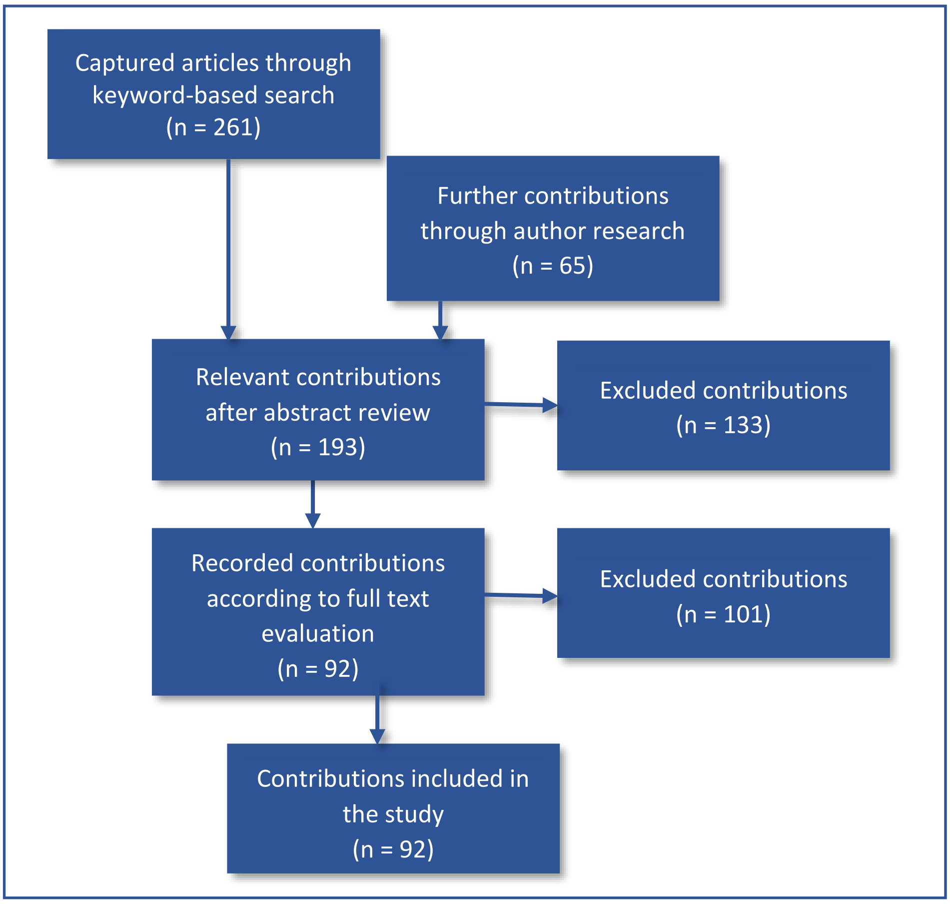
A major objective of the present study is the systematic recording of indirect land use changes in the important oilseed producing countries. For the systematic recording, the current developments of land use should be assessed within the framework of a monitoring procedure. These assessments were to be based on scientific publications in order to obtain reliable information on land use changes. In doing so, it was important to collect and classify the currently available scientific findings on the effects of indirect land use changes in the oilseed sector that have occurred since the RED II directive came into force for a systematic analysis. In the EU Commission's report (COM (2019) 142 final of March 13, 2019) on the status of the expansion of global production of relevant food and feed crops on high-carbon land as defined in RED II (Annex 1 and 2), there is an extensive literature review by the Commission's Joint Research Centre (JRC) on the most relevant findings in the scientific literature in this regard. The literature currently used at that time referred to a period up to 2018. The task of the present study is now to update this literature review with the latest scientific studies and findings.

To achieve this goal, we have taken the topic-related literature of the past 5 years (2018 - 2022) as the current basis. With the help of tabular overviews that chronologically reflect the main studies and contents, a continuation of the development of scientific knowledge in the sense of a monitoring is ensured in terms of concept and content, which can be linked to the Commission report.

For our study, we first began with a systematic review of the literature sources in question. In doing so, we made sure to screen only scientific journals whose articles are published only after a so-called single or double blind review process. This ensures the quality and thus the validity of the studies. We used various search filters to screen out unrelated journals or articles on topics such as biodiversity, climate relevance, geology, geography, hydrology or topics related to cultivation. These sources were then not considered further. This allowed us to initially focus on the main topics such as LUCC or ILUC.

This search identified a total of 261 scientific articles based on the selected keywords. To this selection were added a further 65 contributions, which were included in various ways during the course of the investigation. From the total number of 326 articles, 133 articles were then weeded out as not meeting the target. The remaining 193 articles were then subjected to a "full text" evaluation, resulting in the exclusion of an additional 101 studies. From the remaining list, 92 publications were then selected as relevant for use in the present study. Figure 1 below depicts the sequential selection process.

Figure 1: About the literature selection process



3.1 On the measurement of ILUC

Land use changes per se can usually be easily observed and statistically proven. The detection of potential changes becomes more complex when land use effects are indirectly triggered by various measures, such as policy programs or new technologies. In these cases, land use changes triggered by direct interventions at one site (in one region) may have an impact on land use at another site (in another region). In this context, we also speak of so-called leakage effects, a form of spillover effects that an intervention policy triggers in one location and leads to negative effects elsewhere - thereby potentially reducing expected positive overall effects and reducing the effectiveness of the intervention elsewhere.

According to Meyfroidt et al. (2013), leakage is understood as a displacement effect due to the type of land use, where an intervention policy to reduce negative environmental effects of a given land use leads to a displacement of the negative land use effects to another location. There are numerous studies on the triggering effects of land use change in terms of ILUC, leakage, or even spillover effects (for representative examples, see Meyfroidt et al., 2013 and 2020; Hertel, 2019; Bastos Lima, 2019). We cannot participate in this fundamental discussion of trigger effects in the context of this study. We probed for explicitly stated ILUC effects in the scientific papers and then used these as the basis for our evaluations. In recent years, there has been an increase in scientific work on the direct and especially indirect trigger effects of a policy measure and the associated unintended consequences of an environmental policy or changing consumption patterns, which often occur in spatially distant regions.

Excursus:
In this context, the following causal relationship should also be pointed out: the theoretical basis of indirect land use changes describes possible substitution effects if, due to the need for raw materials for biofuel production, a shift of food and feed production to previously unused land takes place. The resulting indirect greenhouse gas emissions would then be credited to biofuel production in the form of a greenhouse gas surcharge (ILUC value, penalty or factor). However, this inclusion of ILUC values in the greenhouse gas accounting of biofuels is controversial for various reasons. However, focusing this consideration on the biofuel sector has also insufficiently taken into account possible other causes of ILUC. For example, the effects that a reduction in land use and land productivity on highly productive land in the EU could have on indirect land use effects have so far only been marginally addressed, but not explicitly investigated. The objectives of the EU Farm-to-Fork strategy include significant reduction and restriction of the use of yield-enhancing and -stabilizing fertilizers and pesticides, as well as significant expansion of organic farming. All three measures are expected to lead to yield reductions in marketable produce. Assuming a constant level of food consumption in the EU, the food that would then no longer be produced here would have to be produced in other regions. As a consequence, indirect land use changes would be induced elsewhere. A review of the current scientific literature on indirect land use changes in this regard has not resulted in any "hits".

The following section of the analysis presents the current scientific study situation on land use effects, the extent of production expansion, and discussions on trigger effects, differentiated for the individual oilseeds and the respective growing regions.

3.2 Current development trends of indirect land use

3.2.1 Soy production

The study starts with the recent development of land use in the main relevant soybean producing country, Brazil. The basis for the explanations presented here are the latest results of current scientific publications, which are taken into account in this study.

Brazil

Soy production currently occupies about 38% of Brazil's arable land. Most of the soy production in Brazil takes place on consolidated agricultural land. However, a significant expansion of cultivated areas is taking place in the sensitive regions of the Amazon and Cerrado. Both pasture and cropland for soybeans have been steadily expanding, which can be described as both direct and indirect land use changes from previous forest and other used land. In any case, the expansion of soybean production has greatly altered the Brazilian landscape in recent years (Zu Ermgassen et al., 2020).

Since 2000, the area under soybean cultivation in Brazil has nearly doubled to 34 million ha (IBGE, 2017). This expansion is considered a major direct and indirect factor in the loss of forests and other natural vegetation - with significant regional variation. Since a peak in the late 2000s, direct deforestation of native vegetation has declined in favor of soybean cultivation in the Amazon and in older soybean-growing areas in the Cerrado - particularly in Mato Grosso state. However, in the Matopiba region of the Cerrado (consisting of the states of Maranhão, Tocantins, Piauí, and Bahia; as part of the Cerrado), where 0.5 to 0.8 million hectares of soy have been planted annually in the last decade on recently converted land, soy cultivation continues to be a major factor in biogenic habitat loss. Almost half of the Cerrado has been converted to pasture (29.5%) or cropland (11.7%) (Noojipady et al., 2017). About 62% of soybean expansion in the Matopiba region occurred on forest lands (mainly in the Cerrado). In all other states, the proportion was about 11% (including Amazon and Atlantic Forest). Matopiba accounted for about 12% of total soybean production in Brazil (2016/2017 crop season), while all other states combined contributed 88%. Most of the recent expansion occurred in the state of Mato Grosso (including areas in the so-called "Amazon deforestation arc").

The deforestation of the Amazon is complex. This was pointed out by Barona et al. in their work back in 2010 when they assessed the role of pasture and soybean acreage in Amazon deforestation between 2000 and 2006. They concluded that the immediate cause of deforestation in the legal Amazon was primarily pasture expansion, not soybean expansion.

For example, in the Mato Grosso region, there has been an increase in soybean cultivation in regions previously used for pasture, displacing pasture farther north into forested areas. They also refer to this development of deforestation as an indirect land use change.

Deforestation of the Cerrado is considered a major problem. Based on a weighted average of soybean production in these regions, the authors estimated early on that about 17% of Brazil's soybean acreage has expanded into forest areas in recent years.

Recent research on the root cause of the area expansion has found (see Arvor et al., 2017) that Chinese tariffs on U.S. soybean exports have effectively "subsidized" market prices for soybeans from countries other than the U.S. by 4-5% (see also Taheripour/Tyner, 2018). This subsidy has provided foreign producers, particularly the Brazilian soy sector, with additional investment capital and incentives to clear for farmland. In Brazil, where soybean acreage has been shown to be particularly sensitive to price changes, the imposition of tariffs has accelerated land-use change. From 2007 to 2016, Brazilian soybean acreage expanded by about 1.259 million hectares per year, including 214,000 hectares per year on land previously designated as natural vegetation. The expansion of soybean acreage occurred on land with an average carbon stock similar to that of tropical forests.

However, forest cover in Brazil extends beyond the Amazon biome (biogenic habitat), and the rapid expansion of agricultural production in other forested regions could offset some of the climate benefits of recent reductions in deforestation in the Amazon. The success of REDD+ (Reduce Emissions from Deforestation and Forest Degradation) efforts therefore depends on a full national accounting of forest cover change, including emissions from forest conversion in the Cerrado.

For another region in South America characterized by dry tropical forest and savannas, Fehlenberg et al. (2017) studied land use changes during 2000-2012. Using regression models, they sought to identify the triggers for land use change in the Chaco region (a border area between Argentina, Bolivia, and Paraguay). They looked at the extent to which soybean cultivation and pastoralism have impacted deforestation in the region. In the 110 million ha region, approximately 8 million ha of land has been deforested during the study period. The study shows that soybean production is a direct driver of development (with 0.08 ha of new soybean area per ha of forest loss). Pasture farming in all three countries bordering the region is responsible, with 0.02 ha of additional pasture area per ha of forest loss. The model calculations also show that soy cultivation in Argentina indirectly promotes forest loss in neighboring Bolivia and Paraguay.

Soy Moratorium

In the 1990s and 2000s, soybean cultivation increased sharply, especially in the states of midwestern Brazil. To curb deforestation, the Brazilian federal government introduced control policies, and at the same time, soy buyers and civil society organizations implemented the soy moratorium in 2008 and 2014 (see Taheripour/Tyner, 2018), especially for the Cerrado area. At the international level, several initiatives have been established and promoted to introduce an improved green agriculture model (e.g., "Amazon Fund" with Norwegian involvement [Nepstad et al., 2019]), at the Brazilian federal level, the Low Carbon Agriculture Plan by the Ministerio da Agricultura (2012), or the introduction of efficient monitoring and permitting systems, at the state level (e.g., soy and beef moratorium) and at the local level (e.g., Lucas Legal and SorrisoVivo projects). In addition to these activities, Zero Deforestation Commitments (ZDCs) have been implemented. These are voluntary initiatives in which companies or states commit to eliminate products that are causally linked to deforestation from their supply chains. These commitments hold promise for sustainable commodity production, but are undermined by a lack of transparency regarding their scope and impact. Studies show that while ZDC coverage is increasing, it does not adequately address the Cerrado region, where the most extensive deforestation has occurred to benefit soybean production (Zu Ermgassen et al., 2020).

While deforestation rates in the Amazon have been significantly curtailed over the past decade through strong environmental policies, rates of vegetation change in the neighboring Cerrado biome are still 2.5 times higher than in the Amazon (Nepstad et al., 2019). Previous work has shown that the Cerrado savanna is an important lever for stabilizing climate, maintaining biodiversity, and providing important ecosystem services such as water regulation. It is noteworthy, however, that the Matopiba area (consisting of the states of Maranhão, Tocantins, Piauí, and Bahia), is the Brazilian region where soybean cultivation is rapidly expanding and now claims a large portion of the original Cerrado vegetation.

The results of several studies (Taheripour/Tyner, 2018; Nepstad et al., 2019; Amaral et al., 2020; Zalessa et al., 2019) confirm the direct link between soybean cultivation and deforestation in the Amazon biome. A reduction in deforestation rates in this habitat is observed when the scale of soybean cultivation is not expanded in the areas in question. However, since 2008, when the soy moratorium was established, there has been a consistent decoupling of soy cultivation from deforestation. Government programs to reduce deforestation therefore created a new environment for agricultural expansion in line with Brazilian laws and environmental commitments. The soy moratorium reinforced this new order, and the production chains associated with soy cultivation became increasingly the subject of public and private good governance. These public and private impacts demonstrate the importance of coordinated action to achieve effective outcomes, especially in a large, socially and environmentally complex region such as the Brazilian Amazon. While initially soybean acreage increased in newly deforested areas, public and private actions significantly altered this growth trajectory in subsequent years. The decline in deforestation rates and strict controls on the use of new land, with a high risk of embargoes and fines, have become barriers to an investment-intensive crop.

The concrete consequences and land use implications of the soy moratorium continue to be assessed quite differently. For example, various studies (see Nepstad et al., 2019, for a representative example) show that the moratorium has pushed back soy cultivation as a direct cause of deforestation in the Amazon. For example, Busch and Engelmann (2018) estimate that without the policy measure, forest loss in the Amazon would have been 86% higher during the 2005 - 2012 period. Instead of 14.3 million ha, it is more likely that a loss of 26.7 million ha would have been expected. Forest loss due to soybean expansion was reduced to less than 1%, although statistics do not account for indirect contributions of soy to forest loss (Nepstad et al., 2019). In the years following the implementation of the soy moratorium (2008-2014), 40% of new soybean acreage in the Cerrado was replaced by native vegetation, and soybean acreage doubled in Matopiba alone. Of the remaining Cerrado vegetation, 89% is in areas suitable for soy production, and 40% of these suitable areas may be legally cleared under the Forest Code. Estimates (Nepstad et al., 2019) indicate that Cerrado rangeland comprised approximately 58.9 million ha in 2008, of which 54% (31.9 million ha) was suitable for soybeans. Separately, however, it is also argued that a Cerrado soybean moratorium does little to ease competition for the use of cleared production land between pasture use for beef production and use for soybean production.

Paim (2021) also recently came to a similar conclusion in her study. She too confirms that the soy moratorium, in combination with the government's "conservation policy," has led to a decrease in direct conversion of rainforest to soy land use. In her view, the soy moratorium is not yet a perfect tool to counter the deforestation trend, but is seen by her as an important element alongside other initiatives (such as the 2018 Roundtable on Responsible Soy (TRS) setting standards for sustainable soy production) to solve the problem. In another recent study by Villora et al. (2022), the authors show that even a less than perfect implementation of the Amazon Soy Moratorium, can make an important contribution to reducing deforestation rates. Thus, they found that the moratorium at least led to a reduction in deforestation levels. In the Amazon and Cerrado regions, deforestation was still at 238,000 ha. This is down to 23% from the 847,000 ha of soy conversion area measured in the 2011-2016 period.

However, not only in Brazil, but also in Paraguay, protection measures have reduced the deforestation level of forest areas worthy of protection. According to research by Da Ponte et al. (2017), deforestation within protected areas has decreased from 2003 to 2013 compared to non-protected regions. Thus, the average annual area loss in protected areas is about -3.3% (60 km2), six times lower than outside protected areas (-18%).

3.2.2 Palm oil production

Malaysia and Indonesia produce 84% of the world's palm oil. The development in both countries is therefore considered representative of the global production situation in this study.

The stock of primary forests in Asia is threatened in many ways by population growth, the accompanying urbanization of rural areas, and the conversion of land to agricultural plantations, such as palm oil production and other land uses. In Southeast Asia, the spread of oil palm has boomed over the past two decades, with a consequent decline in tropical forest cover. This change has been particularly pronounced in Borneo, where protected areas have been increasingly developed for palm oil production and already deforested areas have been converted into industrial plantations. The main concerns related to this pattern of land-use change are the short- and long-term impacts of deforestation on the natural environment and ecosystems, and how deforestation patterns contribute to global environmental problems such as climate change. By recording and mapping deforestation activities, government institutions are better able to predict land cover changes in a given region as a result of development and deforestation.

The overall contribution of oil palm expansion to deforestation is assessed very differently and depends in part on the coverage (temporal, spatial) and the coverage methods documenting the change (see specifically Meijaard et al., 2020), who reviewed a total of 23 studies of land use change due to oil palm cultivation.

In their study, they state the following: Achieving the Sustainable Development Goals (SDGs) requires balancing the land requirements of agriculture (SDG 2) and biodiversity (SDG 15). The production of vegetable oils, and palm oil in particular, illustrates these competing demands and conflicting goals. Palm oil provides about 40% of the current global annual demand for vegetable oil as food, animal feed, and fuel (210 million tons), yet the area under oil palm is less than 5-5.5% of the total global area under oil (about 425 million ha). This ratio is due to the relatively high yields of oil palm. The recent expansion of oil palm cultivation in the forested regions of Borneo, Sumatra, and the Malay Peninsula, where more than 90% of the world's palm oil is produced, has raised significant concerns about the role of oil palm in deforestation. The direct contribution of oil palm cultivation expansion to regional tropical deforestation varies widely, globally, ranging from an estimated 3% in West Africa to 50% in the Malaysian peninsula of Borneo. Oil palm is also implicated in wetland drainage and peatland burning in Southeast Asia. Documented negative environmental impacts of such expansion include biodiversity decline, greenhouse gas emissions, and air pollution. However, oil palm generally produces more oil per area than other oil crops, is often economically viable in locations unsuitable for most other crops, and provides significant wealth to at least some stakeholders. Global demand for vegetable oils is expected to increase by 46% by 2050. Meeting this demand by further expanding oil palm cultivation relative to other vegetable oil crops will have significant differential impacts on biodiversity, food security, climate change, land degradation, and livelihoods. Several studies highlight that while there remain significant gaps in understanding the relationship between the environmental, socio-cultural, and economic impacts of palm oil production and the scale of cultivation. There is also insufficient research on the impacts of palm oil production and potential substitution relationships with other oleaginous energy crops, which means that assessments of "best" land use on a global scale are also still lacking. Zhang and Su (2020) also come to similar conclusions in their studies of deforestation activities in the Asian coastal regions of Thailand, Indonesia, Vietnam, and Malaysia. For example, in the regions studied, agricultural land has increased from 29.8% to 40.9% over the past thirty years (1988-2018), due in particular to the expansion of oil palm plantation cultivation.

The expansion of oil palm cultivation has significant negative environmental impacts and continues to cause deforestation in some regions. Nevertheless, oil palm contributes to economic development in growing regions and may be compatible with at least some conservation goals, especially when compared to other oil crops. Knowledge about oil palm and the controversial interactions between the crop's environmental, sociocultural, and economic impacts, as well as the scope, rigor, and effectiveness of governance initiatives to address them, is still incomplete, a point also made by the EU Commission (EU Commission 2019). None of these problems and trade-offs are unique to oil palm: they also apply to other vegetable oil crops (Meijaard et al., 2020; Scaramuzza et al., 2017) and to other agricultural products (Kim et al., 2017). In fact, all land uses, not just those in the tropics, have environmental impacts (Nicolau et al., 2019) that can either be prevented or ameliorated (Jaime et al., 2018). However, pressure on the palm oil industry has apparently led to more research on the impacts of palm oil production compared to other oils. In a world with finite land and growing demands, global demand for food, fuel, and industrial applications must be balanced with environmental conservation goals. High palm oil yields mean higher land productivity to meet global oil demand compared to other oil crops. However, to minimize the overall impact of vegetable oil crops, their past, current, and projected distribution and impacts need to be assessed, and their yields, global trade, and uses reviewed. This information is needed to better plan and manage land use for all oil crops, balance risks and opportunities with local conditions and realities, and optimize simultaneous implementation of the SDGs.

Indonesia

The largest land uses of Indonesian oil palm plantations are on the islands of Sumatra and Kalimantan. Kalimantan has seen particularly rapid growth in oil palm plantations since 2000. For Indonesia as a whole, the total extent of this growth, and in particular the proportion of deforested areas, can only be estimated approximately. As will be shown, the estimates are often far apart.

In Indonesia, logging (often illegal) is the primary cause of deforestation, not the expansion of oil palm plantations. This form of land use change and the associated loss of biomass is primarily caused by logging - the establishment of oil palm plantations on previously forested land after logging should be considered a downstream use. According to Austin et al. (2017), the expansion of oil palm cultivation on forest land in Indonesia has varied between about 18 and 63% in recent years. Assuming an average conversion value of about 30%, the majority of land use change (about 95%) primarily affected secondary forest and about 5.1% affected primary forest.

To estimate the extent to which individual countries are ultimately dependent on palm oil through their linkages in international supply chains and the extent to which this triggers land use change in producer countries, Shigetomi et al. (2020) estimated the size of land converted to oil palm plantations, using original data from Austin et al. (2017). They used large-scale mapping of oil palm plantations using satellite imagery in key regions of Indonesia (Sumatra, Kalimantan, and Papua) at five-year intervals between 1995 and 2015 for their study. The rapid increase in international demand for palm oil has led to the expansion of oil palm plantations in producing countries, with the consequence of often negative environmental impacts. Their study examines the complex relationships between palm oil consumption and palm oil production and environmental impact for various Indonesian palm oil supply chains, including a thirteen-year period (2000 - 2013). Global commodity flows of palm oil were established using input-output relationships. The study was able to establish the clear relationship between palm oil consumption along supply chains and associated land use changes due to palm oil plantation expansion. According to their interpretation of the results, consumption of palm oil in India, China, Western Europe, the United States, and Japan account for the largest share of palm oil production use from Indonesia.

In the study by Sharma et al. (2019), five primary ecosystem services of natural vegetation are elaborated and these are analyzed in relation to a further expansion of oil palm plantations for the regions of West Kalimantan and Indonesia. For this purpose, three future scenarios of oil palm cultivation, which were considered plausible, were evaluated:

(1) "business as usual",

(2) conservation, and

(3) sustainable intensification.

The starting point was the current land use policy and spatial planning, as well as an expansion of oil palm production predicted on the basis of past development. The geographic information system ArcGIS was used as an analysis tool for mapping spatial land use changes, and the so-called Integrated Valuation of Ecosystem Services and Trade-offs Tool (InVEST Tool) was used to assess ecosystem services. This allowed the analysis of both historical and future land use changes, valuation and trade-offs of ecosystem services and palm oil production. Sustainable intensification, referred to as scenario (3), has a positive impact on carbon and water storage, although this form of land use also decreases biogenic habitat quality relative to baseline. However, this sustainable intensification scenario offers a compromise solution to future oil palm expansion by ensuring the provision of ecosystem services comparable to the conservation scenario, but without significantly affecting palm oil yield compared to the business-as-usual scenario.

These impact analyses of future land use scenarios highlight the sustainability implications of multiple ecosystem services. The business-as-usual scenario results in negative impacts on ecosystem services due to the intensive expansion of oil palm plantations, especially in areas with old-growth and regenerating forest. Assuming the lowest intensity of oil palm expansion, the conservation scenario improves carbon storage and leads to stable habitat quality compared to current land use (2016 reference). The sustainable intensification scenario, where oil palm is grown only on suitable land and crop yield is improved, has a positive impact on carbon and water storage, while habitat quality in the study area is only slightly reduced.

The study concludes that the sustainable intensification scenario is a compromise solution for the future expansion of oil palm cultivation, as it ensures a supply of ecosystem services comparable to the conservation scenario without significantly affecting palm oil yield compared to the business-as-usual scenario. Smallholders and industrial plantations may choose to sustainably intensify oil palm cultivation if they overcome the technological, social, and economic barriers. However, food security may become a potential concern as agricultural land is converted to oil palm plantations on a large scale under this scenario. Therefore, the future expansion of oil palm cultivation should be done carefully to achieve a balance between the needs of people and the environment.

Malaysia

Forest cover in Malaysia has remained relatively stable since 2010. On the other hand, oil palm cultivation has expanded significantly into cropland and into areas that have been established on previously forested land (see Gunarso et al., 2013). A decline in permanent crops has been observed since the last 25 years. The national harvested plantation area reached about 4.86 million hectares in 2015 (FAO, 2018, http://faostat.fao.org). Capturing or even approximating the actual extent is described by the authors as difficult, as there is often an indirect link between deforestation and the establishment of new oil palm plantations (through prior deforestation). However, oil palm plantation expansion has affected deforestation more directly in Malaysia than in Indonesia (Gunarso et al., 2013). This is true in the Sabah and Sarawak regions (see Gaveau et al., 2017; Gaveau et al., 2018; Gaveau et al., 2021), while early deforestation in Peninsular Malaysia was driven primarily by the expansion of rubber and other crops (Gunarso et al., 2013).

Of the 11.8 million hectares of oil palm plantations in 2015, 6.4 million hectares (54%) were planted after 2000 on land that was forested in 2000. 1.0 million hectares (8.7%) were planted on land that was not forested in 2000. 4.4 million hectares (37%) were planted prior to 2000; the forested status of these areas prior to 2000 could not be determined from the data (Busch et al., 2022). Using an alternative map corresponding to the primary and secondary forest cover types of the Indonesian Ministry of Forestry (Global Forest Watch, 2018) suggests that only 2.1 million hectares of oil palm (18%) were planted after 2000 on land that was forested around 2000. The estimate of the proportion of post-2000 oil palm expansion (see Busch et al., 2022) that occurred on forested land is 86%, which is higher than estimates from previous analyses. This is because the underlying forest cover map includes more forested land (e.g., secondary forests; non-forested tree stands) than forest cover maps used in other studies.

Between 1973 and 2015, an estimated 4.2 million ha of Malaysian Borneo old-growth forest was cleared, while 3.7 million ha of it was used for industrial plantations (palm oil or rubber) (Gaveau et al., 2018). The large stock of forest land and natural resources has led to a rapid increase in agricultural use, which is increasingly unregulated and uncontrolled. As a result, deforestation and forest degradation are becoming increasingly problematic due to the limited land available for agricultural production (see Gaveau et al., 2018).

In a more recent study, Gaveau et al. (2021) are able to make a more precise determination of the change in area using extensive satellite imagery. For the period studied, 2001-2019, the area under oil palm cultivation has doubled, to currently now 16.24 million ha in 2019; of this, 64% was industrially operated plantations and 36% were smallholder plants. These area figures are higher than the official figures, which put the area at 14.72 million ha. The expansion mainly affected virgin forests, of which almost one third (2.85 million ha) was converted to palm oil plantations out of a total of 9.79 million ha. New plantation establishment peaked in the years between 2009 and 2012, after which it declined. The study also finds a clear link between the expansion of palm oil cultivation and oil prices. According to their calculations, a 1% reduction in prices leads to a decrease in new plantation establishment in the order of 1.08%, and thus to a decrease in virgin forest loss of 0.68%.

In a recent study by Aik and Ismail (2020), a land cover assessment based on remote sensing techniques was conducted to analyze changes in Bintulu district (Borneo). This was to measure the growth of oil palm cultivation and its impact on the decline of original forest cover between 2016 and 2018. High resolution satellite imagery (3m spatial resolution) from PlanetScope was used as it helps to distinguish multiple land cover classes at a higher spatial resolution. The results show that the decline of primary forests in Bintulu is about 26.5% in the last two years. This decline is accompanied by a 17.6% increase in oil palm plantation expansion in just 2 years. An increase of 36.1% in deforested areas was observed. These were converted to other land covers, while other land cover classes decreased by at least 20% each year. The accuracy of the results proved to be reasonably accurate with 90.0% confidence with reference to satellite imagery. It has also been shown in their study that the use of high-resolution satellite data makes it possible to monitor land use changes with a high degree of accuracy, even at the local level, for resource management purposes. Timely and reliable assessments can thus be produced. For example, for 2016 land cover distribution in the Bintulu plantation area, it was shown that oil palm plantations cover 25.5% (171 square kilometers) of the study area, while the majority of the area is covered by primary forests (30.9%). This covered area has increased from year to year - from 2017 to 2018 from 173.50 square kilometers (25.9%) to 201.26 square kilometers (30.0%)).

For Malaysia, Tang and Al Qatani (2020) in their review article examined the sustainability of oil palm plantations in Malaysia based on the literature published between 2000 and 2019. They addressed the following questions regarding the sustainability of oil palm plantations:

(1) Were oil palms the main cause of deforestation in Malaysia?

(2) Do oil palm plantations serve as carbon sinks?

(3) Do oil palm plantations promote social sustainability by creating local jobs?

This paper thus examines the sustainability of oil palm plantations in Malaysia by considering environmental, social and economic aspects. In addition, recommendations are made to improve the sustainability of plantations. The study includes a review of existing literature and reports on the environmental, social and economic sustainability of oil palm plantations, with environmental sustainability categorized into biodiversity, deforestation, pollution and peatland conversion.

The outcomes of the review are then assessed against the commonly used models of weak and strong sustainability. Recommendations are also made for sustainable practices in the oil palm sector at the levels of planning, policy making, and implementation. The review shows that oil palm plantations have lower biodiversity compared to deforested forests and cannot be solely blamed for deforestation in Malaysia, especially before 1985 when logging was particularly pronounced. However, the expansion of oil palm plantations has caused pollution and triggered the conversion of peatlands. On a social level, while oil palm plantations have improved the incomes of small farmers, they have also attracted large numbers of foreign workers, which can lead to issues of welfare, human rights, social justice, and demographic change. Oil palm has contributed significantly to Malaysian economic development and is understood as a productive land use. Biodiversity and environmental management, sustainability certification, increased corporate social responsibility, and a review of employment policies are seen as prerequisites for oil palm sustainability.

Key findings:

1. In Malaysia, forest area decreased by 20% from 1975 to 2005, and during the same period, the area planted with oil palm grew from 0.7 to 4 million ha. Wicke et al. (2011) reported a high rate of deforestation between 1975 and 1985, resulting in a total loss of 1.8 million ha of forest area.
2. While timber production was a major driver of initial deforestation until its peak in 1993, the expansion of oil palm cultivation is identified as the main cause of deforestation. According to Global Forest Watch (2018), 7.29 million ha of forest land was lost between 2001 and 2017.
3. Peatland areas accounted for about 7.45% or 2,457,730 ha of Malaysia's total land area, and 69% of peatland areas were in Sarawak, while Peninsular Malaysia and Sabah accounted for 26% and 5% of peatland areas, respectively. In 2010, peatlands with forest cover greater than 70% accounted for only 20% of the total peatland area, and hydrologically intact peat domes were scarce in Malaysia (Wetlands International 2010). In 2016, the area of peat swamp forests in Malaysia was 0.25 million hectares, representing only 10.2% of the total peatland area (Forest Department 2018).
4. In Malaysia, a total of 666,038 ha of peat swamp land was converted to oil palm plantations in 2009, an increase of 113% from the area of peat land cultivated with oil palm recorded in 2003.

The drivers of land use change also tend not to be independently assessed (Tang and Al Qatani, 2020). For example, timber use (forest clearing) almost always precedes the establishment of oil palm plantations. In other cases, it is difficult to demonstrate a direct link, especially when several years elapse between timber exploitation and the establishment of new oil palm plantations. In some regions, oil palm concessions have been used to fraudulently exploit timber resources without the intention of developing them as oil palm plantations. The effects of slash-and-burn clearing would also need to be considered, especially when it is so intense that it turns forest areas into non-forest areas within a few weeks. Logging creates the conditions for fires by opening the canopy so that solar radiation reaches the forest floor and combustable material is created by drying out. Wildfires during common droughts can spread over large areas and have been found to be particularly damaging to peat swamps, where ground fires can damage root systems. Fire has traditionally been used to promote the development of oil palm plantations. However, carelessness can also lead to uncontrolled fires that affect neighboring forest landscapes and cause them to change from permanent forest to scrubland or agroforestry. All these mentioned interrelationships lead to uncertainties in the assessment of the causes of (indirect) land use change.

Peatland

Tropical peatlands are one of the largest reservoirs of organic carbon. However, today's tropical peat swamp forests are threatened by anthropogenic disturbances and have already been largely degraded. Anthropogenic pressure on peatland ecosystems has led to ecological and biogeochemical changes and the release of carbon into the atmosphere. In Southeast Asia, the conversion of peatlands to oil palm plantations has accelerated significantly over the past two decades. This is occurring in both Indonesia and Thailand.

The conversion of peatlands, often through the (illegal) use of fire, has contributed to a significant loss of carbon stocks (see early study by Wicke et al., 2011). The estimated area of industrial oil palm plantations on peatlands in Indonesia increased from 19,000 ha in 1990 to 1.311 million ha in 2010, and Austin et al. (2017) estimate an expansion of oil palm plantations on peatlands of 305,000 ha between 1995 - 2000 and 619,000 ha between 2010-2015. Taking both sources as the basis for an estimate, it can be assumed that for Sumatra, Kalimantan, and Papua, the proportion of total expansion of palm oil cultivation on peatland soils ("wetlands") is about 50% of the area, and in areas corresponding to "tropical forest" also corresponds to a proportion of 50%. Numata et. al (2022) currently found for the Indonesian province of Riau that in the last thirty years (1990-2020), about 45% of deforested areas were converted to the establishment of about 2.08 million ha of oil palm plantations. The newly used areas were mostly mineral soils, but the original peatland areas were also significantly affected. They accounted for about 65% of the remaining forest areas.

For peatland conversion, Srisunthon and Chawchai (2020) examined land use and land cover change (LUCC) before and after the introduction of Thai government policies in 2005, analyzing direct and indirect land use changes (DLUC and ILUC) associated with oil palm expansion and anthropogenic impacts in the Princess Sirindhorn Wildlife Sanctuary (PSWS), Narathiwat, southern Thailand. The analysis is based on land use and land cover data from the Land Development of Thailand from two different time periods: 2000-2009 and 2009-2016. For comparison purposes, the data were categorized into 12 land use types: Oil palm, para rubber, paddy field, abandoned paddy field, orchard, other agricultural land, wetland or peatland, mangrove, evergreen forest, water area, built-up area, and unused area. In addition, the area of net change due to DLUC and ILUC was calculated, and carbon stock changes were estimated using aboveground and belowground biomass and soil organic carbon. The results show that the total area of oil palm plantations increased from 0.04% in 2000 to 6.84% in 2016. A main reason for the area expansion is considered by the authors to be that the Thai government promoted the use of biodiesel and increased the capacity of palm oil production in 2005. Replaced were mainly rice fields, evergreen forests, wetlands and peat bogs. Deforestation of natural forests increased sharply during 2000-2009. The ILUC study shows that the expansion of oil palm plantations, exceeds that of other cultivated areas (such as rice fields, para rubber, and orchards). The results also show that the conversion of natural landscapes (evergreen forests, mangroves, wetlands, and peatlands) to oil palm plantations in the study region have had negative impacts on carbon stocks. LUCC analysis shows that oil palm plantations and built-up areas increased by 6.80% and 2.87%, respectively, between 2000 and 2016. Rice fields (-6.99%) and evergreen forests (-8.17%) were the main areas replaced. The conversion of natural land uses (evergreen forests, mangroves, wetlands, and peatlands) to oil palm plantations resulted in a reduction of carbon stock of about 4 million megagrams C (0.25 million Mg C/year) in the area.

Given the importance of land-use change-induced changes in carbon stocks, this study underscores the need for sustainable land-use management and long-term monitoring.

Interim conclusion

The area expansion of oil palm plantation cultivation in the regions follows a historical trend, at least for the twenty-year period (1995 - 2016), with an average annual growth rate of 7 to 7.7%. There are also measurable differences between regions in the countries concerned. The area expansion in new plantations in Sumatra remains large, but the average annual growth rate has declined from the original 7.6% are to 3.8% over the past five years. Even in Sarawak, which had annual growth rates of between 15 and 20% between 1990 and 2005, growth has slowed somewhat, although there is no indication that rates of change on peat soils are decreasing. Kalimantan continues to expand at near exponential growth rates, a trend that the authors cited believe will slow in the near future. However, if the past is a reliable guide and demand for palm oil continues to grow, it is likely that expansion will continue at annual rates of 7% in the near term, with future expansions potentially shifting to the borderlands of Papua and Papua New Guinea.

Palm oil production is only one of the causes of deforestation. In Indonesia, the single largest cause of historical forest loss has been primarily intensive logging and the effects of fire, which have combined to progressively degrade large areas of forest into agroforestry or shrubland. In Malaysia, direct conversion of forest to oil palm has been more common, especially in Sabah and Sarawak. However, conversion of other land uses, such as rubber, is also more significant there.

3.2.3 Rapeseed production

Canola oil production is concentrated in the regions of Canada, China and the EU28, with around 78% of global production. If India and the United States are added, this share increases to a total of 90%. After oil palm and soybeans, canola is the third most important oil crop. Global production increased by 40% between 2006 and 2016. In contrast to palm oil and soybean producing regions, the relevant countries record net deforestation over the last decade, with the exception of Canada, which had low net deforestation according to FAO data (2018). Thus, initially, there is no obvious link between the recent expansion of canola cultivation and forest use. Also, productivity advances in canola cultivation have been substantial. Global canola production increased 3.3-fold between 1994 and 2018, while acreage only nearly doubled (see Fridrihsone et al., 2020).

Scientific contributions on a direct link between canola production and indirect land use change could not be identified. Only one recent case study addresses the expansion of rapeseed oil cultivation and potential ILUC risks, focusing on the cause-effect relationships using Romania as an example (cf. Brinkman et al., 2018).

This study investigates the land use impacts of rapeseed cultivation for biodiesel production for a comparatively small region (Eastern Romania). Calculations are based on the reference year 2020, the year at which the first target of 10% renewable energy use in the EU transport sector applies.

Based on current 2020 production data and corresponding land use data from the Romanian Institute of Statistics (INSSE), various land use projections for crop production development in the region were conducted using the MIRAGE model (Modelling International Relationships in Applied General Equilibrium). The MIRAGE model is a general equilibrium model developed by the International Food Policy Research Institute (IFPRI). Simply put, the model projects the impact of crop change on supply and demand in various sectors of the global economy. Increased biofuel production is modeled as an exogenous change and a growing population is assumed for demand.

The focus of the study is the greenhouse gas balances of biofuels associated with indirect land use change. The study approach assumes that land not yet in production in the study region is used for biodiesel production. In this way, potential land requirements outside the study regions can be reduced. Canola production is then started on the corresponding areas. This assumes a lower ILUC risk of canola in biodiesel production and lower GHG emissions compared to fossil fuels. For this study, the authors calculate the canola biodiesel potential and GHG emissions for four measures to provide surplus land in the 2020 baseline year. Four scenarios, which differ in assumptions about productivity and sustainability in the agricultural sector, show the differences in the potential of these measures. The study finds that using surplus land to produce canola biodiesel has a potential of 3-64 petajoules (PJ), equivalent to 1-28% of Romania's projected road diesel consumption. Yield increases in arable and livestock production justify the calculated potential savings. If biodiesel poduction were to occur through the expansion of canola cultivation on previously low-productivity land, then this could significantly reduce the risk of indirect land use effects (for example, through increased soybean production elsewhere).

Because GHG emissions from ILUC mitigation measures also occur in the rest of the agricultural sector, it is important to consider this sector as a whole. This means that assessment and monitoring of ILUC mitigation progress should focus on the broader agricultural sector to avoid underestimating ILUC mitigation effects. Since the results of this study are based on MIRAGE model results, it was not possible to consider the market-relevant impacts of ILUC mitigation measures.

The following Figure 2 summarizes the results from the current studies on the individual oilseeds and their changes in area. In some cases, there are major differences in the criteria such as the period under consideration, the focus of the study, the region concerned and the changes in area. A comparability of the results, also in relation to the periods investigated, is therefore only possible to a very limited extent. Nevertheless, significant land use changes are evident, at least for the critical oilseeds - palm and soybean.

Figure 2: Recent study content on the oilseed complex.

Soy				
Period covered	**Region**	**Main focus**	**Absolute area increase in (ha)**	**Study**
2000-2019	South America	Soybean expansion	28,700,000	Song et al. (2021)
2008-2020	Brasil	Soybean expansion and Soybean Moratorium	42 % increase in forest loss (11,088 km^2) occurred between August 2019 and July 2020.	Paim (2021)
2008-2016	12 US-MidWest States	Grass-to-cropland and carbon losses	2,050,000	Zhang et al. (2021)
2004-2011	Amazon biome	Expansion of soybean farming into deforested areas role of soy moratorium	n. a.	Amaral et al. (2020)
2006-2017	Brasil/Mato Grosso/Cerrado	Monitoring zero deforestation commitments	n. a.	Zu Ermgassen et al. (2020)
2016	Brasil	Tariff on soybeans and impact on LUC and GHG	4,000,000	Richards et al. (2020)
2003-2015	Brasil/Cerrado	Soy expansion	1,300,000	Rausch et al. (2019)
		Pathways for recent Cerrado soybean expansion: extending the soy moratorium and implementing integrated crop livestock systems with soybean	The years following the Soy Moratorium's establishment (2007–2013), 40% of new soy expansion in the Cerrado replaced native vegetation; soy area roughly doubled in Matopiba. Of the remaining Cerrado vegetation, 89% is on land suitable for soy production, and 40% of this suitable area is eligible to be legally cleared under the Forest Code.	Nepstad et al. (2019)
2000-2014	Brasil/Mato Grosso/Minas Gerais	Soy expansion	26,0 – 46,1 Mio Hektar	Zalles et al. (2019)
Key message	Recent studies show that soybean acreage in Brazil continues to expand. Soy moratorium led to a decrease in deforested area/rate of deforestation, also due to conversion of pasture land to cropland. Much new cropland is emerging on former rangeland (Zalles et al. 2019). New pasture land is created through new deforestation. Soybean cultivation causes deforestation through this ILUC. However, slowing expansion in Brazil does not preclude expansion elsewhere. In regions not affected by the soy moratorium, e.g. Matopiba, there has been no decline (Zalles et al. 2019).			

Palm I				
Period covered	Region	Main focus	Absolute area increase in (ha)	Study
2001-2016	Indonesia, Malaysia (Borneo)	Peatland Loss in Southeast Asia Contributing to U.S. Biofuel's Greenhouse Gas Emissions	n. a.	Zhu et al. (2022)
Simulation Datenbasis 2010	Indonesia	Impact of EU import ban on palm oil to Indonesian economy and the environmental	Total land use will be reduced by −0.48 % (−0.6 %).	Rum et al. (2022)
2000-2015	Indonesia	Effects of demand-side restrictions in Europe on deforestation in Indonesia	6,400,000 (54%) was planted after 2000 on former forested land; 1,000,000 (8.7%) was planted on land that was not forested in 2000	Busch et al. (2022)
2019	Worldwide	High-resolution global map of smallholder and industrial oil palm plantations	21,000,000 ± 420,000 (72.7%) 15,260,000 ± 400,000 industrial; (27.3%) 5,720,000 ± 220,000 smallholders) (underestimation) South East Asia: 18.690.000 ± 330.000 South America: 910.000 ± 60.000 West Africa: 790.000 ± 110.000 (68.7% smallholders) Central America: 520.000 ± 40.000 Central Africa: 210.000 ± 600.000 (14.5% smallholders) Pacific: 140.000 (26.8% smallholders) Indonesia: 12,050,000 ± 230,000 (66.8% industrial; 33.2% smallholders)	Descals et al. (2021)
2001-2019	Indonesia	Slowing deforestation follows declining oil palm expansion and lower oil prices	The area that was forest in 2000 and is oil palm in 2019 is 3,090,000 (32% of total forest loss: 9,790,000); 2,850,000 (29%) cleared and converted in the same year ("rapid conversion"): 2,130,000 (22%) industry and 720,000 (7%) smallholders. The dataset is produced mostly by visual interpretation and manual delimitation of oil palm development; no direct measure of planted areas, but instead, areas that were "cleared to develop plantations".	Gaveau et al. (2021)

Palm II					
Period covered	**Region**	**Main focus**	**Absolute area increase in (ha)**		**Study**
2035 (projections)	Indonesia	Oil palm production has increased because of expansion of cultivated area rather than due to average-yield increases.	BAU (projection of of historical trends [2001-2018]) + 9,200,000 new land; peat and primary and secondary forest (+29%)	Three different scenarios: - BAU (Business-as-usual) - INT (yield intensification) - INT-TE (C-stock land + conversion practices + R&D)	Monzon et al. (2021)
2016-2018	Malaysia (Borneo)	Detection of deforestation and land conversion from high resolution satellite imageries in Bintulu District, Serawak,	Oil palm plantations cover 25.5% (17,100) of the study area; majority of area is covered by primary forests (30.9%). Palm area: 2016: 17,109 (25.5%); 2017: 17,350 (25.9%); 2018: 20,126 (30.0%)		Aik and Ismail (2020)
1961-2017	Global scale	The environmental impacts of palm oil in context.	Total oilcrops: 1961: 170,000,000; 2017: 425.000.000 Palmoil: 2008-2017: + 700,000 p.a. Malaysian Borneo: 1972-2021: 50% of new plantations are deforestation Review of 23 studies that reported land-use or land-cover change involving oil palm		Meijard et al. (2020)
2000-2010	Indonesia	Trends in global dependency on the Indonesian palm oil and resultant environmental impacts; Indirect contributions to land-use changes in Indonesia by nation 2000–2010.	LUC derived from the oil palm plantation (est. for 2000-2005: 1.400.000; 2005-2010: 3.000.000.	LUC footprints by nations that are depending on palm oil (international supply chains); Trends in the Indonesian palm oil imports and footprints per nation.	Shigetomi et al. (2020)
2000-2016	Southern Thailand	Land-Use Change and Effects of Oil Palm Expansion Peatland	2000-2009: 2,943 2009-2016: 4,716		Srisunthon et al. (2020)
1975-2005	Malaysia	Sustainability of oil palm plantations	1975-2005: + 3,300,000 Forest land - 20% Area planted with oil palms grew from 700,000 - 4,000,000.		Tang and Qahtani (2020)

Palm III				
Period covered	**Region**	**Main focus**	**Absolute area increase in (ha)**	**Study**
1988-2018	Coastal regions South Asia	Land Use Change in the Major Bays	Net loss of natural forest area: 7,702.3 km^2 Net loss of mangrove forests: 1,449.8 km^2	Zhang and Su (2020)
2000-2016	Indonesia, West Kalimantan	Ecosystem services under future oil palm expansion scenarios	+ 1,170,000 Three scenarios: 1) business as usual, 2) conservation and, 3) sustainable intensification, based on current land-use policy, spatial planning, projected oil palm expansion.	Sharma et al. (2019)
Key message	Globally, palm oil plantations grew by 0.7 million ha per year between 2008 and 2017 (Meijaard et al. 2020). Moratorium in Indonesia since 2018. Few data from studies as of 2018: no statement about effect possible. But figures from press or similar sources show that there was a decrease in deforestation rate from 2017/2018. Moratorium expired in September 2021. After moratorium of 2011, deforestation rate has decreased from 91 000 ha per year (2001-2017) to 1 000 ha per year (2012-2017). However, deforestation rate outside the areas which were under moratorium were 35%-396% higher (Chen et al. 2019). Diesel from renewable energy has the potential to save 66.9 - 85.4% in GHG emissions compared to fossil diesel (Xu et al. 2020). When palm oil is used to produce biodiesel, two variables come into play in terms of GHG emissions. The first is land use change, particularly the draining of peatlands, which releases large amounts of GHG emissions. When ILUC is included, GHG emissions increase to 75-280 gCO2/MJ. Second, the use of open ponds (open-pond system) in palm oil mills. Using this system releases 17-18 gCO2/MJ more than closed systems (Xu et al. 2020). For comparison, diesel from fossil fuels is 92.5 gCO2/MJ. Looking at GHG emissions excluding ILUC, biodiesel from palm oil has the lowest GHG emissions per MJ of diesel (Uusitalo et al. 2014; Kim et al. 2017). Conversion of forest to oil palm plantations produces 437 t CO2/ha. In contrast, conversion of a set-aside area to a cultivated area of rapeseed produces only 95 t CO2/ha. Interestingly, the conversion of grassland to palm oil plantations even has a negative CO2 balance, since oil palms store more CO2 than grassland (Schmidt et al. 2010).			

Rapeseed				
Period covered	Region	Main focus	Absolute area increase in (ha)	Study
1994-2018	Europe (Latvia)	Environmental Life Cycle Assessment of Rapeseed and Rapeseed Oil Produced (Case Study)	Absolute expansion in acreage (ha): n.a. Life cycle assessment (LCA) to evaluate environmental impacts of products and processes. LCA-method evaluates the environmental sustainability and the overall impacts, bottlenecks and benefits from the use of bio-based feedstock. In the case of oil produced from winter rapeseed, it is evident that substituting soybean meal fed to ruminant and poultry by rape cake would lead to GHG emission savings (positive ILUC-effects).	Fridrihsone et al. (2020)
2010-2020	Eastern Romania (case study)	Low-ILUC-risk rapeseed biodiesel: potential and indirect GHG emission effects	Absolute expansion in acreage (ha): 242,000 Yield improvements of crops and livestock are crucial to reduce the ILUC risk. Low-ILUC-risk biodiesel production is feasible with low GHG emissions of ILUC mitigation measures under specific conditions.	Brinkman et al. (2018)

4 Economic evaluation of trigger effects for indirect land use change in the context of monitoring (based on the EU calculation model)

One objective of RED II is to determine which feedstocks have a significant expansion of cultivation. A significant expansion of cultivation results in these feedstocks being considered biomass fuels with a high ILUC risk. Three factors are involved in determining whether an expansion is "significant".

1. the absolute relevant amount of land expansion since a given year compared to the total area of production of the crop in question.

2. the proportion of expansion on land with a high carbon stock.

3. the type of crop and high carbon stock land.

The first factor considers both absolute and relative increase. Here, the average annual absolute increase should not exceed 100,000 ha. The relative increase should not exceed 1%. Commodities that do not exceed these values can be excluded because their production increase comes primarily from yield improvements.

However, if these two thresholds are exceeded, the second criterion is decisive. If expanding the acreage of a feedstock to high carbon stock land results in more GHG emissions than are saved by its use as a biofuel, the use of that feedstock does not result in GHG emissions savings compared to fossil fuels. However, biofuels must save at least 50% GHG emissions compared to fossil fuels (RED II). According to calculations by the EU Commission, a threshold value of 10% is set. This means that the expansion of cultivation on areas with high carbon stocks must not exceed a value of 10% compared to the total expansion of cultivated area. Only in this way can significant net savings of GHG emissions be realized.

The third factor relates to both the type of crop and the type of soil. For example, the release of GHG emissions is significantly higher on peat bog land than on other land. Furthermore, emissions are counted toward the energy content of all marketed products, creating differences between permanent crops and annual commodities. The productivity factor is set higher for perennial crops. Accordingly, the following formula results from the three factors mentioned, which describe a significant expansion:

$$x_{hcs} \frac{x_f + 2.6x_p}{PF}$$

Where:

x_hcs = proportion of expansion to high carbon stock areas;

x_f = proportion of expansion to areas referred to in Article 29(4)(b) and (c) of RED II;

x_p = proportion of expansion to areas referred to in Article 29(4)(a) of RED II;

PF = productivity factor.

The PF is 1.7 for corn, 2.5 for palm oil, 3.2 for sugar beet, 2.2 for sugar cane, and 1 for all other crops.

The formula for calculation was applied below as an example. According to the RED II, the reference year for assessing the change in area is 2008. Due to lack of data, other years are used here.

In the first example, the area calculation is performed according to data from Abood et al. (2015). The period considered is 2000 to 2010 and the data collected is for the whole of Indonesia. In the 10 years, there is an increase in area of palm oil plantations of 3,766,000 ha. The expansion to peatland areas is 534,000 ha. These areas are weighted much more heavily in the calculation because of the increased CO2 emissions compared to other areas. Overall, this results in a value of 0.31. This is above the desired 10%, which means that there is a "significant" expansion of palm oil plantation cultivation in Indonesia, at least for the period from 2000 - 2010.

The other values come from a study by Carlson et al. (2013). The authors developed various scenarios for the future development of palm oil cultivation in Kalimantan, Indonesia. If the cultivation of palm oil continues unchanged, as at the time of the study, an area increase of palm oil plantations of more than 9 million ha can be expected within 10 years (2010-2020). The proportion of expansion on high carbon stock land would be 0.47, well above the 10% threshold where GHG emissions from palm oil cultivation do not exceed the amount of GHG emissions from fossil fuels. Furthermore, the formula here was still applied to the 1990-2000 and 2000-2010 periods. Again, the expansion of cropland on high carbon stock land exceeds the threshold.

In the study by Ramdani et al. (2013), values are also found to calculate the proportion of expansion on high carbon stock land. However, the absolute value of the total area increase of palm oil plantations is not exactly given. For this, the relative values for the respective increase on forest areas and on peatland areas are given, so that the formula can still be calculated. The result is a value of 0.84. This is significantly higher than the values from the other studies. However, this value is not surprising, since 70% of all palm oil plantations in the indicated period were established on former peatland areas.

Figure 3: Proportion of expansion on high carbon stock land

Sources	Region	Period	Total increase in area under palm oil plantations (in ha))	Increase in area of palm oil plantations on former forest (in ha)	Increase in area of palm oil plantations on former peatlands (in ha)	x_{hcs}
Abood et al. (2015)	Indonesia	2000-2010	3 766 000	1 600 000	534 000	0,31
Carlson et al. (2013)	Kalimantan, Indonesia	1990-2000	745 800	413 600	25 300	0,26
Carlson et al. (2013)	Kalimantan, Indonesia	2000-2010	2 328 000	1 323 100	376 800	0,39
Carlson et al. (2013)	Kalimantan, Indonesia	2010-2020	9 384 400	6 915 700	1 710 600	0,47
Gunarso et al. (2013)	Indonesia	1990-2010	6 387 000	1 220 000	1 334 000	0,28
Gunarso et al. (2013)	Malaysia	1990-2010	3 252 000	1 239 000	131 400	0,19
Ramdani et al. (2013)	Riau Province (Indonesia)	2000-2012	ca. 200 000	67 877	162 004	0,84
Saswattecha et al. (2016)	Thailand, Tapi river basin	2000-2009	133 769	6 972	863	0,03
Saswattecha et al. (2016)	Thailand, Tapi river basin	2009-2012	26 993	932	50	0,02
Srisunthon und Chawchai (2020)	South Thailand	2009-2016	4 730	23	2 448	0,53
Zhu et al. (2022)	M&I (Malaysia, Indonesia)	2001-2016	11 890 000	k. A.	2 140 000	X_P = 0,18 X_F = ?
Numata et al. (2022)	Indonesia (Riau Region)	1990-2020	2 930 000	1 020 000	2 620 000	0,72

Source: own calculations

Sample calculation Abood:

$X_f = \frac{1600000}{3766000} = 0{,}42$

$X_p = \frac{534000}{3766000} = 0{,}14$

$X_{hcs} = \frac{0{,}42 + 2{,}6 \text{ x } 0{,}14}{2{,}5} = 0{,}31$

Gunarso et al. (2013) also provided data on the spread of palm oil plantations. Here, a differentiation is made between different categories of land use. For the calculations, the categories "undisturbed upland forest" and "disturbed upland forest" were combined, as well as the categories "Undisturbed Swamp Forest, Disturbed Swamp Forest and Swamp Shrub & Grasslands". The calculations also produce results that are above the 10% threshold. As a caveat, it should be mentioned here that this is not a source that has been subjected to peer review. Published under: Reports from the Technical Panels of the 2nd Greenhouse Gas Working Group of the Roundtable on Sustainable Palm Oil (RSPO).

In addition to Indonesia, other countries, such as Thailand, are also affected by an increase in palm oil plantations on peatland. However, the two studies mentioned here, which have as their object of investigation the development of palm oil plantations in Thailand, come to different conclusions. While Srisunthon and Chawchai (2020) conclude that there is a significant expansion on high carbon stock land, the study by Saswattecha et al. (2016) shows substantially lower values. An interpretation must take into account that both studies are based on different study areas.

Further studies on the developments of palm oil plantation cultivation are currently available. Some of these also take a look at the development in relation to peatland areas (Cooper et al., 2020; Monzon et al., 2021; Purnomo et al., 2020; Utari et al., 2021). However, these are not suitable for calculation according to EU Commission specifications. In order to be able to apply the EU Commission's calculation model and measure the proportion of expansion on land with high carbon stocks, the following information is required, in addition to the criteria mentioned above:

- a defined period in which changes in cultivated areas were observed (ideally, the year 2008 should be used as the reference year)
- the share of palm oil plantations on forest areas in the total area of palm oil plantations
- the share of area increase of palm oil plantations on peatland in the total area increase of palm oil plantations.

Many authors mention the problem, the development of palm oil plantations on peatland areas, such as Utari et al. (2021). These have as their object of study an area in southern Sumatra (Indonesia), which is mainly covered by peatland. Between 2014 and 2019, the area of palm oil plantations in this area increased by 83% from 66,588 ha to 121,872 ha. It is not possible to use this information to meaningfully calculate the expansion onto high carbon stock land, as the focus was only on cultivated land on peatland, not cultivated land on forest land. Nevertheless, the results of this study also suggest that there is a significant expansion of palm oil plantations on peatland.

Cooper et al.'s (2020) study of oil palm planting on peatland shows that large amounts of CO_2 and N_2O emissions are generated after conversion, while CH_4 emissions are lower. CO_2 emission fluxes are highest in the drainage phase, while N_2O emissions were highest in young oil palm plantations. Especially in terms of increased greenhouse gas emissions, the cultivation of palm oil plantations on peatlands is discussed. It is estimated that the conversion of peatlands to palm oil plantations causes between 16.6% and 27.9% of the total CO_2 emissions of Malaysia and Indonesia. This is equivalent to between 0.44% and 0.74% of global CO_2 emissions (Cooper et al., 2020).

The draining of tropical peat swamp forests in favor of conversion to agricultural land has significant impacts on greenhouse gas (GHG) emissions; however, the magnitude of these changes remains unclear. Current emission levels from palm oil cultivation grown on drained peatlands vary depending on the timing of coverage in the life cycle of the plantations, and in most cases they also only account for CO_2 emissions. In their study, Cooper et al. (2020) present one of the few direct measurements of greenhouse gas emissions that occur when peatland forests are converted to palm oil plantations. In addition to CO_2, CH_4 and N_2O emissions are also considered. The results show that emission factors for converted peat swamp forest range from 70-117 t CO_2 eq per ha per year (95% confidence interval), with CO_2 and N_2O accounting for about 60% and about 40% of this value, respectively. These measured GHG emissions indicate that conversion of Southeast Asian peat swamp forests accounts for between 16.6 and 27.9% (95% confidence interval) of the total national GHG emissions of Malaysia and Indonesia, or 0.44% and 0.74% (95% confidence interval) of annual global emissions.

In summary, the study shows that the climate impacts of converting tropical peatland to oil palm plantations are greatest during the early stages of plantation development. This shows that a simple comparison between forest and mature palm oil plantations does not adequately account for emissions throughout the oil palm plantation cycle. The evidence also shows that the risk, and therefore the magnitude, of GHG emissions from land-use change, can vary significantly depending on when they are measured. But what would these land use change emissions mean for biofuels from palm oil? Assuming a typical palm oil yield of 3.8 tons per hectare, one hectare of land could produce enough palm oil biodiesel each year to avoid twelve tons of carbon dioxide emissions from diesel combustion, while cultivation and production would produce five tons of carbon dioxide (or eight tons if methane is not captured). Thus, ignoring the carbon cost of land use, the net carbon benefit is five to seven tons of carbon dioxide per hectare per year.

However, if land use is taken into account, the picture changes dramatically. If palm oil biodiesel came from a new plantation on previously forested peatland, instead of a carbon savings, there would be a dramatic increase in estimated net emissions of 120 tons of carbon dioxide per hectare per year. Palm oil on deforested mineral soils would also result in a dramatic increase in carbon dioxide emissions, estimated at 24 tons of carbon dioxide per hectare per year.

While most land use changes lead to an increase in emissions, differentiated considerations must also be made for this. While palm oil plantations store much less biomass carbon than primary forests or even degraded tropical forests, they also store more carbon than other agricultural systems (e.g. in the palm trunks). If palm oil for biodiesel were produced entirely on degraded grasslands, the net benefit would increase to fourteen tons of carbon dioxide per hectare per year. The challenge for policymakers now is to direct the expansion of palm oil production to these areas rather than to high carbon stock ecosystems.

Overall, the few studies listed here provide information on the development of palm oil plantations on both peatland and forest land. However, only by providing this information is it possible to calculate the proportion of expansion on high carbon stock areas and thus infer significant expansion. Unfortunately, these conditions are not met in the vast majority of the studies used in the analysis.

5 Methods for recording land use changes

Numerous scientific studies on indirect land use effects and GHG accounting of oilseed production methodologically employ impact analysis models. Our study primarily recognizes four modeling methods that are used in the political and economic analyses and debates surrounding the valuation of direct and indirect land use change (ILUC). These methods are evaluated below in terms of their informativeness.

5.1 System Dynamic Modeling

The system dynamic modeling approach is applied to value chain analysis (VCA) as a state change model (dynamic). The system dynamic modeling is implemented in several steps, which includes the development of a conceptual model, the specification of variables, model checking, and the creation of scenarios. In addition, there is the VCA, which consists of the following three steps: (1) mapping the beginning of the value chain; (2) conducting a field study; and (3) evaluating the results and developing intervention scenarios.

Representative of the construction of such impact models, the current modeling from the study by Purnomo et al. (2020) is used for Indonesian palm oil production. To show the impact of different policy influences on the development of palm oil production, the authors develop a so-called palm oil simulation model (IPOS) with three main components: (1) representation of the palm oil value chain, (2) formulation of several policy development scenarios, and (3) formulation of output indicators to assess the outcomes of each policy scenario. The model is designed to examine the impacts of key policy measures currently under discussion in palm oil cultivation and then develop future policy options. For each policy measure, a scenario is formulated that quantifies the impact of the policy change on value chain actors with respect to the goal of more sustainable palm oil production.

The palm oil value chain consists of plantations, palm oil mills, refineries and markets. Growers produce fresh palm oil bundles (FFB -Fresh Food Bundle), which are processed by mills into crude palm oil (CPO - Crude Palm Oil) and palm kernel oil (PKO - Palm Kernel Oil). These are processed in refineries to produce edible oil, oleaginous chemicals and biodiesel. These products enter domestic and global markets, generating revenues that flow back to refiners, mills, producers, and the government.

The IPOS model generates different consequences for the selected policy intervention scenarios, expressed, for example, in the change in land use by oil palm plantations (ha), the change in production volumes of primary products such as FFB and CPO/PKO, and derivatives such as edible oil and biodiesel. For each value chain stage, GHG emissions and labor inputs are determined as cost and revenue components. Four policy scenarios were examined in this study: (1) a moratorium on plantation expansion, (2) wetland protection, (3) fundamental agricultural reform, and (4) banning biodiesel production.

The data in this model come from empirical surveys, official sources (e.g., central government ministries and agencies, local governments), research institutions, and academic publications. The model attempts to approximate real-world scenarios by processing the data using system dynamics software (Stella 9.0).

Further, the model uses exogenous and endogenous variables. Exogenous variables (e.g., land use, plantation area, policies, and palm oil price) are independent and influence the model without being influenced by the model itself, while endogenous variables (e.g., palm oil supply and volume effects at value chain stages, employment, and CO2 emissions) are generated by the model itself. The price of palm oil is determined by the estimated supply of palm oil and other vegetable oils from international producers such as Malaysia and Brazil, and by consumer demand.

This model aims to examine the impacts of key policies related to oil palm that are currently under discussion, and to develop future policy options. For each policy, a scenario is proposed which can compensate for the policy's impact on producers and help them shift toward more sustainable palm oil production.

5.2 General and Partial Equilibrium Models

A second group of impact modeling is the partial and general equilibrium models. This group of models attempts to quantify and measure as fully as possible, on a global or sectoral scale, the climate impacts of a biofuel policy. The findings of such studies are intended to provide support to policy makers on future biofuel policies and to clearly demonstrate the impacts of land use changes.

The starting considerations here are the fundamentally possible land use changes that result from an increase in biofuel consumption with an expansion of cultivated areas. A distinction is made between direct and indirect changes:

- Direct land use changes (DLUC) occur when new cropland is created for biofuel feedstock production;

- Indirect land use changes (ILUC) occur when existing cropland is used for biofuel feedstock production, requiring food, feed, and biobased feedstocks to be produced on previously unused cropland.

Direct and indirect land use changes are linked in many ways in reality. The use of the aforementioned models now attempts to capture the manifold relationships, in particular the effects of global market mechanisms with their numerous direct and indirect land use effects, as fully as possible and to model the interrelationships. It is taken into account that numerous effects can only be measured incompletely and that direct measurements can only capture a part of the overall effects.

5.2.1 General Equilibrium Models - Computable General Equilibrium Models (CGEs)

In order to investigate the effects of policy change on the development of, for example, sustainability, comprehensive and reliable analyses are sought that most appropriately assess policy-induced trade-offs and interactions between economic, environmental and social development components.

In our context, one looks for so-called Sustainability Impact Assessment (SIA) studies. There are no standard tools or methods available for these studies, but a mixture of different approaches and models with an interdisciplinary orientation.

Among these are the methods known as General Equilibrium Models. The so-called CGE models (Computable General Equilibrium models) are based on the theory of General Equilibrium, which are based on the concepts of market solution and neoclassical microeconomic optimization under the behavioral assumption of a rationally deciding actor. The microeconomic research approach combined with macroeconomic elements, with the aim of explaining the social and environmental phenomena and effects.

The general equilibrium approach of CGE models is criticized with the argument that a stable market equilibrium will never be achieved, since society is characterized by instabilities and is always in a non-ending process of change with dynamic disequilibrium forces. But it is not only economic theory that calls into question the usefulness of CGE models; it is also the data used in the models. For example, in many cases, annual data (static in nature) are used, which are considered unfalsifiable. CGE models ignore time-series data and refrain from modeling long-term trends, such as modeling changes in income, prices, and technology. Modeling based on equilibrium solutions is usually less well suited to adequately represent adjustment processes or pathways.

CGE models focus on equilibrium positions and are therefore typically not suitable to adequately represent change and adjustment processes. The dynamic approaches in some CGE models do not represent dynamics in the true sense of the term, but are rather comparative-static observations that represent a series of annual snapshots based on perfect macroeconomic stability.

CGE models are typically constructed to ensure more aggregate considerations. In this context, many environmental problems are more local in nature and relevance. These consequences are not adequately captured by CGE models. For all their criticisms, equilibrium models nevertheless reveal interesting insights into a possible magnitude of the policy effects that are formulated and need to be examined.

One popular general equilibrium model is the GTAP model. The model emerged from the Global Trade Analysis Project (GTAP), a global network of researchers and policymakers conducting quantitative analysis on international policy issues. The original GTAP model is documented in Hertel (1997) with a detailed discussion of the theory and derivation of the behavioral equations that go into the model. GTAP is a multi-commodity, multi-region computable general equilibrium (CGE) model that models economic activities (including crop production and marketing, livestock, food, and feed production) at the global scale (see also Taheripour et al., (a) 2019 and (b) 2019).

In terms of capturing potential land use effects, each modeling process step begins with the creation of a map of global agroecological zones (GAEZs), which include both administrative and agroecological information on individual production regions. Understanding the challenges of achieving environmental sustainability goals in the face of future demand for food, non-food, and fuel requires economic models and databases that contain spatially explicit land use and land cover (LULC) information. The GTAP LULC database and its variants have been used extensively in a variety of applications to study the land-environment-energy nexus.

GTAP-BIO Model and its background

Similar to the GTAP standard model, GTAP-BIO maps the production, consumption, and trade of all goods and services (aggregated into different categories) at the global level (see Taheripour et al., 2019(a) and 2019(b) for details). However, unlike the standard model, GTAP-BIO differentiates oil crops and vegetable oils into several subcategories, such as soybean, rapeseed, palm oil crops at the oil crop level, between soybean, rapeseed and palm oil, and other oils and fats for oil fractions, and between soybean, rapeseed and palm kernel meal for protein fraction. In addition to standard goods and services, the production and consumption of biofuels (for example, corn ethanol, sugarcane ethanol, and biodiesel) and their byproducts are also incorporated into the modeling. Unlike the standard GTAP model, the GTAP-Bio model takes into account the use of feedstocks for food and fuel, as well as competition or trade-offs between potential market uses. The model is therefore able to map markets for oil crops, other crops, vegetable oils, and flours presumed to be produced with vegetable oils. It also tracks land use (and changes in land prices) globally at the agroecological zone (AEZ) level. The latest version of this model also accounts for intensification of crop production due to technological advances, multiple cropping, and conversion of unused cropland to crop production. Finally, the parameters of the model have been adjusted to reflect recent observations. The model traces the linkages between the crop, livestock, feed, and food sectors and links them to the biofuel sectors, accounting for forward and backward linkages between these sectors and other economic activities. This model also accounts for resource constraints and technological advances. Therefore, it provides a comprehensive framework for assessing the impact of a constraint on, for example, palm oil production.

In general, the GTAP-BIO model uses demand and supply functions and market equilibrium conditions to endogenously determine the production and consumption of goods/services (including biofuels) and their prices. In this model, demand and supply are functions of relative prices and exogenous variables (e.g., excise taxes or production subsidies). However, it is also possible to determine the production and/or consumption of goods and services exogenously, for example, if the effects of binding biofuel blending obligations were to be studied.

5.2.2 Partial Equilibrium Models - (GLOBIOM)

In economics, one speaks of a partial equilibrium analysis if one only considers the market or sector that is directly affected. Economic linkages with the overall economy or other sectors are not taken into account. A partial equilibrium analysis either ignores the effect on other industries in the economy or assumes that the sector being treated is very small and therefore has no significant effect on other industries or sectors. Partial equilibrium analysis using partial equilibrium models for impact analysis is sufficient when the feedback effects of initial actions are so small that they can be ignored without thereby biasing the analysis. Under these circumstances, partial equilibrium analysis can yield good approximations of future trends.

GLOBIOM is such a partial equilibrium model that includes only agricultural and forest products - other important land uses such as urbanization are not part of the modeling.

GLOBIOM (Global Biosphere Management Model) was developed by the International Institute for Applied Systems Analysis (IIASA) and has been in use since the late 2000s. The partial equilibrium model represents the main land use sectors, including agriculture and forestry. The supply side of the model is structured from agricultural production (spatially explicit land cover, land use, farming systems, and economic cost information) to marketing (regional commodity markets). This detailed structure allows a wide range of environmental and socioeconomic parameters to be considered.

The supply side of the model is spatially mapped for high-resolution production areas (5 to 30 arcmin grid cells), which are simulation units grouped into identical elevation, slope, and soil classes for individual countries. For crops, livestock, and forest products, spatially explicit leon low production functions covering alternative production systems are parameterized with biophysical models.

GLOBIOM captures major greenhouse gas emissions from agriculture, forestry, and other land use (AFOLU) based on IPCC accounting guidelines, including N2O from manure and slurry application to soils, N2O from slurry application to pastures, CH4 from rice cultivation, N2O and CH4 from manure management, and CH4 from enteric fermentation, as well as CO2 emissions and removals from above- and below-ground biomass changes for other natural vegetation. CO2 emissions from afforestation, deforestation, and timber production in managed forests are estimated using a geographically explicit G4M model linked to GLOBIOM.

In addition, GLOBIOM endogenously represents climate change mitigation technologies, including technological and structural mitigation options.

Commodity markets and international trade are modeled at the level of 37 aggregate economic regions, with prices determined endogenously at the regional level to achieve market equilibrium. Trade is modeled using the concept of spatial equilibrium based on cost competitiveness and the assumption of homogeneous commodities, which allows tracking of bilateral trade flows between individual regions. In addition to primary products for the various sectors, the model includes several final products and by-products for which processing activities are defined. The model calculates a market equilibrium for agricultural and forest products by allocating land use among production activities to maximize the sum of producer and consumer surpluses, taking into account resource, technology, demand, and policy constraints. GLOBIOM captures the multiple interactions among the various systems involved in the provision of agricultural and forest products, such as population dynamics, changes in socioeconomic and technological conditions, ecosystems, and climate that lead to adjustments in product mix and use of land and other productive resources. The model is solved recursively-dynamically and can provide projections up to the year 2100.

A GLOBIUM modeling approach follows the general principles of ILUC modeling that have been used in a number of studies comparing a "world with additional biofuels" (the policy scenario) with the same world "as it would have evolved without the additional biofuels" (the so-called baseline).

One of these simulations is used in the recent study by the Ecofys, IIASA, and E4tech consortium (Valin et al., 2015). The policy scenarios are based on the European Union Renewable Energy Directive (RED II). The calculated ILUC impact of the additional biofuels is the difference between the emissions in the policy scenarios and those in the baseline. This difference is then attributed to the additional biofuel demand in the policy scenarios. The modeling does not indicate the extent to which land conversion is caused directly or indirectly. For this reason, this study refers to "LUC values" rather than "ILUC values" and to "land use changes" rather than "direct or indirect land use changes."

The main findings from this modeling (Valin et al., 2015) are:

(1) Conventional biodiesel feedstocks have high LUC effects compared to direct emissions from the biofuel production process, with very high emissions for palm oil (231 grams CO2 eq per megajoule of biofuel consumed - g CO2 eq/MJ), high emissions for soybean oil (150 g CO2 eq/MJ), and 63 and 65 g CO2 eq/MJ for sunflower and canola, respectively;

(2) Peatland drainage in Indonesia and Malaysia plays a major role in LUC emissions for vegetable oils. This is especially true for palm oil: 69% of gross LUC emissions for palm oil are caused by peatland oxidation after land conversion;

(3) The large and local emission source of peatland oxidation affects the LUC levels of other vegetable oils through the substitution effect, and the vegetable oils are interchangeable to some extent. Based on empirical data, the authors hypothesize a relatively limited substitution effect, hence the large difference in LUC values for palm oil - the lowest cost

vegetable oil - compared to other higher cost vegetable oils. Accordingly, it is hypothesized that this substitution effect, albeit small, transfers some peatland emissions from palm oil production to other vegetable oils;

(4) The conventional ethanol feedstocks - sugar and starch - have much lower LUC emission impacts: 14 and 34 g CO_2 eq/MJ biofuel consumption for corn and wheat, 17 g CO_2 eq/MJ for sugarcane, and 15 g CO_2 eq/MJ for sugar beet. These feedstocks are much smaller contributors to GHG emissions from peatland dehydration and deforestation compared to vegetable oils.

Modeling with the GLOBIOM model leads to some criticisms:

1. There is a lack of complete transparency about the GLOBIOM report data on which the calculations are based. Only selected data are available and many figures are based only on summarized data, with missing baseline data.
2. The results for biodiesel from rapeseed and sunflower show that the model isolates the European market from the world market. In fact, the reported price variations for the same oil show large differences between the European market and the world market.
3. The GLOBIOM report does not sufficiently mention the compound effects between oil production and protein feed production and the resulting attenuated indirect land use effects. The following examples demonstrate the weaknesses of the findings:

   - The importance of protein by-products from biofuel feedstocks, which partly replace other raw materials in animal feed - cereals or other protein meals, are not considered in the calculations.

   - Shifts in demand in favor of greater demand for biofuel, leading to a general increase in the price of agricultural products, are shown. In contrast, it is not taken into account that these shifts in demand would tend to lead to declining prices for the protein fraction of oilseeds due to their composite production. Calculations of corresponding cross-price elasticities are omitted.

The GLOBIOM model, on the other hand, shows the opposite phenomenon:

   - For soybean biodiesel as well as for rapeseed and sunflower, the demand shock leads to an increase in the consumption of meat and milk. For soybean biodiesel, animal product consumption increases by 0.15%, while for canola and sunflower biodiesel, animal product consumption and grain consumption increase by 1 million tons.

4. The yield/price elasticity is fundamental to ILUC: it determines the allocation between additional land and yield increases to supply the additional production needed to meet additional biofuel demand. Obviously, the yield/price elasticity in the GLOBIOM model is low, leading the model to favor increases in land rather than yields. Potential yield increases, and thus productivity improvements, are assumed to be much lower than the expected increases in land area if demand for biodiesel increases:

- Soybeans: +82% area, +18% yields;
- Canola: +80% area, +20% yields;
- Wheat: +83% area, +17% yield.

This is in contrast to the GLOBIOM reference scenario, where the evolution of production (+70% between 2000 and 2030) results in only an 11.1% increase in land use. This means that 84.3% of the additional production was provided by productivity improvements and 15.7% by additional cropland - exactly the opposite of what the model simulates with regard to biofuels.

Most indirect land use change studies conclude that palm oil has the highest land use change emissions among biodiesel feedstocks, but also attribute significant emissions to other vegetable oils. It should also be noted that due to the interconnectedness of the global vegetable oil market, an increase in demand for other vegetable oils results in an indirect increase in demand for palm oil, so deforestation and peatland drainage in Southeast Asia also contribute to the calculated land use change emissions for the other oils.

However, it is equally important to understand that emissions from land use change occur in many regions and that tropical deforestation is not the only source. Even if the link to the palm oil market were ignored, the MIRAGE and GLOBIOM analyses would still show relatively high indirect emissions from land use change for soybean, canola, and sunflower oils. However, the results presented in the table also show the significant differences in the analysis results of the individual model calculations.

Figure 4: Indirect Land Use Change Results for Palm Oil Biodiesel (Summary)

Modell und Studie	Peat emissions factor (t CO_2 eq/ha/yr)	Fraction of expansion on peat	Land use change emissions (g CO_2 eq/MJ)
GLOBIOM	61	-33%	231
IFPRI MIRAGE (2011)	55	30%	54
IFPRI MIRAGE (2010)	19	-19%	50
CARB	95	50%	83
US EPA	95	11,5%	58
US EPA (adjusted)	95	33%	102

Source: Malins (2017)

5.3 Evaluation of Model Concepts

It is undisputed, and this is also repeatedly found in the many modeling applications, that the cultivation of bioenergy crops can lead to displacement effects between different agricultural regions and land use systems. As the results available so far have shown, this development can certainly be observed for individual regions.

These observations and concrete results apply in particular to direct land use changes (dLUC), such as the conversion of grassland to cropland for biofuel production. These are captured through existing certification schemes under the RE Directive and are included in the GHG balances of the biofuel produced on the respective land.

It is much more difficult to capture ILUC effects of biofuel production, as evidenced by the use of different methodological approaches. At the international level, different approaches to ILUC calculation are used, which can be classified into the following two sets of methods:

- ⇨ Complex econometric models.
- ⇨ Simplified deterministic approaches.

Econometric calculation models include, for example, the GTAP model (Global Trade Analysis Project) of Purdue University, the IMPACT (MIRAGE) model of IFPRI (International Food Policy Research Institute) or CAPRI model (Common Agricultural Policy Regional Impact Analysis) of the University of Bonn. All study results modeled using the above methods show ILUC effects that are discernible when biofuel production is increased.

No mathematical or econometric models are used in **deterministic models**. The models that are applied work with data and causal relationships that are assumed to represent reality in the best possible way. In principle, the results obtained in this way depend on the exogenous determination of the variables considered relevant and plausible and their interconnection. It is hoped that the application of such models will make it easier and more plausible to interpret the expected consequences of the issues under investigation.

The application, especially of econometric models, has increased in recent years. At the same time, however, there has been increased criticism of the modeling and the assumed interrelationships. For example, the models arrive at quite different results for the same questions (cf. Figure 4). Here, for example, the indirect land use changes for palm oil biodiesel vary between 50 and 231 g CO_2 eq/MJ (cf. Malins, 2017). The results of the model calculations scatter very widely and lead to large differences in results even for comparable facts behind the questions. For example, Malins et al. (2020) show in their recent study that an assessment of indirect land use effects via GTAP-BIO models often lead to subjective modeling approaches, and thus to uncertainties in the assessment, due to limited data availability and inconsistent causal relationships.

In the end, it can be stated that the conception of the models and their underlying assumptions are different, and thus also show (partly considerable) different results.

The analysis of the approaches developed so far shows that models that identify indirect land use change as a global effect and derive highly aggregated governance factors for ILUC mitigation from it are not sufficiently robust from a scientific point of view. Since ILUC is supposed to be a global phenomenon moderated via international agricultural trade, it can also only be captured via global models. However, a convincing quantification has not been achieved so far.

In contrast to the model concepts discussed above, so-called geographic information systems have been increasingly used in recent years to identify land use changes. In principle, this is a regional approach to calculating ILUC. This is based on small-scale observations with satellite records. The land use changes observed over time are then calculated. Ultimately, a relationship is established between changes in biofuel consumption "in the world" and land use changes in the respective cultivation regions. These observations are supplemented by the description of the conditions prevailing in the respective regions and the data changes resulting from the country statistics. With the help of this kind of balance calculations one tries to represent greenhouse gas emissions caused by indirect land use changes as a regional as well as a global system. However, even here it is difficult to prove the level or significance of the ILUC effect.

5.4 Modeling by Very High Resolution Satellite Imagery - (GIS)

In order to record the extent of cultivation and its changes, various methods are used to produce global crop maps (Very high-resolution satellite imagery).

Several methods are used for this purpose:

1. Recent advances in access to remote sensing data make it possible to produce land use maps in a more accurate way. Some studies present maps of oil palm plantations with closed canopy by typology (industrial plantations versus smallholder plantations) at a global scale and with very high detail (10 m resolution) for specific years. Various high-resolution radar satellite images are used for this purpose. For example, the DeepLabv3+ model, a neural network (CNN) for segmenting the regions of interest, was trained to integrate accurate imagery into a land cover map for oil palm (for the detailed procedure, see Descals et al., 2021). The characteristic backscatter behavior in satellite observations of closed oil palm stands and the ability of the neural network to learn spatial patterns such as crop road networks enable discrimination between industrial and smallholder plantations on a global scale (overall precision = 98.52 ± 0.20%). They thus outperform the accuracy of existing regional oil palm datasets that used conventional machine learning algorithms. The global evaluation shows that closed canopy oil palm plantations are found in 49 countries and cover a mapped area of 19.60 million ha; the area estimate was 21.00 ± 0.42 million ha (72.7% industrial and 27.3% smallholder plantations). Southeast Asia is the main producing region with an

estimated oil palm area of 18.69 ± 0.33 million ha or 89% of the world's closed canopy plantations.

The analysis (see Descals et al., 2021) also confirms that there are significant regional differences in the relationship between industrial and smallholder producers. A detailed global map of planted oil palm would be a useful tool to support the ongoing debate on the environmental impacts of oilseed cultivation. Because these models can be periodically restarted as new imagery becomes available, they can be used to monitor the spread of oil palm in monoculture environments. The global oil palm view for the second half of 2019 with a spatial resolution of 10 m can be found in Descals et al. (2021).

2. In another method, high-resolution imagery was used for land use based on the IKONOS and GeoEye-1 satellites operated by GeoEye and the Quickbird, WorldView-1, and WorldView-2 satellites operated by Digital Globe (see Song et al., 2021; Fagua and Ramsey, 2019; Nepstad et al., 2019; Rausch et al., 2019; Furomo et al., 2017; Kastens et al., 2017). These satellites have a spatial resolution of 0.5 to 1.5 m and provide accurate coverage of industrial croplands, including plant species identification. The data used for the accuracy assessment covered 4% of peatlands at 30 different sites. Within these sampling locations, 600 sample plots were selected using stratified random sampling. Half of the plots were selected outside of the industrial plantations to determine the degree of omission error in the mapping. Half of the sample plots were selected within areas classified as industrial plantations to assess the accuracy of plantation species identification and the level of commission errors in mapping.

The following Figure 5 provides a detailed insight into the methodological diversity of spatial coverage models, their issues studied, and the extent of their use in scientific studies to date.

Figure 5: Methods for measuring indirect land use effects

Satellite data - Spatial coverage			
Method	**Description**	**Adressed Issues**	**References**
Landsat Methods to process Landsat imagery and extract cropland field parcels consisted of image normalization, temporal compositing of spectral indices, extraction of land cover objects (i.e., groups of pixels), per pixel (30 m) estimates of cropland, forestland, and other land cover classes.		Expansion of Soybean, forest loss	Song et al. (2021), Nepstad et al. (2019), Nicolau et al. (2019), Zalles et al. (2019), Benami et al. (2018), Graesser et al. (2018), Scaramuzza et al. (2017)
MODIS (Moderate Resolution Imaging Spectroradiometer)		Mapping LUC	Song et al. (2021), Fagua und Ramsey (2019), Nepstad et al. (2019), Rausch et al. (2019), Furomo et al. (2017), Kastens et al. (2017)
CBERS (China-Brazil Earth Resources Satellite Program)		Soybean Expansion	Nepstad et al. (2019)
GLOBIOM A global partial equilibrium model that simulates the competition for land among the main sectors oft he land-use-economy (i.e. forestry, agriculture and bioenergy) that are subjected to resource, technology and policy restrictions.		Future development of agriculture and deforestation in Brazil	Sotterroni et al. (2018)
OSIRIS	A spatial explicit model of land-use-change in Indonesia	Effects of demand-side restrictions on high-deforestation palm oil in Europe on deforestation and emissions in Indonesia	Busch et al. (2022)
Sentinel-1 and Sentinel-2 half yearly composites	Earth observation satellites	Creating a high-resolution global map	Descals et al. (2021)

Land-use-maps			
Method	**Description**	**Adressed Issues**	**References**
The global cropland maps for 2003, 2007, 2011, 2015 and 2019, cropland dynamic maps (net cropland gain and loss) and sample data are publicly available from https://glad.umd.edu/dataset/ croplands. The MODIS NPP data are publicly available from https://lpdaac.usgs.gov/products/mod17a3hgfv006. Statistical data on arable land extent and population at the national level are available from https://www.fao.org/faostat/en/#data/RL and https://population.un.org. GIS country boundaries are available from GADM (https://gadm.org). Source data are provided with this paper.			Potapov et al. (2021)
TerraClass Cerrado			Nepstad et al. (2019)
PRODES	INPE deforestation maps developed by the Amazon Moitoring Program PRODES		Godar et al. (2014)
GFW (Global Forest Watch)	Forest monitoring	Deforestation	Milodowski et al. (2017)
SIAD-Cerrado conversion maps	Cerrado Maps	Expansion of Soy	Rausch et al. (2019)

GIS			
Method	**Description**	**Adressed Issues**	**References**
QGIS	A free geographic information system software for viewing, editing, capturing, and analyzing spatial data.	Land Use and Land Cover change	Utari et al. (2021)
Arc Map	Geographic information system software for viewing, editing, capturing and analyzing spatial data.		Nicolau et al. (2019)

ArcGIS	Spatial analysis tool	Analyzing LUC; identify different types of land use, converted to palm oil	Srisunthon et al. (2020), Sharma et al. (2019), Saswattecha et al. (2016)
Land Mapper	Web based application, which provides geographical imaging and mapping services	Characterizing oil palm expansion	Furumo et al. (2020)
DeepLabv3+ model	A convolutional neural network, for semantic segmentation. It was trained, to classify images onto an oil palm land cover map.	Create an accurate global crop map	Descals et al. (2021)
Geospatial Agroecosystem Modeling System (GAMS)	GAMS integrates multiple sources of geospatial and surveyed datasets to define homogeneous spatial modeling units (HSMUs); units represent groups of grids of the same soil type, land use, and county boundary. The GAMS further formats the data for each HSMU to drive EPIC modeling.	Simulation of the environmental impacts from the conversion of grassland to corn and soybeans.	Zhang et al. (2021)

Other Methods I			
Method	**Description**	**Adressed Issues**	**References**
Literature Review		- Review recent progress and challenges ahead - Environmental Impacts of palm oil - evaluate Life-Cycle GHG-Emissions	Meijaard et al. (2020), Xu et al. (2020), Tang und Qahtani (2020), Arvor et al. (2017)
Regression Analysis		- Impact, Efficiency of the Soy Moratorium - Causes for deforestation	Amaral et al. (2020), Silverio et al. (2015), Jusys et al. (2016)

Other Methods II			
Method	**Description**	**Adressed Issues**	**References**
REML (residual maximum likelihood method)	Mixed methods using REML	Testing differences in GHG fluxes between land uses	Cooper et al. (2020)
VCA (Value Chain Analysis)	The VCA consists of several steps: (1) map the start of the value-added chain; (2) conduct a field survey; and (3) evaluate findings and develop intervention scenarios	This study developed a model called the Indonesian Palm Oil Simulation (IPOS). The architecture of the IPOS model follows the VCA. It has three main components: (1) the palm oil value chain; (2) the policy development scenarios; and (3) the output indicators to evaluate the results of each scenario.	Purnomo et al. (2020)
LCA (Life Cycle Assessment) LCA is a technique to assess the environmental aspects associated with production of a product (e.g. oilseeds) over ist life cycle.		- GHG-Emissions - Global Warming Potential - Environmental Impact and economic benefits of biodiesel production	Yang et al. (2021), Uusitalo et al. (2014), Iriarte et al. (2010), Schmidt et al. (2010)
Environmental Policy Integrated Climate (EPIC) EPIC is a process based agroecosystem model capable of simulating key biophysical and biogeochemical processes, such as plant growth and development, water balance, (C) and nutrient cycling, soil erosion, and greenhouse gas emissions.		Simulation of the environmental impacts from the conversion of grassland to corn and soybeans.	Zhang et al. (2021)
Soil sampling; GHG sampling	For the determination of soil C and N contents, isotopic composition and soil bulk density; Chambers are installed on field to sample GHG (CO_2, CH_4, N_2O) fluxes	Quantify the changes of soil organic matter due to changes in land use and cropland management. Quantify the changes of GHG fluxes due to changes in land use and cropland management	Siqueira-Neto et al. (2020)

Other Methods III			
Method	**Description**	**Adressed Issues**	**References**
SEI-PCS method SEI-PCS uses customs declarations and/or pershipment bills of landing to establish the dates of departure, volumes, ownership, exporting facility, port of export, and the country of import for specific shipments of soy. A logic-based decision tree is then used to map soy export flows back to a 'logistic hub'. Logistic hubs are supply chain nodes in a specific municipality where soy is produced, stored, handled, or transformed before export. The decision tree crosses the consolidated customs information with other independent data sets, including on the logistics and taxation of trading companies, as well as production and country-specific export permissions per facility, so that multiple lines of evidence are used to confirm a given subnational location as the origin of production of a given shipment.		Evaluation of the impact of Zero deforestation commitments	Zu Ermgassen et al. (2020)
GTAP-BIO (Global Trade Model) This model traces production, consumption, and trade of all goods and services at the global scale. Unlike the standard model, GTAP-BIO disaggregates oil crops, vegetable oils, and meals into several categories, including soybean, rapeseed, oil palm, other oil seeds, soy oil, rapeseed oil, palm oil, other oils and fats, soy meal, rapeseed meal, palm kernel meal, and other meals. In addition, GTAP-BIO represents production and consumption of biofuels and their by-products and traces land use across the world		Effects of demand-site restricitons on high-deforestation palm oil in Europe on deforestation in Indonesia	Busch et al. (2022); Richards et al. (2020); Zhu et al. (2022)
ERenEf (energy renewability efficiency indicator)	ERenEf measures the percentage of the (bio)fuel energy content (FEC) obtained from renewable sources by subtracting from FEC all the inputs of nonrenewable primary energy.	Implications of uncertainty in the life cycle (LC) energy efficiency and greenhouse gas (GHG) emissions of rapeseed oil (RO) as an energy carrier displacing fossil diesel (FD).	Malca et al. (2010)
Emergent Threat Analysis, a process integrating Emerging Hot Spot Analysis of deforestation, visual classification of deforestation outcomes over time, and spatial quantification of contemporary forest condition. Application of Emergent Threat Analysis to tropical Southeast Asia, a global epicentre of biodiversity threatened by deforestation.		How drivers of deforestation vary spatiotemporally, and where to focus limited conservation resources in protecting the most integral yet threatened forested landscapes.	Jamaludin et al. (2022)

6 Relevant journal articles from 2018 – 2022 (September)

The following Figure 6 contains a compilation of the scientific literature reviewed and evaluated for the study's questions. For the study period from 2018 to 2022, a total of 87 national and international scientific journals were identified and articles related to the topic were examined for relevance. As stated at the beginning of Section 3, not all articles found in the first steps could be used for further investigation. It can be seen that relevant articles and studies are published in a large number of different kind of journals.

Figure 6: Journals reviewed and selected studies

Sequence no.	Journals examined	Number of relevant articles	Quality of journals
1	Agriculture	11	peer-review (single-blind)
2	Applied Energy	1	peer-review (single blind)
3	Applied Geography	6	peer-review (double blind)
4	Biofpr - Biofuels Bioproducts & Biorefining	2	peer-review (single-blind)
5	Biofuels	2	peer-review (double-blind)
6	Biological Conservation	1	peer-review (double blind)
7	Biomass and Bioenergy	3	peer-review (single blind)
8	Bioresource Technology	1	peer-review (single blind)
9	Bulletin of Indonesian Economic Studies	1	peer-review (double-blind)
10	CATENA	1	peer-review (single blind)
11	Choices	2	peer-review
12	Clean Technologies and Environmental Policy	3	peer-review (single blind)
13	Conservation Letters	4	peer-review (single-blind)
14	Current Opinion in Environmental Sustainability	1	peer-review (double blind)
15	Earth´s Future	1	peer-review (single-blind)
16	Earth Syst. Sci. Data	1	peer-review (single blind)
17	Ecological Indicators	1	peer-review (single blind)
18	Ecology and Society	1	peer-review (double blind)
19	Ecosystem Services & Management	2	peer-review (single blind)

20	Energies	1	peer-review (single blind)
21	Energy & Environmental Science	1	peer-review (single blind with a double blind option)
22	Energy for Sustainable Development	2	peer-review (single blind)
23	Energy Policy	1	peer-review (single blind)
24	Energy Strategy Reviews	1	peer-review (single blind)
25	Environment Development and Sustainability	1	peer-review (double blind)
26	Environmental Impact Assessment Review	1	peer-review (double blind)
27	Environmental Progress & Sustainable Energy	1	peer-review (single blind)
28	Environmental Research Communications	1	peer-review (double blind)
29	Environmental Research Letters	53	peer-review (double blind)
30	Environmental Science & Policy	1	peer-review (single blind)
31	Environmental Science & Technology	4	peer-review (single-blind)
32	Environmental Science and Pollution Research	1	peer-review (single blind)
33	European Journal of Agronomy	1	peer-review (double blind)
34	European Journal of Soil Science	1	peer-review (single blind)
35	Forest Policy and Economics	2	peer-review (double blind)
36	Frontiers in Earth Science	2	peer-review (collaborative review)
37	GCB-Bioenergy	4	peer-review (single-blind)
38	Geo-spatial Information Science	1	peer-review (single-blind)
39	Global Change Biology	3	peer-review (single-blind)
40	Global Ecology and Conservations	1	peer-review (single blind)
41	Global environmental change	2	peer-review (double blind)
42	Integrated Environmental Assessment and Management	1	peer-review (single-blind)
43	International Journal of Agricultural Sustainability	1	peer-review (single-blind)
44	International Journal of Biodiversity Science, Ecosystem Services & Management	1	peer-review (double-blind)
45	International Journal of Global Warming	1	peer-review (double-blind)
46	International Journal of Life Cycle Assessment	1	peer-review (single blind)
47	Journal of Agricultural Economics	1	peer-review (double blind)
48	Journal of Arid Environments	1	peer-review (single blind)

49	Journal of Cleaner Production	14	peer-review (single blind)
50	Journal of Environmental Management	1	peer-review (single blind)
51	Journal of Industrial Ecology	1	peer-review (single blind)
52	Journal of Integrative Environmental Sciences	1	peer-review (double blind)
53	IEEE-Journal of Selected Topics in Apllied Earth Observations and Remote Sensing	1	peer-review (single blind)
54	Journal of Traffic and Transportation Engineering	1	peer-review (double-blind)
55	Land	3	peer-review (single blind)
56	Land Use Policy	10	peer-review (double blind)
57	Landscape Ecology	1	peer-review (single blind)
58	Marine Pollution Bulletin	1	peer-review (single blind)
59	Methods in Ecology and Evolution	1	peer-review (single blind)
60	Mitigation and Adaption Strategies for Global Change	3	peer-review (double blind)
61	Nature	2	peer-review (single blind with a double blind option)
62	Nature Climate Change	2	peer-review (single blind with a double blind option)
63	Nature communications	5	peer-review (single blind with a double blind option)
64	Nature Food	1	peer-review (single blind with a double blind option)
65	Nature plants	1	peer-review (single blind with a double blind option)
66	Nature Sustainability	3	peer-review (double-blind)
67	Nonlinear Processes in Geophysics	2	peer-review (open discussion)
68	Oilseeds and fats,Crops and Lipids	3	peer-review
69	Plant and Soil	1	peer-review (single blind)
70	PLoS One	9	peer-review (single blind)
71	PNAS	9	peer-review (single-blind for direct submissions)
72	Review of European, Comparative & International Environmental Law	3	peer-review (double blind)
73	Renewable and Sustainable Energy Reviews	5	peer-review (single blind)
74	Renewable Energy	3	peer-review (single blind)
75	Research Square	1	peer-review (single blind)
76	Ressources, Conservation and Reycling	1	peer-review (single blind)

77	Revista Brasileira de Cartografia	1	peer-review (double-blind)
78	Science	4	peer-review (single-blind)
79	Science of The Total Environment	6	peer-review (single blind)
80	Scientific reports	2	peer-review (single-blind)
81	Sustainability	3	peer-review (single blind)
82	Sustainability Science	2	peer-review (single blind)
83	Sustainable Production and Consumption	1	peer-review (single blind)
84	Terrestrial, Atmospheric and Oceanic sciences journal	1	peer-review (single-blind)
85	The International Journal of Life Cycle Assessment	5	peer-review (single blind)
86	Trade, Law and Development	1	peer-review (double-blind) optional
87	World Development	1	peer-review (double blind)
Total number of articles searched		**261**	
… thereof processed articles		**92**	
Miscellaneous sources (e.g. White Paper)			
	GTAP Research Memorandum No. 30	1	Reportl
	http://www.mightyearth.org/avoidablecrisis/	1	no Journal
	IUCN Oil	1	Report
	Malaysian Palm Oil Board	1	Report
	Roundtable on Sustainable Palm Oil	1	Report
	White Paper	2	Reportl
	Working Paper – ICCT	1	no Journal
	Biotechnology and Biofuels	1	Journal
	Journal of Land Use Change	2	Journal

7 Summary of project findings

Continuously monitoring the development of indirect land use changes (ILUC) is a task that is stipulated in Directive (EU) 2018/2001. The global expansion of food and feed crop production areas onto high carbon stock land is to be regularly recorded and monitored using relevant scientific information and studies. This study addresses this objective by examining and evaluating the relationship between biofuel use and its feedstocks soybeans, oil palm, and canola and indirect land use change (ILUC) in three steps based on the current scientific literature.

The main focus of the study is firstly, the content assessment of the results of scientific studies on the topic of land use change that have been published in qualified scientific journals. Secondly, an economic evaluation of the possible trigger effects for an indirect land use change is carried out in the context of a monitoring, in continuation of the calculation model developed by the EU Commission. Thirdly, the validity of the different methodological approaches used to measure land use change will be evaluated in order to provide a valid assessment of land use change and the possible cause-effect relationships between biofuel policies and (indirect) land use change.

The basis of the study was laid by an extensive review of qualified scientific publications (so-called peer-reviewed journals) for the period 2018 - 2022. Out of a total of 261 identified studies from 87 journals, 92 studies on the topic complex were ultimately evaluated.

Although the study results included in the analysis are difficult to compare with each other with regard to their respective study objectives, the study periods, the methods used to record land use changes, as well as the respective geographical reference areas (countries, vegetation regions, federal states), comparable results can nevertheless be highlighted.

The first part of the project on current indirect land use effects shows for oilseeds, soybean and palm, which are particularly in focus, a continuing expansion of cultivated areas in sensitive areas in all studies. For example, soybean production in Brazil has now grown to about 38% of the Brazilian cultivated area. Although most of the soy production there is on existing agricultural land, significant expansion of cropland continues to take place in the sensitive regions of the Amazon and Cerrado. Both pasture and cultivated areas for soybeans have been steadily expanding, due to both direct and indirect land use changes from previous forest and other used land.

For palm oil production, a similar trend can be seen in the studies. This is especially true for Malaysia and Indonesia, which dominate the market with about 84% of the global palm oil supply. However, not only these two countries, but the entire Southeast Asian region has experienced a boom in the expansion of palm oil production over the last two decades. With the consequence, a significant decline in tropical forest areas.

In another point the study results coincide. Currently, a shift of land use changes to other regions is observed. While deforestation rates in the Amazon region have been reduced over the last decade due to stricter environmental policies, increased land use changes can be observed in the neighboring Cerrado region. Most notably, the Matopiba region (comprising the states of Maranhão, Tocantins, Piauí, and Bahia) is now the Brazilian region where soybean cultivation is rapidly expanding and altering much of the original Cerrado vegetation.

Comparable conditions also apply to palm oil production. For the island of Borneo, for example, it can be observed that protected areas there in particular have been increasingly developed for palm oil production, and already deforested areas have been converted into industrial oil palm plantations. There are still large expansions of new plantations in various regions of Southeast Asia. However, in isolated cases, it can also be observed that the average annual growth rates are declining. Should demand for palm oil continue to increase, expansion rates in established regions will decline due to increasingly limited land availability, with future expansions then shifting to the borderlands of Papua, Papua New Guinea, and Thailand.

The studies disagree in their assessment of the cause-effect relationships between the biofuel production policies of the consuming countries and the trigger effects on indirect land use changes. Thus, additional trigger effects are also discussed for both South America (soy) and the Southeast Asian region (palm). The stock of primary forests in Asia is threatened in many ways by population growth, the accompanying urbanization of rural regions, and the conversion of land to agricultural plantations, such as palm oil production and other land uses (rubber). The causes of land use change are generally not independent of each other. For example, deforestation almost always precedes the establishment of oil palm plantations. If several years then elapse between timber harvesting and the establishment of new oil palm plantations, it is difficult to prove a direct link to land use change. The same applies to soybean cultivation in South America, where the direct cause of deforestation is primarily the expansion of pastureland.

The impact of policy interventions to curb deforestation is assessed differently in the studies. For example, although the soy moratorium introduced in 2008 and 2014 in Brazil's Cerrado region and a 2011 palm oil moratorium in Indonesia have reduced soy cultivation and oil palm cultivation, respectively, in the regions in question. However, deforestation rates have increased significantly in areas that were not protected by the moratorium. Overall, moratoria, as they are currently designed, are not considered to be a perfect control instrument; however, it is assumed that they and other initiatives send important signals against the deforestation trend.

The fact remains, however, that deforestation for the benefit of palm oil production and soybean cultivation (although not directly in this case) continues to take place on a considerable scale.

These developments are also supported by another study result: the application of the formula developed by the EU Commission to calculate the share of expansion on areas with high carbon stock. Areas with high carbon stock are forests, but especially peatlands, which are drained. Besides Indonesia, an increase in palm oil plantations on peatland is also observed in other countries, such as Thailand. In the relevant studies, the main reason for the expansion of areas is the state subsidy for biodiesel production. Thus, the planting of oil palms has mainly displaced rice cultivation, natural forests, wetlands and peatland. Updating the calculations on the basis of the EU Commission's formula shows that it is necessary to speak of significant expansions, since the proportion of expansion on land with a high carbon stock is higher than the envisaged limit.

The evaluation of the methodological approaches used in the numerous studies for the analysis of indirect land use effects indicates a large scope for interpretation. Numerous scientific studies on indirect land use effects and GHG accounting of oilseed production use econometric-based impact analysis models. The use of these models has increased in recent years. At the same time, however, there has been increased criticism of the modeling and the assumed relationships. For example, the model calculations arrive at different results for the same questions. Due to the underlying causal relationships between the cause-effect relationships and the data used, the results of the model calculations vary considerably. Even in the case of comparable facts behind the questions, there are large differences in the results, which lead to uncertainties in the assessment.

In addition to econometric model concepts, so-called geo-information systems have been increasingly used in recent years to identify land use changes. In principle, this is a regional approach to calculating ILUC. This is based on small-scale observations with satellite records. The land use changes observed over time are then calculated. Ultimately, a relationship is established between changes in biofuel consumption "in the world" and land use changes in the respective cultivation regions. With the help of this type of balance calculation, an attempt is made to map greenhouse gas emissions caused by indirect land use changes as a regional as well as a global system. But here, too, it is difficult to prove the level or significance of the ILUC effect.

In summary, it is clear that palm oil production but also soybean production for the extraction of biodiesel are accompanied by land use changes and associated increased GHG emissions. Rapeseed cultivation, on the other hand, has not been the subject of studies in the relevant scientific journals with regard to indirect land use changes. The studies focus mainly on life cycle assessments (LCA) and evaluation of the consequences of canola cultivation for GHG balances. Scientific contributions on a direct link between canola production and indirect land use changes could only be identified for one case study. Studies in the relevant scientific literature on the ecosystem services of canola cultivation could also not be identified. Currently, as a digression in the study shows, such scientific evidence is being worked on, where the main focus is on a re-evaluation of LCA and system boundaries in the assessment of rapeseed cultivation. To date, they have not been published.

The scientific studies analyzed in terms of content in the present study have been chronologically arranged, systematically recorded and evaluated in a literature database. This form of documentation ensures a constant updating and continuation of the scientific study situation and, as a supporting database, forms the core of the monitoring concept of the study.

EXCURSUS on rapeseed GHG emissions and life cycle analysis

The vast majority of scientific papers identified for this study examine direct and indirect land use changes triggered by increased biodiesel production. As could be shown, indirect land use changes are almost exclusively associated with soybean cultivation and palm oil production. The cultivation of rapeseed for biodiesel production is justifiably not brought into the context of possible indirect land use changes in the scientific debate. The impacts of canola production, on the other hand, tend to be addressed in relation to GHG emissions and life cycle analysis (LCA).

Although this topic area is not part of the actual study area, the main findings from the current literature are discussed here as part of an excursus. In this way, the fourth set of questions from the original objective is taken up in a modified form. As has become apparent in the course of the study, this field of investigation in connection with land use changes is not a central object of consideration in the relevant scientific literature, but is considered here as an important side aspect.

The methodological approach to determine the contribution of rapeseed oil production to ecosystem services is mainly based on the preparation of so-called life cycle analyses (LCA). These attempt to capture the GHG emissions of canola production throughout its entire production and utilization chain. In principle, the methodology is a tried and tested procedure. However, meaningful and robust calculations fail both at national and international level due to the availability of suitable data for such life cycle analyses. There is still considerable potential for improvement here, as the demand for such analyses is seen as an important building block of European agricultural and climate policy with regard to the sustainable use of resources.

In their model calculations, the available studies attempt to capture the GHG emissions over the entire life cycle of canola production (from seed to farm gate assessment - LCA) in a cause-related and methodologically sound manner. For each study, the LCA models are based on a case-specific agricultural production practice that is intended to be representative of the regions studied and the time periods considered. The study by Fridrihsone et al. (2020) illustrates such an approach using Latvia as an example. In the (case) study, the life cycle assessment of winter and spring rapeseed cultivation and rapeseed oil production is presented for a period from 2008-2016. Using life cycle analysis (LCA) and a specified holistic approach, the environmental sustainability and overall impacts, bottlenecks and benefits of using bio-based feedstocks from rapeseed production are assessed. The LCA is performed according to ISO standards and frameworks (see ISO 14044). The LCA software SimaPro 9.0 from Pré Consultants and the ecoinvent v3.5 database are used to build the LCA model and perform the impact assessment calculations. The cumulative energy demand (CED) of a product or process represents the direct and indirect energy consumption in MJ throughout its life cycle (see Huijbregts et al., 2006). CED takes into account primary energy consumption - both from renewable and non-renewable energy - and energy flows destined for energy as well as material purposes, as well as energy consumption triggered by transport operations (cf. Arvidsson et al., 2015). Energy consumption indicators are considered good proxy indicators for environmental impacts in general (see Huijbregts et al., 2010).

The mentioned study by Fridrihsone et al. (2020) designs an LCA for a canola oil produced by cold pressing. The LCA was calculated using the ReCiPe impact assessment method version 1.03, a hierarchical recovery perspective, together with the cumulative energy demand method v1.11. In the ReCiPe method[1] ("Recipe for Calculating Life Cycle Category Indicators" as a so-called damage-based approach), environmental impacts are aggregated into three types of damage: human health, ecosystem quality, and resources. The aggregated environmental impacts are expressed as a ReCiPe score (point system). This principle ensures that the results are easier for decision makers to understand and interpret (see Brinkman et al., 2018).

The study concludes that growing winter oilseed rape has lower environmental impacts than growing summer oilseed rape due to higher agricultural inputs and higher yields. Mineral fertilizers (production and application) and agricultural machinery are responsible for the largest environmental impacts. The results for the processing stage of rapeseed oil show that the choice of allocation method has a significant impact on the results of the environmental balance.

The comparison of cumulative energy demand (KEB) results shows that summer canola cultivation requires 36% more energy than winter canola cultivation, which is due to the lower yield of summer canola and the higher production input. Mineral fertilizer is the agricultural input with the highest environmental impact for both canola varieties. Another significant input is the use of agricultural machinery for various field operations. In contrast, transportation and crop protection have minimal impacts, accounting for less than 15%. Seed for sowing has a negligible impact in all impact categories except water use, which is less than 4%. The research results make it clear that oil crop yield is a critical factor in the environmental analysis, as impacts decrease with higher yields. Growing winter canola has advantages over growing summer canola.

In addition to the above statements, the following connection to the GHG reduction potential of rapeseed production should also be pointed out. For the evaluation of the GHG reduction potential of rapeseed oil fuel and biodiesel as an alternative energy source, strict specifications with narrow system limits apply with the GHG inventory and RED II. For pure canola oil, RED II specifies a default value of 40 g CO2-eq. MJ-1, which takes into account the process steps of canola production, transportation, and oil extraction. Here, too, the combustion of the biofuel is included in the GHG balance with zero emissions. However, the fact that, in addition to rapeseed oil, the oil extraction process also produces a high-quality protein animal feed in the form of rapeseed press cake is not taken into account. For Germany, the TFZ-Bayern has currently carried out case calculations on a regional level (cf. Dressler,

[1] The acronym is composed of the initials of the institutes that have significantly developed the method: RIVM and Radboud University, CML and PRé Consultants.

2020). For this, two variants were taken as a basis and the corresponding alternative calculations were made (for details, please refer to the article). In the first variant, an energy allocation by calorific value is made according to the requirements of RED II. The division (allocation) of emissions between rapeseed oil and rapeseed press cake is carried out according to the calculation rules of RED II via the calorific value of the two products. This means that the press cake is not evaluated as animal feed. In the second variant, the calculations of the GHG value of the co-products are carried out without allocation. This extended the narrow system boundaries of the RED II specifications and evaluated the substitution potential and possible credits of co-production. A life-cycle-based GHG balance with expansion of the system boundaries was used as a basis, i.e., both canola cultivation, transport of the produced canola to the oil mill, processing, and use of the canola oil fuel and canola press cake as animal feed were calculated. In the life-cycle-based GHG balance with system space expansion, a GHG credit for the substituted reference system is given for the use of the canola press cake as protein feed. As is well known, canola press cake can replace soybean meal as protein feed in dairy farming.

Different calculations have been made depending on which scenario is used, for example whether it is assumed that the expansion of land for soybean cultivation in South America is directly related to the clearing of rainforest as well as the conversion of scrubland to cropland, or whether a GHG credit for substituted soybean meal is shown both with and without land use changes in South America in the case of system space expansion.

Excluding land use changes, the LCA results with system space expansion and substitution differ only slightly from those calculated with energy allocation. The energy allocation with distributed generation results in a GHG reduction of 64.5%. The calculation results for a system space expansion with the same data basis result in a GHG reduction of 59% compared to the fossil reference. The default value of RED II indicates a GHG reduction of 57 %.

If land use changes are included, the result is different. Due to the very high impact of proportional land use changes in soybean cultivation, rapeseed production and its coupled use as fuel and as protein feed can lead to a GHG reduction of 120%.

Another aspect that cannot be mapped with the energy allocation is the positive effect of rapeseed production on the subsequent crop. Thus, reference is made to the paper by Pahlmann et al. (2013), who show how mineral fertilizer can be saved in subsequent wheat cultivation and how these effects can be credited to rapeseed production through system space expansion. The credit is according to 7.3 g CO2-eq. MJ-1 and increases the GHG mitigation potential of canola production and use to 127% (cf. Dressler, 2020). Machholdt et al. (2020) also point to greater yield stability, better utilization of mineral fertilizer and thus positive environmental impact, and a tendency toward higher yields in crop rotations with rapeseed as the preceding crop compared to rotations with a high proportion of cereals.

Dressler points out another aspect in her paper: The system boundaries of the country- and sector-specific GHG inventory are the narrowest and those of the life-cycle assessment (LCA) the broadest. However, country- and sector-specific boundaries can lead to shifting effects (carbon leakage) without considering the polluter-pays principle. This is particularly illustrated by the accounting of GHG emissions to provide protein feed from rapeseed compared to soybean meal from overseas. While a life-cycle based GHG balance of soybean meal from overseas with consideration of land use change shows GHG emissions amounting to 13.5 kg CO2 equivalents, these emissions are completely disregarded in the GHG inventory of the agriculture sector in Germany due to country-specific system boundaries. In contrast, GHG emissions from domestic feedstuffs such as rapeseed press cake and rapeseed extraction meal are very much accounted for in the GHG inventory. Consequently, the 100% import of feed could lead to an improvement of the GHG inventory in Germany, while in South America the cultivation of soybeans and thus the conversion of rainforest and scrubland into arable land continues to increase.

In Dressler's view, the system boundaries for evaluating climate protection measures would have to be reviewed and adjusted. She advocates evaluating measures and support instruments for climate protection and the expansion of renewable energies with a life-cycle-based approach. This is because under the current scheme, there would still be a risk of shifting GHG emissions to other systems. Therefore, canola production and use should be evaluated using the holistic life-cycle-based approach for government climate change mitigation measures and support instruments. With current specified system boundaries, the GHG mitigation potential of biofuels would be underestimated.

In her article, the author also points out that there is not yet a uniform approach for dealing with crop rotation effects in greenhouse gas balances and other environmental assessments. At the same time, she mentions that the definition and testing of methodological aspects is currently the subject of many investigations and research projects.

Figure 7: Research articles on LCA and GHG analyses

Oilseeds – LCA – GHG I				
Region	**Main focus**	**Method**	**Results**	**Study**
Central Germany (CG; Saxony, Saxony-Anhalt, Thuringia)	Life cycle analyses (LCA) for rapeseed to evaluate the environemental impact and the economic benefits of biodiesel production. What is the optimized operating capacity of each biodiesel plant in terms of the minimum environmental impact and maximum economic benefit and which plant is most effi cient in CG?	Optimization of the biodiesel plant production capacity by employing the generalized reduced gradient non-linear optimization method. The approach is aimed to maximize the economic benefits while minimizing the environmental burdens.	Emissions from the rapeseed cultivation process comprised the largest proportion of total emissions across the studied environmental impact categories, ranging from 48.22% to 91.94%. The optimized operating capacities of the biodiesel plants in CG generally ranged from 51.31% to 53.15%. This finding indicates a gap between the regional rapeseed supply and the rapeseed demand of all the biodiesel plants in CG. If the biodiesel plants in CG ran at their full capacities, severe ILUC might occur because the supply gap must be filled by importing rapeseed from other regions. In general, the observed performance of each plant also suggests that there was a strong economies of scale effect in the biodiesel production industry. None of the studied plants in CG could run at their installed capacity without negatively impacting the environment. The high-protein press cake used as a soybean replacement in livestock feed has been mentioned. But, its value (or likely positive effects on ILUC) have not been subject of their analysis.	Yang et al. (2021)
Global scale	Estimation of carbon and biodiversity footprints, per unit of oil produced, of the world's five major vegetable oil crops.	Global maps of harvested areas and yields for the year 2010, the most recent available spatial data; global maps of harvested areas and yields for oil palm, soybean, rapeseed, sunflower and groundnut. 5 arc-minute (~10 km at the equator)	Oil palm has the lowest carbon loss and species richness loss per-tonne-oil, but has a larger impact on range-restricted species than sunflower and rapeseed. Global areas for oil crop expansion that will minimise future carbon and biodiversity impacts are identified. Closing current yield gaps and optimising the location of future growing areas will be much more effective at reducing future environmental impacts of global vegetable oil production than substituting any one crop for anothers.	Beyer et al. (2020), „Preprint“

Oilseeds – LCA – GHG II				
Region	**Main focus**	**Method**	**Results**	**Study**
Malaysia & Indonesia	The main objective of this study is to evaluate the life-cycle GHG emissions and energy balance of renewable diesel (RD) production from PFAD (Palm Fatty Acid Distillate); Few remarks to substitution effects of soy and rapeseed oil.	Review of Literature	Total life-cycle fossil energy consumption for petroleum diesel is about 1.2 MJ per MJ fuel consumed. In contrast, overall fossil energy consumption by the PFAD to RD pathway is much lower than that of petroleum diesel, ranging from 0.14 MJ (PFAD as a residue) to 0,27 MJ (PFAD as a co-product) per MJ RD produced. This means RD produced from PFAD could potentially reduce GHG emissions by 66.9–85.4%, relative to petroleum diesel, as simulated in the models. ILUC: The results suggest that, with high ILUC emissions counted, neither refined palm oil (RPO)- nor PFAD-derived RD would deliver carbon emission reductions, relative to conventional petroleum diesel.	Xu et al. (2020)
Global scale	The focus of this article is on the potential land use change impacts associated with the oilseed-based biodiesel consumption. Main crops used for biodiesel production are oilseed rape (OSR), soybeans and oil palm. The objective of is to provide a technical assessment of potential land use change arising from the growth of these three major crops at global level.	The assessment is based on: (1) a literature review of land use change (e.g. dynamics of cropland, pasturelands, forestlands and wetlands), emissions associated with Agriculture, Forest and Other Land Use (AFOLU), oil crop productivity, and the production of vegetable oils; and (2) estimates using historical data (e.g. oil production, land area and crop yields) from FAO, USDA and EUROSAT databases. Based on a broad country-level analysis for the major producing countries.	Soybean area has approximately the carbon stock for average cropland. The expansion occurred over areas with an average carbon stock similar to tropical forestland. The soy expansion over native vegetation has emitted about 88 Mt CO_2 eq per year, including changes in soil carbon. We calculate the global average greenhouse gas emissions intensities based on the ILUC-risks as 56 g CO_2 eq/MJ for soy oil and 108 g CO_2 eq/MJ for palm oil. For rapeseed oil all the assessed countries presented net afforestation/reforestation in the past decade, apart from Canada, which presented a small net deforestation area. There is no apparent correlation between the recent expansion of oilseed rape and forest dynamics. The study does not find evidence for high ILUC-risk expansion of oilseed rape.	Strapasson et al. (2019)

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