Decomposing biofuel feedstock crops and estimating their ILUC effects

Task 1-3 of tender ENER/C1/2013-412

- Confidential –

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A cooperation of Ecofys, IIASA, Agra CEAS and E4tech

Table of contents

1 Introduction

1.1 Aim and relevance of the study

Ecofys, IIASA, E4tech and Agra CEAS Consulting have been commissioned to perform study ENER/C1/2013-412 by the European Commission to estimate the indirect land use change (ILUC) impact of feedstock components as an alternative approach to the feedstock-specific evaluation conducted so far, with a conceptual part and several case-studies.

Indirect land use change associated with bioenergy production has been assessed so far by type of crop feedstock, such as wheat, maize, sugar beet, sugar cane for ethanol, or rapeseed, soybean, sunflower, palm fruit for biodiesel (see IFPRI and GLOBIOM studies). However, these different materials are not consumed entirely for the production of bioenergy, only a part of their components is converted to biofuel. Other components are fed back to the market as coproducts and consumed for different purposes.

The aim of the study is to develop an evaluation tool which can be used to estimate ILUC values for biofuel feedstocks and feedstock components with a 2020 perspective and to obtain insights in the ILUC impact of feedstocks that are (1) currently not included in state-of-the-art ILUC modelling studies or (2) have only indirect links to the food and feed markets.

The study has the following tasks:

- Task 1: Identify and describe categories of components
- Task 2: Decompose crops used as biofuel feedstocks into component categories
- Task 3: Calculate, based on existing ILUC value estimates for biofuel feedstocks, ILUC emission values for the component categories (including the development of an ILUC evaluation tool)
- Task 4: Carry out two case studies
    - Task 4a estimates ILUC emissions from using animal fats as biofuel feedstock
    - Task 4b estimates ILUC emissions from using grass/hay as biofuel feedstock

This report provides the outcomes of task 1-3. Task 1, led by CEAS, describes feedstock component categories, their specifications and their quality, whereas the actual decomposition takes place in Task 2, which was also led by CEAS. Within each component there are certain characteristics, e.g. amount of protein or fatty acids, which will be described. Task 3, led by IIASA, assesses the LUC impact of crop component categories using two different approaches. The two case studies are very much separate studies and therefore presented as separate study reports.

Within this study the following definitions have been used:

- **Primary feedstocks**: crops produced on land for the purpose of biofuel production, e.g. wheat, rapeseed, soy, sunflower.

- **Biofuel feedstocks**: the biofuel component included in primary feedstocks, e.g. rapeseed oil is a component and a biofuel feedstock
- **Biofuel co-products**: the counterpart of the biofuel feedstock, i.e. the remaining share of the crop which is not used for biofuel production, e.g. DDGS, rape or soy meal.
- **Component**: an elementary material contained in feedstocks, e.g. rapeseed oil.
- **Component category**: category which classifies the different feedstock components, e.g. vegetable oil, starch or sugars.

1.2 Crops and feedstocks included in our assessment

The table below shows which crops are assessed in this report. Most crops are decomposed with the exception of animal fats, used cooking oil and crude tall oil because these are used in their entirety as biofuel feedstock or for other purposes[1].

Table 1: Selected crops and other biofuel feedstocks to be assessed in this study report

Feedstock	Described in Task 1+2	Decomposed in Task 1+2	LUC quantification in Task 3
Wheat	√	√	√
Maize	√	√	√
Sugar beet	√	√	√
Sugar cane	√	√	
Rapeseed	√	√	√
Palm Fresh Fruit Bunch	√	√	
Soybean	√	√	√
Sunflower	√	√	√
Short rotation plantation wood	√	√	
Wheat/cereal straw	√	√	
Grass/hay	√	√	
Animal fats	√		
Used Cooking Oil	√		
Crude Tall Oil	√		

[1] Where data is available this is also provided (notably water content of oils, as well as minimal protein and fibre content of animal fats).

2 Task 1. Feedstock component categories

Description of disaggregated component categories

2.1.1 Main biomass crop components

The main component categories of biomass materials are macro-nutrients (so-called because in food and animal feeding terms, they are energy providing chemical substances which are needed in relatively large quantities). These include:

- Protein – containing amino acids
- Fats – containing natural esters of glycerol and various fatty acids; and
- Carbohydrates – molecules of carbon, hydrogen and oxygen in various forms, including:
    - sugars;
    - starch; and
    - cellulose (one of the components of fibre).
- Fibre - technically a type of carbohydrate, but is classed separately because its structural properties make it hard to break-down to release energy (sugars) contained within, including:
    - cellulose;
    - hemicellulose;
    - pectin; and
    - lignin.

Other component categories include **micro-nutrients**, i.e. minerals and vitamins, so-called because in nutritional terms they are non-energy providing chemical substances which are only needed in relatively small quantities; and **water**, which is generally present in varying concentrations throughout all living organic structures (e.g. stems, leaves, seeds, etc.).

In this assessment, the feedstock component disaggregation focusses on the macro-nutrients, with the three main types of carbohydrate treated separately to make a total of five component categories:

- Protein
- Fats
- Sugars (carbohydrate)
- Starch (carbohydrate)
- Fibre (carbohydrate[2])

[2] See chapter 2.1.7. for details of how the carbohydrate (sugars and starch) contained within fibre are assessed.

The following chapters outline how these components are measured and present the feedstock component disaggregation analysis results.

2.1.2 Measurements and methodology

The feedstock component category data are based on the results of proximate analysis in laboratories. Proximate analysis is a partitioning of compounds in a feedstock into six categories (water, ash, crude protein, crude fat, crude fibre and nitrogen-free extracts (digestible carbohydrates) based on the chemical properties of the compounds.[3] In addition, other component specific analysis methods are used to refine the results, e.g. sequential detergent analysis for fibre and specific methods based on ethanol extraction for sugars and starch.

Many of the laboratory methods have been developed for livestock feed material analysis purposes, but also for human food and increasingly other bio-industries. Nevertheless, regardless of the origins of the laboratory methods described, the component category values are relevant for all bio-based industries including inter alia biofuels, biochemicals and other emerging biotechnologies.

There are established methods for undertaking this analysis which are specified by standard setting organisations such as the International Organization for Standardization (ISO) and Association Française de Normalisation (AFNOR); as well as methods specified by other institutions such as the European Commission (EC) and the Association Of Analytical Communities (AOAC).

The methods outlined in the following chapter are all used as part of the full component decomposition; however we have highlighted where a single method is sufficient to describe an individual component as summarised in the results tables presented in this report. The methods are summarised as follows:

- **Protein** - as measured by crude protein (see section 2.1.3);
- **Fats** - as measured by ether extract (see section 2.1.4);
- **Sugars** - as measured by ethanol extraction (see section 2.1.5).
- **Starch** - as measured by ethanol extraction (see section 2.1.6);
- **Fibre** - as measured by sequential Neutral Detergent Fibre (NDF), Acid Detergent Fibre (ADF) and Acid Detergent Lignin (ADL) analysis to disaggregate cellulose, hemicellulose and lignin fractions (see section2.1.7).

It is important to note, however, that the proximate and sequential analysis is not a nutrient analysis - it is a categorisation of components based upon common chemical properties. As such, there is inevitably an element of double counting or under-reporting of components depending upon the accuracy of laboratory testing methods for individual component categories since some components

[3] Proximate analysis is an attempt to duplicate animal digestion. After extracting the fat, the sample is subjected to an acid digestion, simulating the acid present in the stomach, followed by an alkaline digestion, simulating the alkaline environment in the small intestine. The crude fibre remaining after digestion is the portion of the sample assumed not digestible by monogastric animals (e.g. pigs). In the proximate analysis of feedstuffs, crude protein, ether extract, crude fibre and ash are determined chemically.

cannot be measured exactly and may be present within more than one component category (notably in the case of fibre) (see section on Double Counting).

2.1.2.1 Sample size

The number of samples for each feedstock tested is presented in the table below.

Table 2: Feedstock sample size (n=) for component composition analysis

Feedstock	Sample size (n=)	Feedstock	Sample size (n=)
Wheat	7,068	Soybeans	1,162
Maize	2,634	Sunflower seed	182
Sugar beet	131	Short Rotation Plantation Wood	n/a
Sugar cane	440	Cereal straw	236
Rapeseed	959	Grass/hay	79
Palm fruit bunch	n/a	Animal fats	n/a

Source: Agra CEAS Consulting

2.1.2.2 Accounting for water

Biomass feedstock materials contain water in varying quantities. However, since the other measurable components of feedstock are contained in the dry matter portion, i.e. the residual matter measured after desiccation, composition of feedstock is commonly expressed either as a percentage or quantity per unit of weight on the basis of:

- dry matter - assumes no water is present; or
- as-fed - includes water.

The as-fed basis is selected because it represents the feedstock in its natural state rather than following processing/drying to remove water. This is consistent with reporting of feedstock commodity supply and demand quantities as well as price data. Nevertheless, when the water component is known, it is a simple calculation to convert the data from 'as-fed' to 'dry matter (DM) basis and *vice versa* using the following equations:

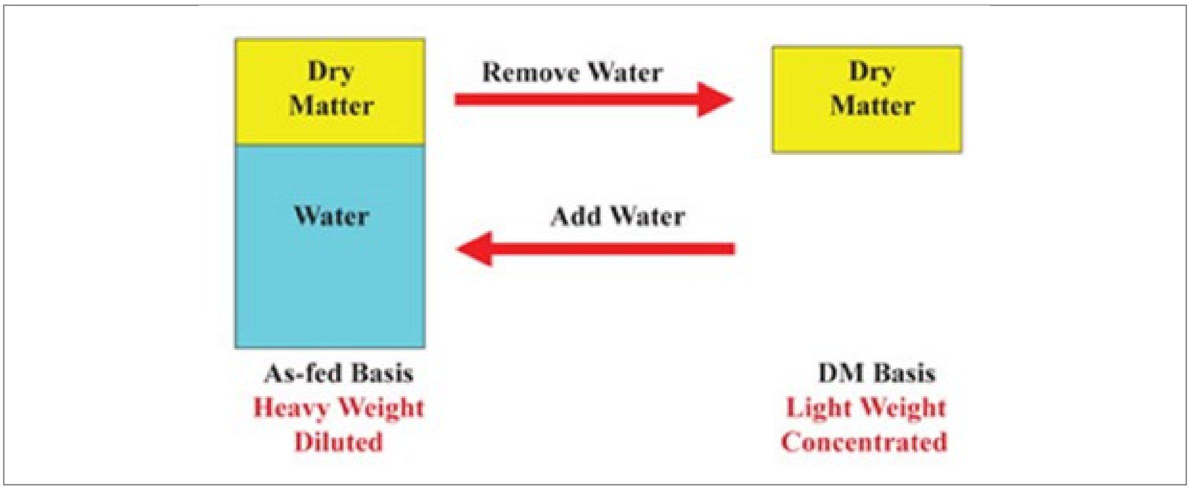

Figure 1: Dry Matter Conversions (Source: Reiling (2011)[4])

Convert from as fed to dry matter basis:

$$\frac{\%\ \text{component as-fed basis}}{\%\ \text{feedstock DM}} \times 100$$

E.g. wheat has a dry matter content of 86.8% and contains 10.5% protein on an as-fed basis:

(10.5 ÷ 86.8) x 100 = 12.10% protein on a DM basis

Convert from dry matter to as fed to basis:

E.g. wheat has a dry matter content of 86.8% and contains 12.10% protein on a DM basis:

12.10 x (86.8 ÷ 100) = 10.5% protein on an as fed basis

2.1.2.3 Double or under-counting

As indicated above, the analysis is designed to categorise components into groups based upon common chemical properties, i.e. protein, fats, fibre, starch and sugars. As such, there may be an element of double counting or under-reporting of components within categories and therefore the component category shares presented in nutritional decomposition tables do not add up to 100%.

This is because some components are present in more than one category, notably within fibre[5] which is very difficult to decompose; and because of limitations of the laboratory analysis techniques described. The laboratory analysis techniques used cannot always isolate each component and rely

[4] Reiling, B. (2011). *Feed Dry Matter Conversions*. Institute of Agriculture and Natural Resources. University of Nebraska–Lincoln, USA.

[5] Fibre contains cellulose, which is a form of carbohydrate (a saccharide). There are 3 main forms of carbohydrate present in biomass feedstock; the other two are sugars and starch. Cellulose is thus a constituent of both the carbohydrate and fibre components of feedstock (see fibre in section 2.1.7 below).

instead on destroying one component (or group of components) in order to measure the decrease in mass to derive values for components. For example, techniques have evolved to separate the starch and sugars from the feedstock and convert it into ethanol and these component shares are well understood. Nevertheless, sugars and starch are also present in ligno-cellulosic fibre, which require different separation processes. Laboratory techniques have now been developed to sequentially destroy groups of components within fibre in order to release the sugars and convert them to ethanol, but in the process there are efficiency losses and thus the techniques can only provide an estimate of component shares (albeit the most accurate currently available).

The data presented represents the best available data regarding the categorisation of components from individual feedstocks. There is therefore no specific method to deal with any crossover of components between categories, e.g. the presence of protein, starch or sugars within fibre. This is also the case in industrial processes, e.g. the conversion of sugars or starch to ethanol, which are not themselves 100% efficient as both sugars and starch are also present in the co-product residues.

Therefore it is implicit that there may be some double counting or under-reporting of component categories within feedstocks, but this is because of the nature of the categories themselves, i.e. groups of components with similar properties as opposed to separate individual chemicals.

2.1.3 Protein

Protein is needed for tissue growth in plants and animals and is thus one of the main structural materials of living organisms and also form the enzymes required for chemical reactions. A key element contained in protein is nitrogen. Each protein molecule is composed of amino acids. In animals (including humans) protein must be consumed in the diet because animals have no storage provision for either protein or amino acids.

There are two main approaches to analyse protein and individual amino acids content:

- **Crude protein** – estimated by multiplying total nitrogen by 6.25 (i.e. it is based on the assumption that the protein in typical animal feeds contain an average 16% nitrogen). Nitrogen content is determined by mineralisation techniques, e.g. Kjeldahl method (AFNOR NF V18-100, 1977) or Dumas method (AFNOR NF V18-120, 1997).
- **Amino acids** – methods based on hydrochloric acid (HCl 6N) hydrolysis followed by chromatography. Different approaches are used for some amino acids, e.g. methionine and cysteine are obtained by performic acid (CH_2O_3) oxidation; tryptophan by alkaline hydrolysis.

<u>The data presented are from protein analysed using the crude protein method</u>, since an estimate of crude protein content is the starting point for all protein evaluation systems which assess the digestive and metabolic use of protein. Protein is the main nitrogen-containing component of plant food and therefore measuring nitrogen is used to estimate the crude protein content. It is only an estimate, since in reality nitrogen is also present in other compounds such as amides (particularly in root crops). The crude protein value is based on the assumption that all food protein contains 16% nitrogen, i.e.:

$$\%CP = \%N \times (100/16) \text{ or } \%CP = \%N \times 6.25$$

Data for specific amino acids content of protein for each feedstock (where available) is provided in the supporting spreadsheet. Data is provided on a g/kg feedstock (as fed) basis and as a share of crude protein (%) where data was available.

Table 3: Composition of biofuel feedstocks – protein (average[1], % as fed)

Feedstock	Protein	Feedstock	Protein
Conventional feedstocks		**Advanced cellulosic feedstocks**	
Wheat	10.5	Short rotation plantation wood	5.0
Maize	8.1	*- Alder*	*5.9*
Sugar beet	1.5	*- Ash*	*4.8*
Sugar cane	0.9	*- Birch*	*4.5*
Rapeseed	19.1	*- Poplar*	*6.1*
Palm fresh fruit bunch [e]	3.5	*- Willow*	*3.7*
Soybeans	34.8	Cereal (wheat) straw	3.8
Sunflower seed	16.0	Grass (meadow) hay	15.0
		Other advanced feedstocks	
		Crude Tall Oil	n/a
		Animal fats	0.35
		Used Cooking Oil	n/a

Note: [1] Average based on number of samples tested (see Table 2); [e] estimate based on derived co-product data (see section 2.2); n/a = data not available.

Source: Agra CEAS Consulting.

2.1.4 Fats

Fats serve a similar function to carbohydrates, i.e. serving both a metabolic[6] role as an energy source as well as a structural role as an energy store. Fats are often categorised according to their physical properties at room temperature, i.e. oils are liquid at room temperature whereas fat is solid. However, there is some ambiguity in this terminology and so often the general term lipid is used. Fats are esters of organic acids formed with the alcohol glycerol, i.e. composed of fatty acids (which is a key determinant of the quality and suitability of fats for different uses).

There are two main approaches to analyse fat and individual fatty acids content:

- **Crude fat / ether extract** – extraction of lipid (fat) substances by a solvent such as diethyl ether (hence the term *ether extract*) (AFNOR NF V18-117 (1997)). Hydrochloric acid (HCl) hydrolysis before extraction is sometimes also used.

[6] Metabolism encompasses the whole range of biochemical processes that occur within any living organism.

- **Fatty acids** – analysis methods are based on the use of chloroform/methanol, methylation and extraction of methyl esters followed by chromatography. A fatty acids to crude fat conversion co-efficient is then typically used to compare feedstocks.

The data presented are from fats analysed using the crude fat / ether extract method. Data for specific fatty acids content of fats for each feedstock is provided in the supporting spreadsheet.

Table 4: Composition of biofuel feedstocks – fats (average[1], % as fed)

Feedstock	Fats	Feedstock	Fats
Conventional feedstocks		**Advanced cellulosic feedstocks**	
Wheat	1.5	Short rotation plantation wood	1.0
Maize	3.7	*- Alder*	*1.1*
Sugar beet	0.1	*- Ash*	*0.9*
Sugar cane	0.4	*- Birch*	*1.2*
Rapeseed	42.0	*- Poplar*	*0.9*
Palm fresh fruit bunch [e]	37.7	*- Willow*	*0.8*
Soybeans	17.9	Cereal (wheat) straw	1.3
Sunflower seed	44.6	Grass (meadow) hay	3.1
		Other advanced feedstocks	
		Crude Tall Oil	99.5
		Animal fats	99.5
		Used Cooking Oil	98.1

Note: [1] Average based on number of samples tested (see Table 2); [e] estimate based on derived co-product data (see section 2.2); n/a = data not available.

Source: Agra CEAS Consulting

2.1.5 Sugars

Sugars (and starch) are one example of a type of chemical compound known as saccharides, which provide and store energy in the plant cells. Types of saccharide differ in the way that energy is stored and made available – with sugars used to directly supply energy to living organisms (in contrast to starch which is a structure to store energy in a form that can be readily broken down to release the energy when needed). These differences are important in e.g. the ethanol industry, with different conversion technologies applied to sugar feedstock processing (beet and cane; as well as molasses co-product produced from raw sugar refining) and starch feedstock (e.g. wheat, maize, cassava, etc.).

The data presented are from sugars analysed mainly by the Luff[7]-Schoorl[8] method based on ethanol extraction; but enzymatic methods are also used. The Luff-Schoorl method is based on the reduction

[7] A. P. Luff (1855-1938), Fellow of the Chemical Society, Fellow of the Royal College of Physicians, and Doctor at St. Mary's Hospital, London.

[8] N. Schoorl (1872–1942), Professor of Pharmacy at the University of Utrecht, Netherlands.

of copper (II) ions in an alkaline medium by the sugar and the subsequent back-titration of the added in excess reagent. The most important monosaccharides (D - glucose and D – fructose) and the main Disaccharide (D - lactose and D – maltose) can be determined. Non-reducing sugars (such as D – sucrose) can be quantified only if they can be split by acid hydrolysis into reducing monosaccharides.

Table 5: Composition of biofuel feedstocks – sugars (average[1], % as fed)

Feedstock	Sugars	Feedstock	Sugars
Conventional feedstocks		**Advanced cellulosic feedstocks**	
Wheat	2.4	Short rotation plantation wood	n/a[2]
Maize	1.6	*- Alder*	*n/a*[2]
Sugar beet	13.6	*- Ash*	*n/a*[2]
Sugar cane	9.9	*- Birch*	*n/a*[2]
Rapeseed	5.1	*- Poplar*	*n/a*[2]
Palm fruit bunch [e]	0.2[2]	*- Willow*	*n/a*[2]
Soybeans	7.7	Cereal (wheat) straw	1.5
Sunflower seed	2.4	Grass (meadow) hay	9.1
		Other advanced feedstocks	
		Crude Tall oil	n/a[3]
		Animal fats	n/a[3]
		Used Cooking Oil	n/a[3]

Note: [1] Average based on number of samples tested (see Table 2). [2] Note that most of the carbohydrate is contained in fibre (see section 2.1.7); [3] Note that most of the carbohydrate is contained in fats (see section 2.1.4); [e] estimate based on derived co-product data (see section 2.2); n/a = data not available.

Source: Agra CEAS Consulting

2.1.6 Starch

As indicated above, starch is the other main example of a type of chemical compound known as saccharides, which provide and store energy in the plant cells. In contrast to sugars, starch is a type of structure used to store energy in a form that can be readily broken down to release the energy when needed.

The data presented are from starch analysed using the Ewers[9] polarimetric method (Directive (EC) 72/199, 1980). Starch standards are prepared by dissolving starch in dilute hydrocholoric or trifluoroacetic acid and then stirred in a bath of boiling water. A 4% sodium phosphotungstate solution is added and then the solution is filtered. The filtrate is then measured using a saccharimeter and by thermal gravimetric analysis. A value of zero is given for starch-free materials such as oilseeds, sugar beet and cane.

[9] Ewers, E. (1908). Zeitschrift für öffentliche Chemie 14, S. 150-157.

Table 6: Composition of biofuel feedstocks – starch (average[1], % as fed)

Feedstock	Starch	Feedstock	Starch
Conventional feedstocks		**Advanced cellulosic feedstocks**	
Wheat	60.5	Short rotation plantation wood	n/a[2]
Maize	64.1	*- Alder*	*n/a[2]*
Sugar beet	0.0	*- Ash*	*n/a[2]*
Sugar cane	0.0	*- Birch*	*n/a[2]*
Rapeseed	0.0	*- Poplar*	*n/a[2]*
Palm fresh fruit bunch [e]	0.0[2]	*- Willow*	*n/a[2]*
Soybeans	0.0	Cereal (wheat) straw	0.7
Sunflower seed	0.0	Grass (meadow) hay	0.0
		Other advanced feedstocks	
		Crude Tall oil	n/a[3]
		Animal fats	n/a[3]
		Used Cooking Oil	n/a[3]

Note: [1] Average based on number of samples tested (see Table 2). [2] Note that most of the carbohydrate is contained in fibre; [3] Note that most of the carbohydrate is contained in fats (see section 2.1.4); [e] estimate based on derived co-product data (see section 2.2); n/a = data not available.

Source: Agra CEAS Consulting

2.1.7 Fibre

Fibre is the term used for the structural components of plant cells, comprising mainly carbohydrate in the form of cellulose, hemicellulose, and lignin, as well as pectin[10]. Although mainly composed of carbohydrate, a distinction is made in nutrient analysis because fibre is not readily broken down to release the energy stored (in contrast to simple sugars and starch).

There is no single method that can accurately capture the total fibre content or separate fibre components (e.g. cellulose, hemicellulose, pectin, lignin, etc.). The most accurate methods to date are based on the sequential analysis developed by Professor P.J. Van Soest (Emeritus Professor, Department of Animal Science, Cornell University), i.e. Neutral Detergent Fibre (NDF), Acid Detergent Fibre (ADF) and Acid Detergent Lignin (ADL).

The Van Soest sequential method for fibre analysis (AFNOR NF V18-122, 1997) is described below. It is based on the concept that plant cells can be divided into mostly digestible cell contents (i.e. proteins, starch, sugars, pectin, etc.) and the less digestible cell walls (contains hemicellulose, cellulose and lignin).

[10] Pectin is one of the cell contents contained in fibre (along with proteins, starch, sugars, organic acids and lipids) which is not captured by the sequential Van Soest NDF analysis.

The analysis does not further decompose cellulose and hemicellulose, even though they are composed of sugar molecule chains. This is consistent with the treatment of starch (see section 2.1.6), which is also composed of sugar molecule chains but distinguished from simple sugars due to the carbohydrate structure. By also disaggregating fibre into cellulose and hemicellulose (as well as lignin) we differentiate distinct carbohydrate structures.

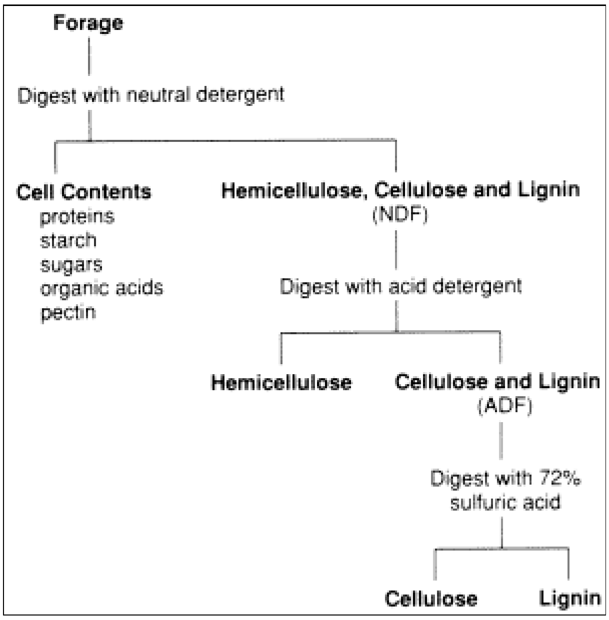

Figure 2: Diagram illustrating the Van Soest sequential method of fibre analysis

Source: Pacific Field Corn Association (1999)[11]

The three specific sequences in the van Soest fibre analysis are:

- **Neutral Detergent Fibre (NDF)**: cell wall material obtained by the action of sodium-lauryll sulphate / dodecyl sulphate in a neutral medium, sometimes including the use of enzymes (amylase and protease). NDF is approximately equivalent to hemicellulose, true cellulose and lignin (also includes silica and other components), but does not measure other fibre components, e.g. pectin, lipids, protein, oligosaccharides, etc.
- **Acid Detergent Fibre (ADF)**: ligno-cellulose obtained by the action of cetyl trimethyl ammonium bromide (CTAB) in a medium acidified by sulphuric acid (H_2SO_4) on the NDF residue.
    - *The hemicellulose component of fibre can be derived by subtracting the ADF value from NDF (see spreadsheet data).*
- **Acid Detergent Lignin (ADL)**: lignin estimated after acid destruction of true cellulose in the ADF residue using sulphuric acid (H_2SO_4 72%).
    - *The cellulose component of fibre can be derived by subtracting the ADL value from the ADF (see spreadsheet data).*

[11] Pacific Field Corn Association (1999). *Advanced Forage Management*. Agassiz, BC. Canada.

The data presented are from fibre analysed using the sequential Neutral Detergent Fibre (NDF), Acid Detergent Fibre (ADF) and Acid Detergent Lignin (ADL) methods described above.

Table 7: Composition of biofuel feedstocks – fibre (average[1], % as fed)

Feedstock	Total (NDF)	Hemicellulose	Cellulose	Lignin	Feedstock	Total (NDF)	Hemicellulose	Cellulose	Lignin
Conventional feedstocks					**Advanced cellulosic feedstocks**				
Wheat	12.4	*2.1*	*9.3*	*1.0*	SRPW[2]	14.0	*6.2*	*4.9*	*3.0*
Maize	10.4	*2.1*	*7.8*	*0.5*	*- Alder*	13.2	*5.4*	*5.2*	*2.6*
Sugar beet	3.8	*2.0*	*1.4*	*0.4*	*- Ash*	12.9	*6.2*	*3.9*	*2.8*
Sugar cane	11.3	*5.8*	*4.6*	*0.9*	*- Birch*	14.3	*6.3*	*5.3*	*2.7*
Rapeseed	17.6	*6.9*	*5.2*	*5.5*	*- Poplar*	13.0	*6.1*	*3.8*	*3.1*
Palm fruit bunch [e]	38.8	*18.0*	*9.5*	*11.3*	*- Willow*	16.8	*6.8*	*6.1*	*3.9*
Soybeans	11.0	*5.4*	*4.6*	*1.0*	Cereal (wheat) straw	72.1	*38.3*	*26.3*	*7.5*
Sunflower seed	28.8	*13.0*	*10.1*	*5.7*	Grass (meadow) hay	48.6	*24.3*	*21.1*	*3.2*
					Other advanced feedstocks				
					Crude Tall oil	n/a[3]	n/a[3]	n/a[3]	n/a[3]
					Animal fats	0.3	n/a[3]	n/a[3]	n/a[3]
					Used Cooking Oil	n/a[3]	n/a[3]	n/a[3]	n/a[3]

Note: [1] Average based on number of samples tested (see Table 2). [2] Short rotation plantation wood (SRPW) [3] Note that most of the carbohydrate is contained in fats (see section 2.1.4); [e] estimate based on derived co-product data (see section 2.2); n/a = data not available.

Source: Agra CEAS Consulting

2.1.8 Micronutrients

Biomass feedstocks contain very small quantities of micro-nutrients, so-called because they are both present in and needed by living organisms in very small quantities. The two main types are minerals and vitamins.

Mineral elements are naturally occurring substances which are taken up by plants where they are concentrated and stored. For both plants and animals they facilitate the production of enzymes, hormones and other substances essential for proper growth and development, e.g. nitrogen which is a key component of protein and necessary for growth.

The most common methods used to analyse the mineral component of biomass are based on incineration (ash) in conjunction with dissolving in acid. Spectroscopic methods are required to quantify individual mineral elements.

- **Ash** - methods based on incineration (hence the term ash) (AFNOR NF V18-101).
- **Insoluble acid fraction** - residue after incineration and hydrochloric acid (HCl) treatment (AFNOR NF V18-102).

- **Trace elements** - spectroscopic methods adapted for each mineral, such as calcium (AFNOR NF V18-108) and phosphorus (AFNOR NF V18-106).

Vitamins are water or fat soluble organic compounds, which like minerals are present and required by living organisms in very small quantities for the purpose of maintaining normal function, health and productivity. They can be synthesised by plants, but animals can only obtain the vitamins that they need via feed intake. Vitamins are difficult to measure and generally data are based on published tables with no methodology described. Therefore they are not assessed in this project.

Data for micro-nutrients are presented in the supporting spreadsheet data, but are not one of the key components which are the focus of this study.

2.1.9 Water

The water content of plant material is measured by desiccation (AFNOR NF V18-109). However, rather than referring specifically to water content, it is more typical to describe the organic matter or dry matter percentage (% DM), i.e. 100% less the water content, e.g. wheat has an average dry matter content of 86.8% (as-fed). Nevertheless, data for water calculated on the basis of feedstock dry matter percentage are presented in the table below.

Table 8: Composition of biofuel feedstocks – water (average[1], % as fed)

Feedstock	Water	Feedstock	Water
Conventional feedstocks		**Advanced cellulosic feedstocks**	
Wheat	13.2	Short rotation plantation wood	70.0
Maize	13.6	*- Alder*	*70.1*
Sugar beet	81.2	*- Ash*	*71.2*
Sugar cane	77.4	*- Birch*	*70.2*
Rapeseed	7.8	*- Poplar*	*70.2*
Palm fruit bunch [e]	15.5	*- Willow*	*68.2*
Soybeans	11.9	Cereal (wheat) straw	8.6
Sunflower seed	7.0	Grass (meadow) hay	10.4
		Other advanced feedstocks	
		Crude Tall oil	0.5
		Animal fats	0.22
		Used Cooking Oil	1.9

Note: [1] Average based on number of samples tested (see Table 2); [e] estimate based on derived co-product data (see section 2.2); n Water calculated on the basis of dry matter percentage of feedstock (see section 2.1.2.2).

Source: Agra CEAS Consulting

2.2 Selected component categories

Table 9 below presents the major component categories of the selected feedstocks (Note: it was agreed that two feedstocks, namely crude tall oil (CTO) and used cooking oil (UCO) did not require decomposition). Comparing feedstocks composition in the different components, one can draw the following observations:

Protein - the results show a clear distinction between feedstocks grown and valued for protein content, particularly by the livestock feeding sector, notably the oilseeds (rapeseed, soybeans, sunflower seed), cereal grains (wheat and maize) and also grass/hay.

Fats - it is notable that the feedstocks which contain the highest protein content also feature the highest fat component also, i.e. the oilseeds (rapeseed, soybeans, sunflower seed). Oilseeds are among the highest value combinable crops due to the two main co-products which can be extracted, i.e. the oil (fat component) which is valued for food, livestock feed and industrial uses; and the meal residue, which is valued for its protein content by the livestock feed sector.

Sugars - all biomass feedstocks contain a certain amount of sugars as this is the most readily available source of energy for plant growth. However, some feedstocks are noted for their high sugar content, i.e. sugar beet and sugar cane, and are thus valued by the sugar industry as well as by the ethanol industry.

Starch - high starch feedstocks include cereal grains and are valued for food, livestock feed and industrial uses. High starch feedstocks tend to be low in sugars, however, since both sugars and starch are types of saccharide carbohydrate, feedstocks share the attribute of being high in energy. This is the key reason why maize and wheat are the predominant starch based ethanol feedstocks.

Fibre - feedstocks such as cereal straw and grass/hay are valued primarily for their fibre content, however, they are an important component of livestock feed for ruminant (cattle, sheep, etc.) animals because a) fibre is required to maintain digestive function; and b) ruminants have specially adapted digestive systems which allow microbes to break down certain parts of fibre to release protein and sugars.

Table 9: Composition of biofuel feedstocks – main categories[1] (average[2], % as fed)

Feedstock	Water [3]	Protein	Fats	Sugars	Starch	Fibre: Fibre (NDF)	Fibre: *Cellulose*	Fibre: *Hemicellulose*	Fibre: *Lignin*
Conventional biofuel feedstocks									
Wheat	13.2	10.5	1.5	2.4	60.5	12.4	*2.1*	*9.3*	*1.0*
Maize	13.6	8.1	3.7	1.6	64.1	10.4	*2.1*	*7.8*	*0.5*
Sugar beet	81.2	1.5	0.1	13.6	0.0	3.8	*2.0*	*1.4*	*0.4*
Sugar cane	77.4	0.9	0.4	9.9	0.0	11.3	*5.8*	*4.6*	*0.9*
Rapeseed	7.8	19.1	42.0	5.1	0.0	17.6	*6.9*	*5.2*	*5.5*
Palm fruit bunch	15.5	3.5	37.7	0.2	0.0	38.8	*18.0*	*9.5*	*11.3*
Soybeans	11.9	34.8	17.9	7.7	0.0	11.0	*5.4*	*4.6*	*1.0*
Sunflower seed	7.0	16.0	44.6	2.4	0.0	28.8	*13.0*	*10.1*	*5.7*
Advanced cellulosic biofuel feedstocks									
Short rotation plantation wood	70.0	5.0	1.0	*n/a*	*n/a*	14.0	*6.2*	*4.9*	*3.0*
- *Alder*	70.1	5.9	1.1	*n/a*	*n/a*	13.2	*5.4*	*5.2*	*2.6*
- *Ash*	71.2	4.8	0.9	*n/a*	*n/a*	12.9	*6.2*	*3.9*	*2.8*
- *Birch*	70.2	4.5	1.2	*n/a*	*n/a*	14.3	*6.3*	*5.3*	*2.7*
- *Poplar*	70.2	6.1	0.9	*n/a*	*n/a*	13.0	*6.1*	*3.8*	*3.1*
- *Willow*	68.2	3.7	0.8	*n/a*	*n/a*	16.8	*6.8*	*6.1*	*3.9*
Cereal straw	8.6	3.8	1.3	1.5	0.7	72.1	*38.3*	*26.3*	*7.5*
Grass/hay	10.4	15.0	3.1	9.1	0.0	48.6	*24.3*	*21.1*	*3.2*
Other advanced feedstocks									
Crude Tall Oil	0.5	*n/a*	99.5	*n/a*	*n/a*	n/a	*n/a*	*n/a*	*n/a*
Animal fats	0.2	0.35	99.0	*n/a*	*n/a*	0.3	*n/a*	*n/a*	*n/a*
Used Cooking Oil	1.9	*n/a*	98.1	*n/a*	*n/a*	n/a	*n/a*	*n/a*	*n/a*

Note: [1] Categories do not sum to 100% because of issues with under- or double counting of components (see section 2.1.2.3).
[2] Average based on number of samples tested (see Table 2).
[3] Water calculated on the basis of dry matter percentage of feedstock (see section 2.1.2.2).

Source: Agra CEAS Consulting

Component data for Palm fresh fruit bunch (FFB) are estimated based on data for derived products (namely Empty Fruit Bunch, Palm oil, Press fibre, Oil Mill Effluent, Shell, Palm Kernel Meal and Others[12]) and the relative quantities derived in oil palm mills (as a percentage of the Fresh Fruit Bunch.

[12] Other products are also derived from palm fresh fruit bunch, but component composition data was not available for additional products.

However, it is noted that data availability for sugars and starch components was general unavailable with the exception of kernel meal and therefore these components may be under-estimated for the Fresh Fruit Bunch as a whole. Palm fresh fruit bunch is the product harvested from palm trees, but is not technically a feedstock in its own right and is processed to extract the high value components, i.e. crude palm oil, palm kernel oil and palm kernel meal (see Figure 3) for industrial and livestock feed use. This processing takes place in 5 key stages with residues and co-products (underlined below) produced at each stage:

1) Threshing of the palm fresh fruit bunch to separate the palm fruit from other biomass residue known as empty fruit bunch (historically discarded and burned/decomposed to return nutrients to the soil, but now also co-fired for power, composted for fertiliser and under research as a source of fibre for animal feeding).
2) The palm fruit is then 'pressed' (physical and/or chemical process) to extract crude palm oil, which leaves palm press fibre/cake and palm oil mill effluent residues.
3) The palm nut is then separated from the palm press fibre/cake. The palm press fibre can be used as a source of high fibre feed for livestock.
4) The palm nut is then cracked to separate the shell (another high fibre residue) from the palm kernel.
5) The palm kernel is processed (crushing and solvent extraction) to separate the palm kernel oil from the palm kernel meal.

As indicated above, there appears to be no laboratory analysis data of nutrient components for palm fresh fruit bunch; although we have provided data from various sources for the major (high value) co-products and in the accompanying spreadsheet data.

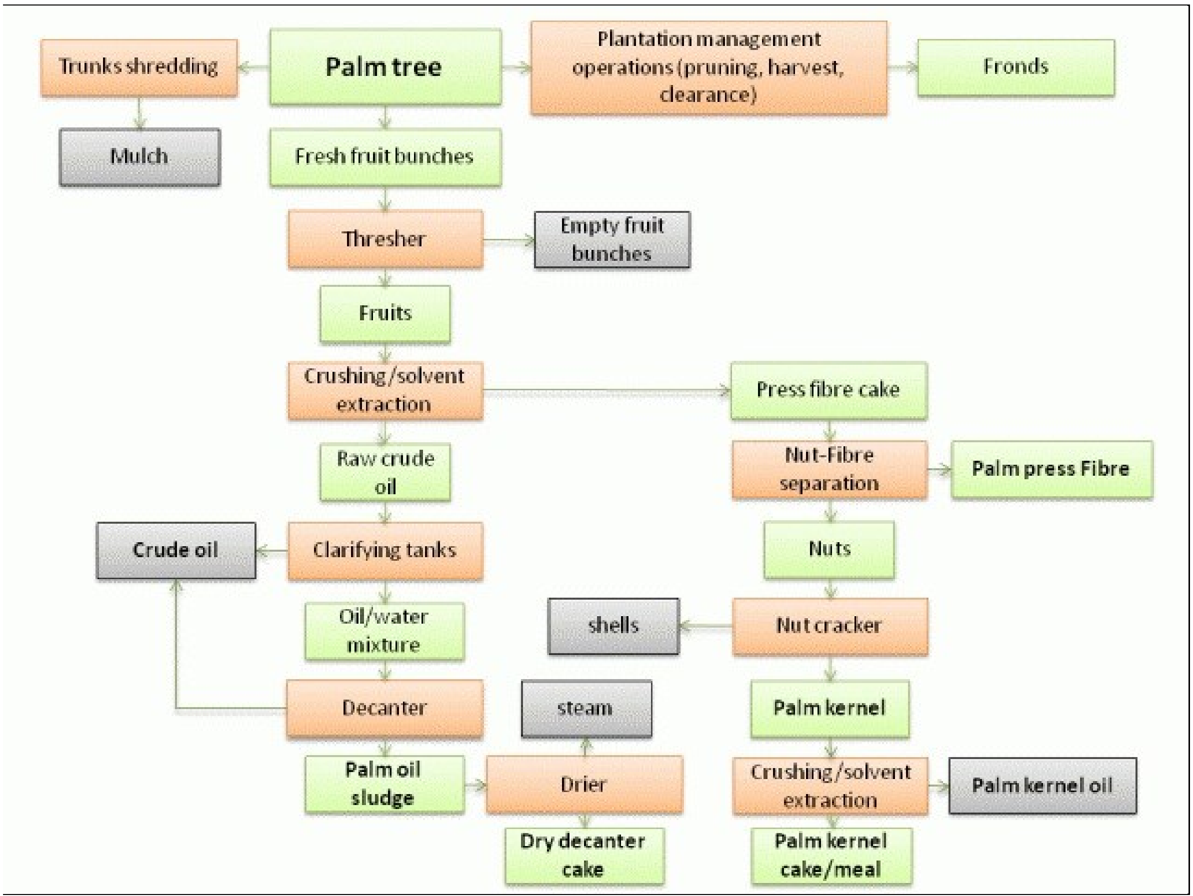

Figure 3: Diagram illustrating the processing of palm fruit bunch into co-products

Source: Heuzé (2015)[13]

[13] Heuzé, V. (2015). *Palm oil mill effluent*. Association française de zootechnie (AFZ). France.

3 Task 2. Component markets and prices

3.1 Description of component markets

Biomass feedstocks are primarily used in four main sectors of the economy: food, animal feed, energy and industry. While economic data on the food, feed and energy use of biomass is available, little economic data exists for industrial uses, many of which are still in the early stages of development or commercialisation. The following chapter does not aim to provide a comprehensive overview of all markets for biomass feedstock and their component categories (protein, fats, sugars, starch and fibre); rather it provides an overview of which components are typically used for the purpose of food, animal feed and energy generation or biofuels.

3.1.1 Protein

The primary use of protein is in the animal feed and food industries.

Animal feed
Protein is a key component category for use in animal feed markets. It is required as the source of amino acids used for the synthesis of body tissues. Sources of protein for the livestock feed industry include feedstock commodities, but crucially also include co-products from feedstock commodity processing, e.g. oilseed meals.

Food
Just as for livestock feed, protein is a key component of human food consumption. Unlike the livestock feed industry, however, sources of protein for human food tend to focus on the primary feedstock commodities themselves, e.g. grains and oilseeds, rather than the co-products of feedstock processing, which are fed to livestock in order to produce meat and animal products for human consumption.

3.1.2 Fats

The primary use of fats is in the animal feed, food and oleochemicals industries, but it is also an important source of feedstock for the production of biodiesel.

Animal feed
Fats serve a similar function to carbohydrates, i.e. serving both a metabolic role as an energy source as well as a structural role as an energy store. In the livestock feed industry, fats in the form of vegetable oils are sometimes added to feed rations to balance the energy requirements of livestock, but generally speaking livestock obtain most of the fats they require directly from digesting feed materials.

Food
Just as for livestock feed, fats are a key component of human food consumption. In addition to fats obtained directly through digestion of food materials, vegetable oils are an important source of added fat and are consumed directly as well as being used for cooking.

Oleochemicals
Oleochemicals are chemicals derived from plant and animal fats. They are analogous to petrochemicals derived from petroleum and their use by the chemicals industry has been increasing over time as crude oil prices have increased and as industries have increasingly begun to take steps to reduce their environmental impact through increased use of renewable feedstocks.

Various chemical and enzymatic reactions are used to produce basic oleochemical substances such as fatty acids, fatty acid methyl esters (FAME), fatty alcohols, fatty amines and glycerols. From these basic oleochemicals, intermediate products such as alcohol ethoxylates, alcohol sulfates, alcohol ether sulfates, quaternary ammonium salts, monoacylglycerols (MAG), diacylglycerols (DAG), structured triacylglycerols (TAG), sugar esters, and many others are manufactured.

In addition to the edible vegetable oils, e.g. rapeseed oil, sunflower oil, soybean oil, olive oil, palm oil, etc., non-edible oils such as crude tall oil (CTO) from the paper and pine chemical industry are used to produce chemicals such as rosin, linoleum, turpentine, adhesives, rubbers and inks; while used cooking oil (UCO) and animal fats are also used as a source of renewable feedstock material for processing.

Biodiesel
Biodiesel (FAME) production is a key user of vegetable oils, notably soybean, rapeseed and palm oils; as well as used cooking oil (UCO) and animal fats. Crude tall oil (CTO) has historically been used for the production of other chemical products; however, some Scandinavian countries have pioneered technology for biodiesel conversion.

3.1.3 Sugars

The primary use of sugars is in the food industry, but it is also an important source of carbohydrate for animal feed and also for the production of ethanol.

Food
In most parts of the world, sugar is an important part of the human diet, both as a source of carbohydrate and sweetener. It is refined primarily from sugar beet and sugars cane crops. According to the FAO food balance sheets, sugar from sugar beet and cane is the third most important source of calories after cereals and vegetable oils in human food consumption. However, in addition to refined sugars, naturally occurring sugars in fruits and vegetables are also an important source of sugars in the human diet.

3.1.3.1 Livestock feed

Livestock feed

Just as in humans, sugars provide an important source of carbohydrate for energy in animal feed. Animals are typically fed residues from the sugar beet and cane refining process, such as pulp or molasses. It can also be obtained through digestion of naturally occurring sugars in other feed materials.

ethanol

Sugar-based ethanol production is predominantly supplied by sugar beet and sugar cane feedstocks, but also molasses (a by-product of the refining of sugar cane or sugar beet. The largest growth in ethanol production worldwide in recent years has been for the growing use of biofuels in transport. Other major uses of ethanol are for food and beverage production, pharmaceuticals and other industrial applications.

3.1.4 Starch

Starch is another form of carbohydrate composed of sugar molecules held in a saccharide chain which provide and store energy in plant cells. In contrast to cellulose (fibre), starch is a type of structure used to store energy in a form that can be readily broken down to release the energy when needed. It has a substantial number of food and industrial uses.

Food

Starch is the most common form of carbohydrate consumed in the human diet. Major sources include cereals (rice, wheat, maize) and root vegetables (potatoes and cassava). As in livestock, starch is broken down by digestive enzymes to release constituent sugars and ultimately energy.

In the food industry, starch has a very wide range of uses, notably in its various modified forms; notably hydrolysed starch and chemically modified starch:

- <u>Hydrolysed starch</u> - Starch can be hydrolysed into simpler carbohydrates by acids and/or enzymes to produce dextrins, which are the most common starch based food ingredient and typically used as a sweetener. Dextrins include:
  - Maltodextrin - used as a bland-tasting filler and thickener.
  - Glucose syrups - used as sweeteners and thickeners in processed foods.
  - Dextrose - a commercial form of glucose sugar.
  - High fructose syrup - the principal sweetener used in processed foods and beverages and the main competitor to sucrose sugar from sugar beet and cane.
  - Sugar alcohols (e.g. maltitol, erythritol, sorbitol, mannitol and hydrogenated starch hydrolysate) – made by reducing sugars and used as sweeteners.

- <u>Chemically modified starch</u> – starch can be chemically modified to alter its physical properties under various conditions, e.g. high heat, high shear, low pH, freeze/thaw and cooling. Modified starches with food industry applications include:
  - Dextrin;

  - Acid-treated starch;
  - Alkaline-treated starch;
  - Bleached starch;
  - Oxidised starch;
  - Starches, enzyme-treated;
  - Monostarch phosphate;
  - Distarch phosphate;
  - Phosphated distarch phosphate;
  - Acetylated distarch phosphate;
  - Starch acetate;
  - Acetylated distarch adipate;
  - Hydroxypropyl starch;
  - Hydroxypropyl distarch phosphate;
  - Hydroxypropyl distarch glycerol;
  - Starch sodium octenyl succinate;
  - Acetylated oxidised starch;

Livestock feed

Just as in human food, cereal grains are the most common form of carbohydrate used in livestock feed, notably maize, wheat and barley. Carbohydrates are broken down by digestion to release constituent sugars and ultimately energy. In addition to starch from cereal grains, residues from the food and industrial processing of feedstocks for starch manufacture are consumed, e.g. DDGS, gluten, etc. While these feed materials are typically used as a concentrated source of protein, a significant amount of starch carbohydrate remains, particularly for ruminant (cattle) digestion, which in addition are able to digest some starch from cellulosic fibre.

Other industrial uses

In addition to the livestock feed and food industries, there are many other industrial applications of starch, including inter alia: pharmaceuticals, paper and pulp, corrugated board adhesives, laundry, construction, textiles, adhesives/glues, oil exploration, packaging, printing, powders, bioplastics and synthetic polymers, ethanol and hydrogen.

- Pharmaceuticals - starch is used as an excipient (an inactive substance that serves as the vehicle or medium for a drug or other active substance), as a tablet disintegrant, or as a binder. It is also used as a substitute for talcum powder and in other health and beauty products.
- Paper - the largest non-food application for starch. Starch is typically used to increase the wet and dry strength of paper; and as a binder in paper coatings.
- Corrugated board adhesives - the second largest non-food application for starch. Starch glues are used in the manufacture of corrugated board along with some additives e.g. borax and caustic soda.
- Laundry - a liquid prepared by mixing a vegetable starch in water used in the laundering of clothes.
- Construction - chemically modified and/or unmodified starch is used in the manufacture of gypsum wall board and act as a glue for the cured gypsum rock and paper covering, as well as providing rigidity to the board.

- Adhesives / glues – used for book-binding, wallpaper adhesives, paper sack production, tube winding, gummed paper, envelope adhesives, school glues and bottle labelling.
- Textile chemicals - warp sizing agents are used to reduce breaking of yarns (mainly cotton) during weaving and modified starch is used as textile printing thickener.
- Oil exploration - starch is used to adjust the viscosity of drilling fluid and suspend the grinding residue in petroleum extraction.
- Packaging - starch is also used to make some packing peanuts and drop-ceiling tiles.
- Printing - starch is used in anti-set-off spray powder used to separate printed sheets of paper.
- Bioplastics and synthetic polymers – starch is used in the manufacture of biodegradable plastics and polymers, e.g. polylactic acid (PLA) based on glucose from starch.
- Hydrogen – research is ongoing into ways to use glucose from starch as the raw material for hydrogen production using enzymes.

Ethanol
The two major feedstocks for starch-based ethanol production are wheat and maize grains, although other grains (e.g. rye and barley) and root crops (e.g. potato and cassava) are also used. The largest growth in ethanol production worldwide in recent years has been for biofuels in transport. Other major uses of ethanol are for food and beverage production, pharmaceuticals and other industrial applications.

3.1.5 Fibre

Fibre serves an important role in food and animal feed, as well as being an important component for a number of industrial and energy uses. In food and animal nutrition, fibre it serves an important role to aid the passing of food slowly through the gastro-intestinal tract so that enzymes are able to break down food into molecules that can be absorbed into the bloodstream. Ruminant animals (e.g. cattle, sheep, horses, etc.) have specially adapted digestive systems which allow microbes to break down part of the cellulose fibre to release the sugars from the carbohydrate structure. Fibre is also a key feedstock for advanced biofuel production, since fibre contains cellulose; and fibre also has a number of uses in the textiles, pulp and paper, as well as wood product industries.

Food
Fibre is required in the human diet to provide roughage to help to keep the food moving through the gastro-intestinal tract so that enzymes are able to break down food into molecules that can be absorbed into the bloodstream. Fibre is only found in foods that come from plants. In human nutrition terms, there are two different types of fibre – soluble and insoluble:

- Soluble fibre - can be digested and may help to reduce cholesterol in the blood. Sources include *inter alia*:
  - oats, barley and rye
  - fruit, such as bananas and apples
  - root vegetables, such as carrots and potatoes
  - golden linseeds

- Insoluble fibre - can't be digested and passes through the gastro-intestinal tract without being broken down, helping to prevent digestive problems. Sources include *inter alia*:
    - wholemeal bread
    - bran
    - cereals
    - nuts and seeds

Animal feed

Fibre is required and performs a similar function in animal feeding as it does for humans. However, ruminant livestock (e.g. cattle) require supplementary high fibre materials in the diet as bulk roughage (e.g. hay, straw or other forage material). Ruminant animals also have specially adapted digestive systems which allow microbes to break down part of the cellulose fibre to release the sugars from the carbohydrate structure. It is therefore the cellulose portion of fibre which is most desirable for ruminant livestock nutrition.

Other industrial uses

Fibre also has a number of uses in the pulp and paper, textiles, as well as wood product industries.

- Pulp and paper – pulp s a lignocellulosic fibrous material prepared by chemically or mechanically separating cellulose fibres from wood, fibre crops or waste paper. The timber resources used to make wood pulp can be either from softwood trees (e.g. spruce, pine, fir, larch and hemlock) or hardwoods (e.g. eucalyptus, aspen, birch, poplar, willow). The aim of pulping is to break down the bulk structure of the fibre source into the constituent cellulose, hemicellulose and lignin fibres. The main applications for are paper and board production.

- Textiles - Textile manufacturing is a major industry based on the conversion of fibre into yarn and fabrics. Many different types of fibre can be used, including
    - Cotton (globally the most important);
    - Bast fibres such as flax, jute, hemp, kenaf, urena, ramie and nettle;
    - Leaf fibres such as sisal, abacá and henequen; and
    - Protein fibres such as wool and silk.
    - Synthetic fibres can also be used but are not produced from biomass.

- Wood industry products – products from wood vary widely from timber used in the construction and furniture industries, wood fuel (including logs, wood chip and wood pellets), medium-density fibreboard (MDF) and oriented strand board (OSB), as well as chemical products such as rayon, viscose and cellulose.

Ethanol

Fibre is also a key feedstock for advanced (ligno-cellulosic) biofuel production. There is currently intensive research and development into methods to produce ethanol from cellulose and hemicellulose

3.2 Description of factors that affect market substitutability

This section discusses the properties of feedstock components (protein, fats, sugars, starch and fibre) which affect substitutability between feedstock products (not component categories).

3.2.1 Protein

The livestock feed industry is the largest single market for protein from biomass, which is sourced from a variety of feed materials, including materials that can be used for biofuel feedstock. **Figure 4** presents the protein content of selected feedstock products (as described in chapter 2.1.3) and compares these feedstocks to a number of close substitutes. This clearly shows that the feedstock and co-products that contain the highest levels of protein per tonne are the oilseed meals; followed by oilseeds and DDGS. Apart from the component yield, two key factors which affect the substitutability of feedstocks as sources of protein include the amino acid ratios and the protein digestibility.

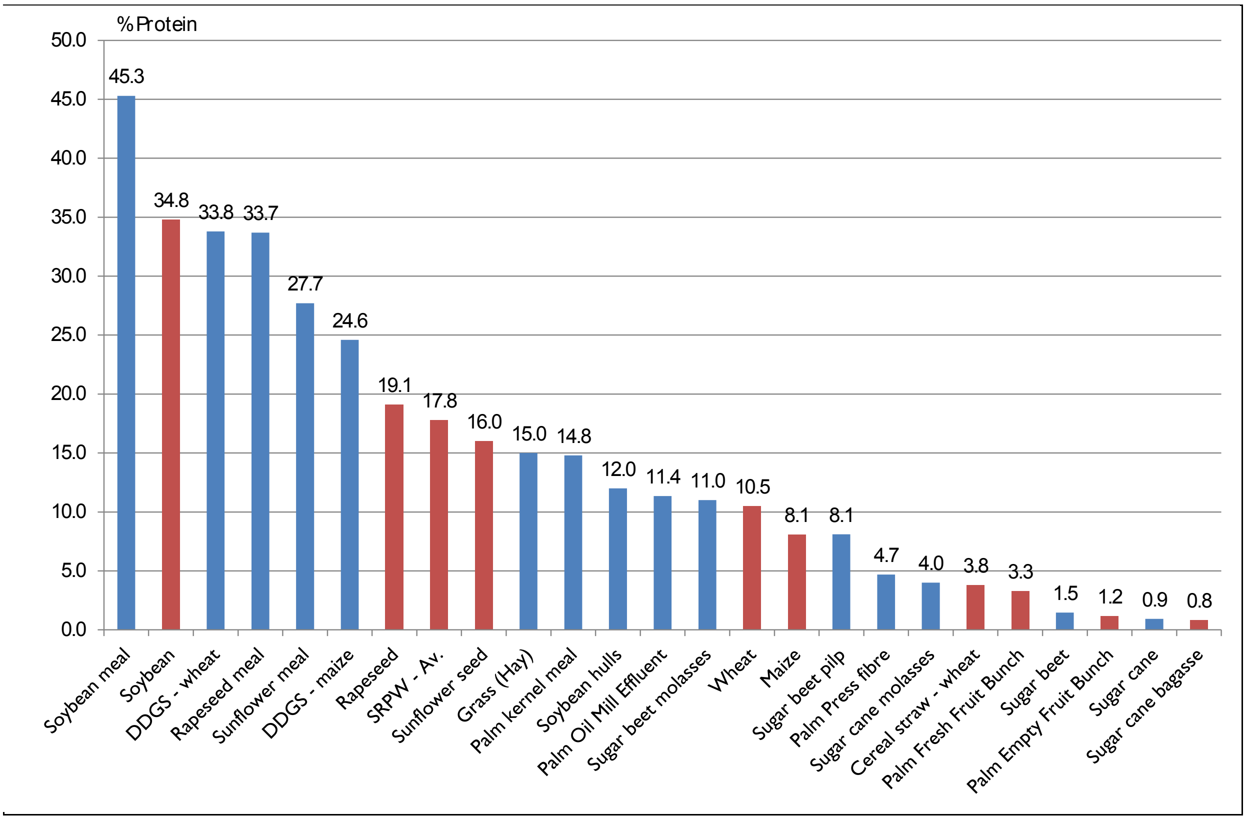

Figure 4: Protein content of selected feedstock and potential substitutes (%)

Note: selected feedstocks which are the focus of this study are highlighted in red

Source: Agra CEAS Consulting

Amino acids

The key component of protein is amino acids, which play an important role in improving the efficiency of overall protein utilisation in animal feeding. The amino acids requirements of animals are well documented and vary depending on the species and age of animals. These requirements can be met either by selected feed materials which contain appropriate levels of amino acids, or by supplementary feeding of manufactured crystalline amino acids.

Where specific amino acids are lacking in the diet, the growth and production potential of animals may be affected. By comparing requirements and the actual amino acids present in feed, the order of 'limiting amino acids' (the essential amino acid found in the smallest quantity in the particular feed material) can be estimated. Due to the relatively low levels found in the major livestock feed materials, namely cereals and soybeans, two of the most common 'limiting amino acids' are Methionine and Lysine; followed by Threonine and Tryptophan.

- Methionine - classed as an essential amino acid and cannot be synthesized by the animal itself, meaning that a sufficient supply is required in the diet. It is important because:
    - besides cysteine, methionine is the only sulphur-containing amino acid;
    - it plays an important role in the synthesis of other proteins;
    - it has a fat-dissolving effect and reduces the depositing of fat in the liver; and
    - it is an important cartilage-forming substance since cartilage in the joints requires sulphur for its production.

- Lysine - classed as an essential amino acid and cannot be synthesized by the animal itself, meaning that a sufficient supply is required in the diet. It is important because it plays a major role in:
    - calcium absorption;
    - building muscle protein;
    - production of hormones, enzymes and antibodies.
    - Lysine deficiency causes immunodeficiency in chickens.

As a result, global annual production of crystallised methionine and lysine for supplemental feeding is estimated at around 700Kt each, with production of Threonine estimated at around 30Kt and Tryptophan at around 1Kt. Figure 5 shows the relative content of limiting amino acids in crude protein from various selected feedstock materials.

Amino-acids such as lysine and methionine are relatively deficient in cereals feeds, as well as in DDGS, which inherits the amino acid profile of the cereal it comes from. Furthermore, some amino acids, particularly lysine, are to some extent selectively destroyed in the drying of DDGS. In order to reach the minimum amino acid requirements of animal feed, the amount of DDGS incorporated must be increased to well over the minimum requirement for total protein, or relatively expensive synthetic lysine or methionine (or fish meal) must be added. Furthermore, the drying process can also damages some of the protein content in DDGS, which can reduce its value as the effective protein content is lower than measured; although measurements of protein are estimated based on nitrogen content, which is not affected by drying [14].

[14] Based on correspondence between the authors and Robert Edwards, JRC, 2016.

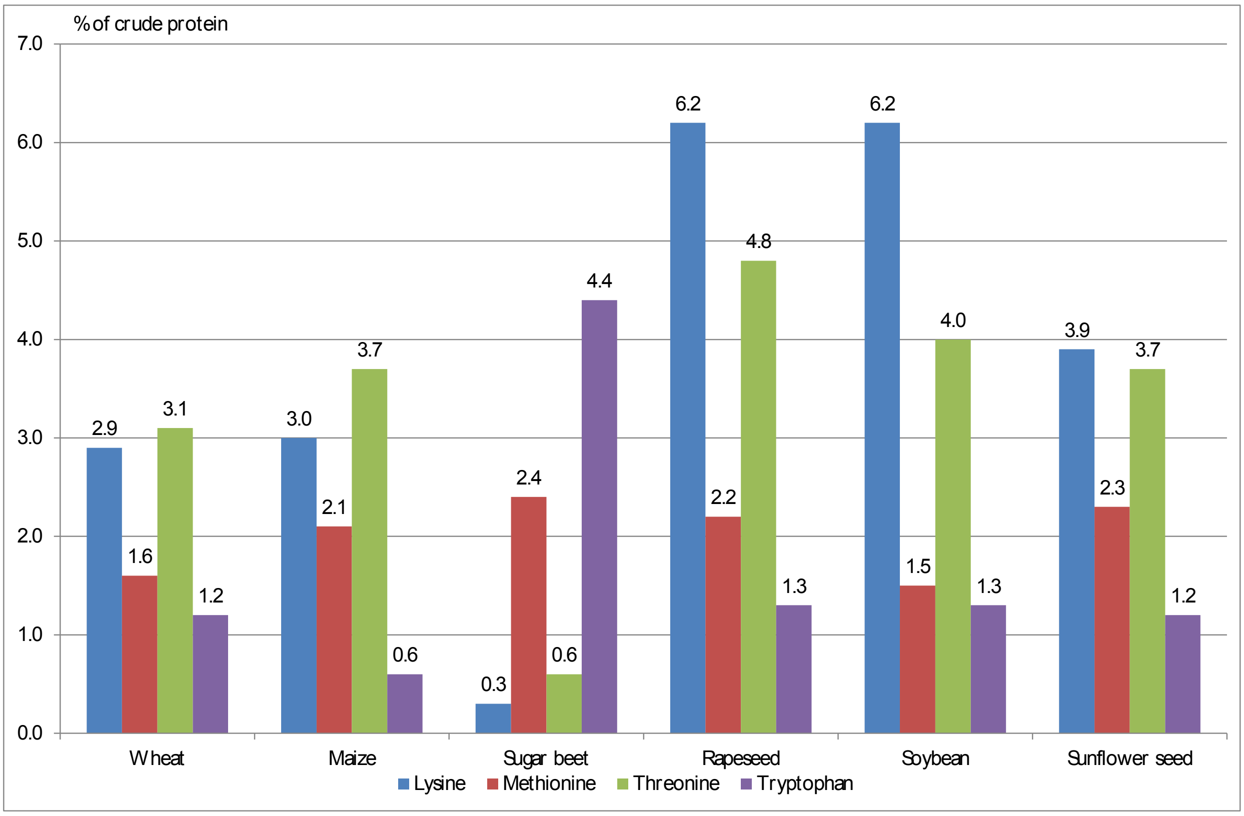

Figure 5: 'Limiting' amino acids content of crude protein in selected feedstock

Source: Agra CEAS Consulting

Protein digestibility

Crude protein does not take into account the efficiency of protein utilisation by livestock. Therefore measures of protein digestibility, i.e. the ability of the animal to utilise nutrient components to meet the requirements of the various body processes, such as nitrogen digestibility (Nd) can provide an indicator of substitutability between feedstock types. Table 10 below indicates the relative protein (nitrogen) digestibility of the selected biofuel feedstock for which data are available. The data suggests the comparative availability of protein to livestock through feeding. The values are given as a percentage which can be digested and therefore an indication of substitutability between feedstocks.

Table 10: Protein (Nitrogen) digestibility (Nd) of biofuel feedstocks (MJ/kg; %)

		Wheat	Maize	Sugar beet	Sugar cane	Rapeseed	Palm Fruit Bunch	Soybeans	Sunflower seed
Conventional biofuel feedstocks									
Pigs (growing)	%	84	75	*n/a*	*n/a*	89	*n/a*	85	80
Pigs (sows)	%	87	80	*n/a*	*n/a*	84	*n/a*	91	87
Ruminants	%	70	66	52.1	65	75	*n/a*	79	69
Advanced cellulosic and other biofuel feedstocks									
		Short Rotation Plantation Wood	**Cereal straw**	**Grass (Hay)**	**Animal fats**				
Pigs (growing)	%	*n/a*	0	46	*n/a*				
Pigs (sows)	%	*n/a*	42	59	*n/a*				
Ruminants	%	*n/a*	-5 *	72	*n/a*				

Note: * Negative nitrogen balances occur when the animal excretes more nitrogen than it consumes. n/a = data not available.

Source: Agra CEAS Consulting

3.2.2 Fats

Figure 6 presents the fats content of selected feedstock products (as described in chapter 2.1.4) and compares these feedstocks to a number of close substitutes. This clearly shows that the feedstock and co-products that contain the highest levels of fat per tonne are the oilseeds and co products, i.e. meals and oils. Palm fruit bunch has the highest fat content of the major oil crops, followed by rapeseed and sunflower seed. Soybeans have a comparatively low fat content, although bean yield at 3.0 t/ha (in the USA) is higher than for most other oilseeds (except rapeseed) and of course protein yield is high.

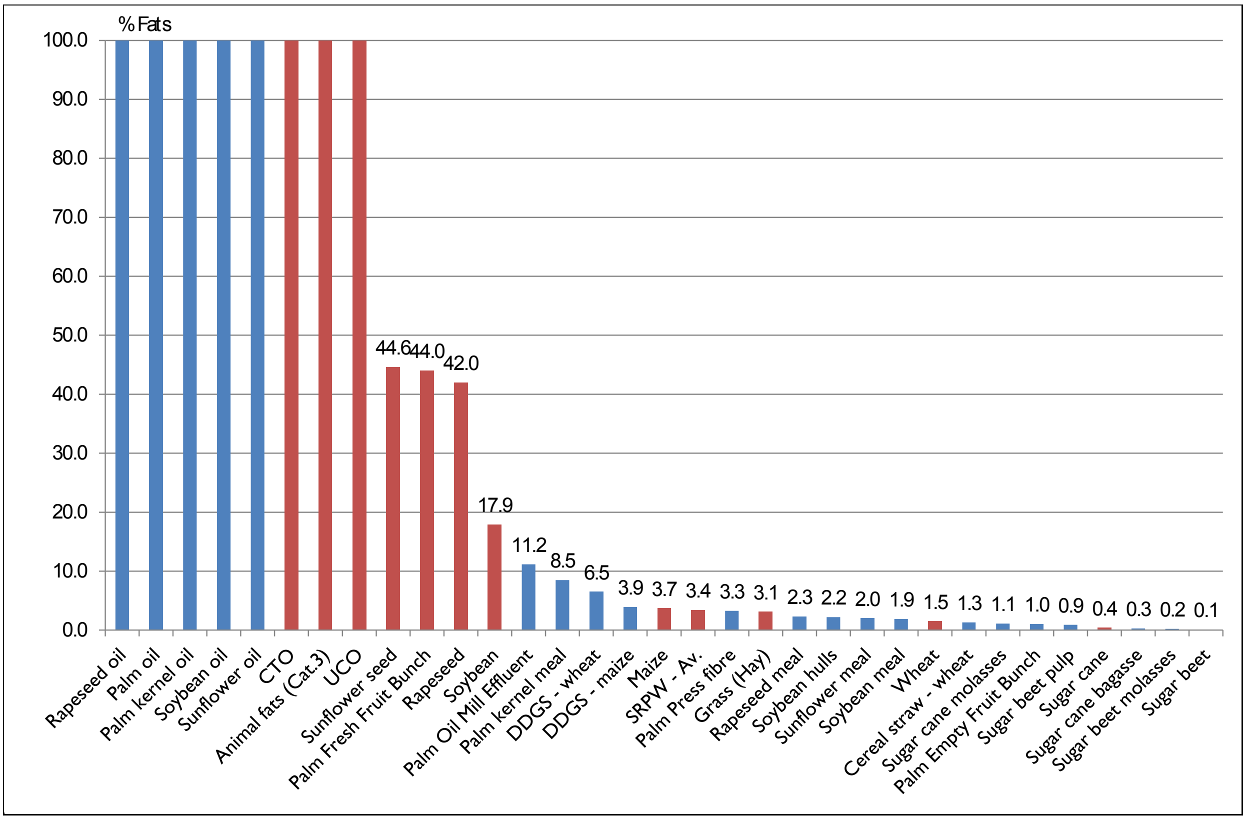

Figure 6: Fats content of selected feedstock and potential substitutes (%)

Note: selected feedstocks which are the focus of this study are highlighted in red

Source: Agra CEAS Consulting

Different applications for fats require different quality parameters which must be guaranteed for food, feed or fuel uses. The main quality specification parameters can be briefly summarised as follows:

- **Water content** – has implications for processing and can lead to quality deterioration, e.g. through hydrolysis and the formation of free fatty acids (see chapter **Error! Reference source not found.**).
- **Insoluble impurities** - ISO 663:2007 specifies a method for the determination of the insoluble impurities content of animal and vegetable fats and oils. The typical procedure involves a Soxhlet extraction, i.e. using a solvent to separate lipids (fat) from other insoluble materials, i.e. dirt and other foreign matter such as mechanical impurities, mineral substances, carbohydrates, nitrogenous substances, various resins, calcium soaps, oxidized fatty acids, fatty acid lactones, and (in part) alkali soaps, hydroxy-fatty acids and their glycerides.
- **Free Fatty Acids (FFA)**: indicates the degree of hydrolysis (see chapter **Error! Reference source not found.**).
- **Saturated/unsaturated fat content** – this is indicated by the iodine value; fully saturated fats have a value of zero (see chapter **Error! Reference source not found.**).
- **Melting or solidification point** – affects the *cloud point* and *cold pour point* values (see chapter **Error! Reference source not found.**).

- **Smoke point** - the temperature at which cooking fat or oil begins to produce bluish smoke. It varies between different fat sources and decreases with increasing FFA (see chapter **Error! Reference source not found.**).

In addition, animal fats can be categorised based on their origin and suitability for human consumption:

- Category 1: can be used for energy purposes; not permitted to enter the human or animal food chains.
- Category 2: can be used for soil enhancement and technical uses, e.g. oleo- and other specialty chemicals (after appropriate treatment).
- Category 3: can be used for animal feed, cosmetics and pet food.
- Other (no number): Animal fats intended for human consumption.

Fatty acids

One of the key components of fats are fatty acids. Figure 7 illustrates the relative fatty acids content as a proportion of total fats (as measured by ether extract; see chapter 2.1.4). Vegetable oils (including used cooking oil) have a particularly high fatty acid content compared to other sources of fats.

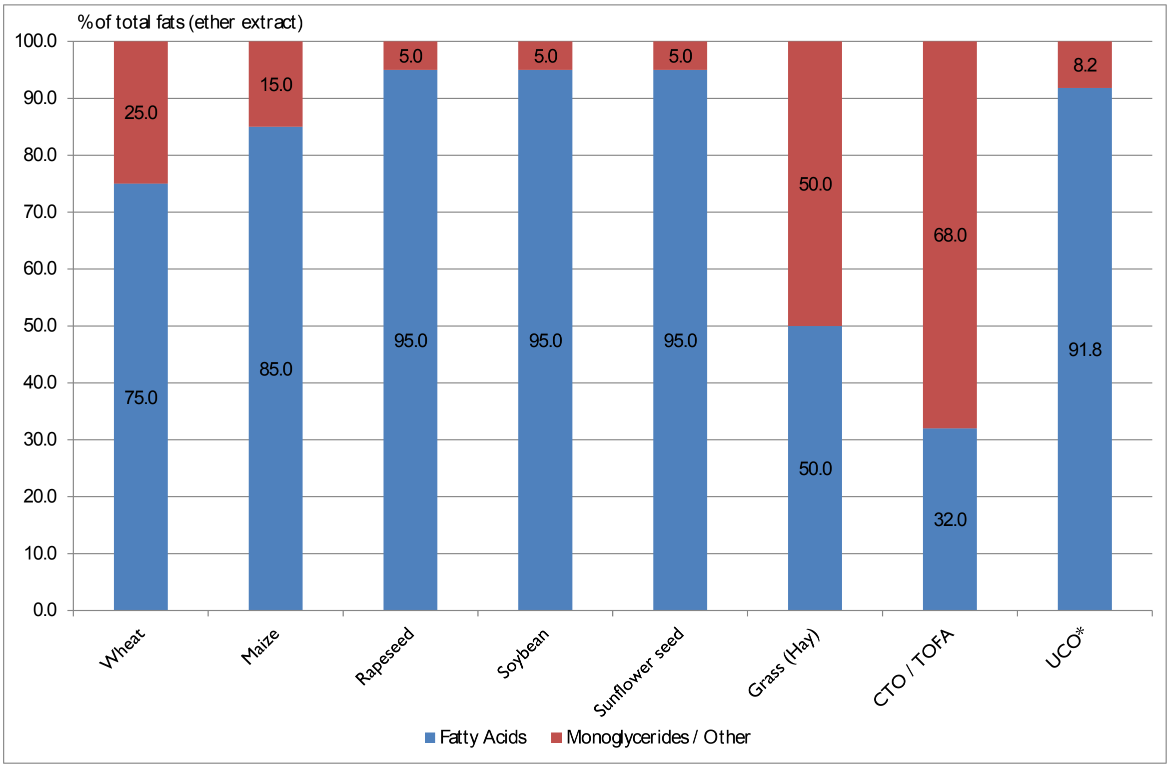

Figure 7: Fatty acids content of selected feedstock (% of total fats (ether extract))

Note: * UCO estimate based on ethyl ester content; no fatty acids data available for sugar beet, sugar cane, palm fruit bunch (although crude palm oil is analysed subsequently -see below), short rotation plantation wood and cereal straw.

Source: Agra CEAS Consulting

There are many different types of fatty acids, which can be categorised into two main groups, namely saturated and unsaturated fatty acids. Most fats contain a combination of saturated an unsaturated fatty acids, with plant fats typically containing less saturated fats than animal fats (a notable exception being palm oil). Other than the specific types of fatty acids themselves (discussed in more detail below), differences between both the various types of unsaturated fatty acids, as well as between saturated and unsaturated fatty acids, play an important role in biological processes and in the construction of biological structures (such as cell membranes), which also makes the distinctions important for various commercial applications and thus affect the substitutability of fats from different sources. For example:

- Biodiesel: the content of saturated and unsaturated fats in the feedstock oil affects the ***cloud point*** and ***cold pour point*** values of the biodiesel itself. Soybean and other related oleaginous oils are high in unsaturated fatty acids which have a high fluidity at 25°C resulting in biodiesel *cloud point* of 0°C and a *cold pour point* of 2°C. In contrast animal fats are high in saturated fatty acids which solidify at temperatures below 14-18°C, which correspond also to the *cloud point* and *cold pour point* of biodiesel from animal fats.

- Food industry: saturated fatty acids content of foods have health implications, notably for cardio-vascular disease. In 2003, the World Health Organization (WHO) and Food and Agriculture Organization (FAO) expert consultation report concluded that "intake of saturated fatty acids is directly related to cardiovascular risk" and went on to emphasize that the intake of saturated fatty acids should be less than 10% of daily energy intake (7% for high-risk groups), noting that within these limits, intake of myristic and palmitic fatty acids should be substituted by fats with a lower content of these specific fatty acids.

Two of the most commonly occurring saturated fatty acids in biofuel feedstock are palmitic and stearic acids; while two of the most common unsaturated fatty acids are oleic and linoleic acids.

- Palmitic acid (saturated) is the most common fatty acid. Palmitic acid (sodium palmitate obtained by saponification of palm oil) is used to produce soaps, cosmetics, and release agents. It is also used to add texture to processed foods; and cetyl alcohol (produced by hydrogenation of palmitic acid) is used to produce detergents and cosmetics.

- Stearic acid (saturated) is used mainly in the production of detergents, soaps, and cosmetics. Stearate salts are used as components of lubricants (e.g. lithium stearate grease), softeners (e.g. zinc, calcium, cadmium, and lead stearates are used to soften PVC) and release agents (e.g. in the manufacture of vehicle tires).

- Oleic acid (unsaturated) acid salts are mainly used as an emulsifying agent in the manufacture of soap and as an emollient. Smaller quantities are also used as an excipient[15] in pharmaceuticals, as well as emulsifying or solubilising agents in aerosol products. The

[15] an inactive substance that serves as the vehicle or medium for a drug or other active substance.

quantity of oleic acid is also used as an indicator for determining free fatty acids content (see chapter **Error! Reference source not found.**).

- Linoleic acid (unsaturated) is used in the manufacture of quick-drying oils for paints and varnishes; and linoleyl alcohol (produced by reducing linoleic acid) is increasingly used in beauty products as t has anti-inflammatory and moisture retentive properties.

Figure 8 illustrates the share of these specific fatty acids within the total fatty acids content of the selected feedstock which are the focus of this study.

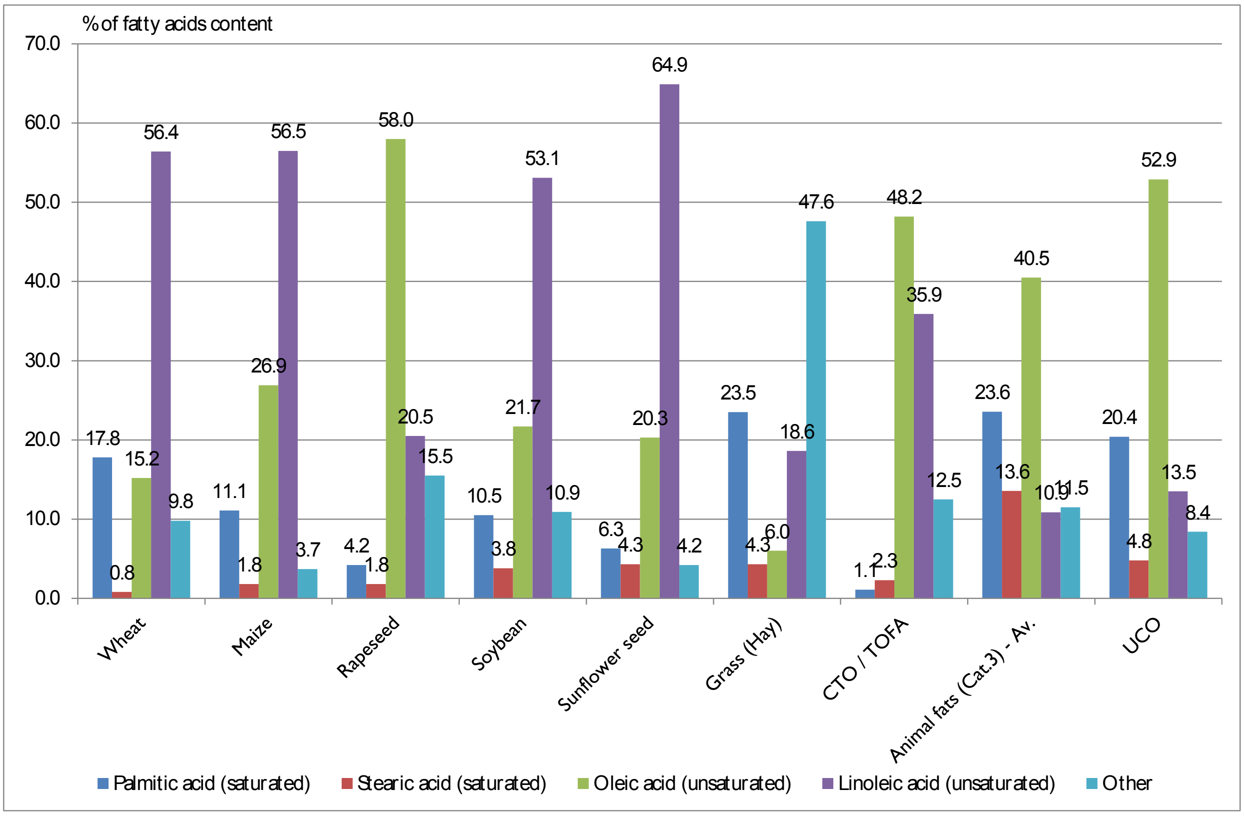

Figure 8: Fatty acids content of selected feedstock (% of total fatty acids)

Note: no fatty acids data available for sugar beet, sugar cane, palm fruit bunch (although crude palm oil is analysed subsequently -see below), short rotation plantation wood and cereal straw.

Source: Agra CEAS Consulting

Figure 9 presents data on the share of these four most commonly occurring fatty acids within the total fatty acids content of selected oils which are used as feedstock for biodiesel. As can be seen, palm oil is unique among vegetable oils because it is has a high (around 50%) share of saturated fatty acids, whereas the others are primarily composed of unsaturated fatty acids.

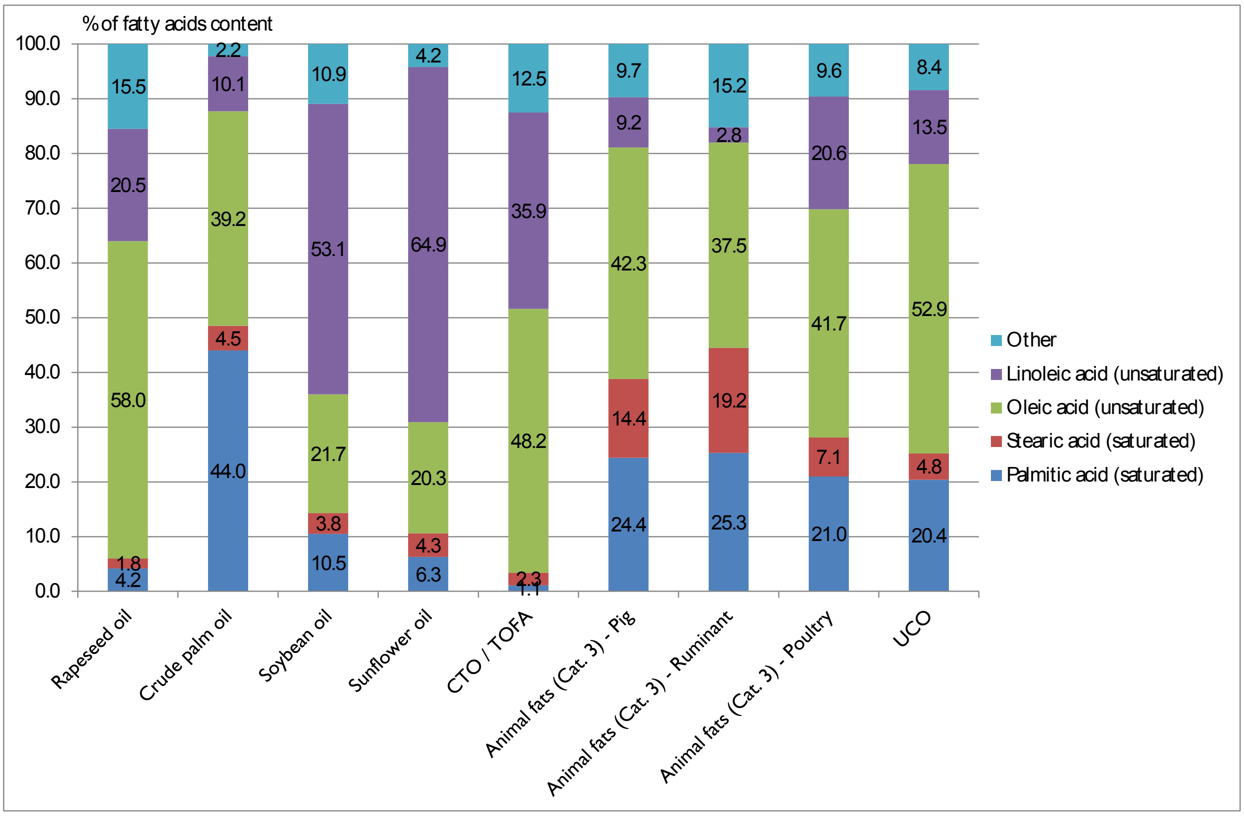

Figure 9: Fatty acids content of selected biodiesel feedstock (%)

Source: Agra CEAS Consulting

Free fatty acids'

Fatty acids nearly always naturally occur in the form of triglycerides, i.e. a chain of three fatty acids to one glycerol molecule. The length of this fatty acid chain gives rise to a number of distinguishing properties of fats, notably their **water solubility, acidity** and **saponification** (soap forming) tendency.

Fatty acids do not show a great variation in acidity, although this small variation is significant for some chemical processes: as the fatty acid-glycerol chain length increases, the solubility of the fatty acids in water decreases very rapidly. Those fatty acids that are insoluble in water will generally dissolve in warm ethanol. This water or ethanol solubility is used to determine the free fatty acid content (short-chain, volatile fatty acids) of fats, i.e. the proportion of the triglycerides that have been hydrolysed (separated from the glycerol in the triglyceride chain).

The percentage of free fatty acids in the feedstock oil is a key concern for the production of biodiesel because the free fatty acids react with the alkali catalyst in biodiesel production to form soap (saponification) instead of biodiesel, which reduces the level of free catalyst and thus reduces the speed of the trans-esterification reaction. Soap formation tends to inhibit the separation of the ester from the glycerin and slow down the reaction. This soap must be removed and thus the extent of saponification affects the biodiesel yield, i.e. more soap formation means less biodiesel production.

In feedstocks such as used cooking oil and animal fats, the free fatty acids content is particularly high, typically ranging from 10% to 25% FFAs which is far beyond the level that can be converted to biodiesel using an alkaline catalyst. These feedstocks also typically have a high **moisture (water) content**, which must be removed. It has been suggested that such feedstocks should be pre-treated to achieve a moisture level of less than 0.06% and a free fatty acid content of less than 0.5% (Boey, *et al*., 2012[16]).

For these high free fatty acid feedstocks, an alternative process called glycerolysis can be used which involves adding glycerin at around 200°C and letting it react with the free fatty acids to form monoglycerides, a glycerol molecule to which one free fatty acid has been joined. These monoglycerides can then be processed using a standard alkaline catalyst transesterification process. Glycerolysis can be expensive because of the heat energy required as well as the capital cost of a high-pressure boiler and the labour cost of a trained boiler operator. Waste glycerine from biodiesel processing can be used in this process; however a vacuum must be applied while heating to remove water that is formed during the reaction. Another disadvantage is that the glycerin will also react with the triglycerides in the oil to convert some of them to monoglycerides, which although not affecting the reaction itself, means that more glycerin is required for the process and consequently separated and removed after trans-esterification.

Finally, another characteristic of fats related to the free fatty acids content is the **smoke point**, i.e. the temperature at which cooking fat or oil begins to produce bluish smoke, which varies between different fat sources and decreases with increasing free fatty acids content.

3.2.3 Sugars and Starch

Figure 10 presents the sugars content of selected feedstock products (as described in chapter 2.1.5) and compares these feedstocks to a number of close substitutes. Apart from component yield, factors which affect the substitutability of feedstocks as a source of sugars include the ethanol yield, as well as various geographical and technical factors.

[16] Boey, P.L.; Ganesan, S.; Maniam, G.P.; Khairuddean, M.; Lim, S.L. (2012). A new catalyst system in transesterification of palm olein: Tolerance of water and free fatty acids. Energy Convers. Manag. 2012, 56, 46–52

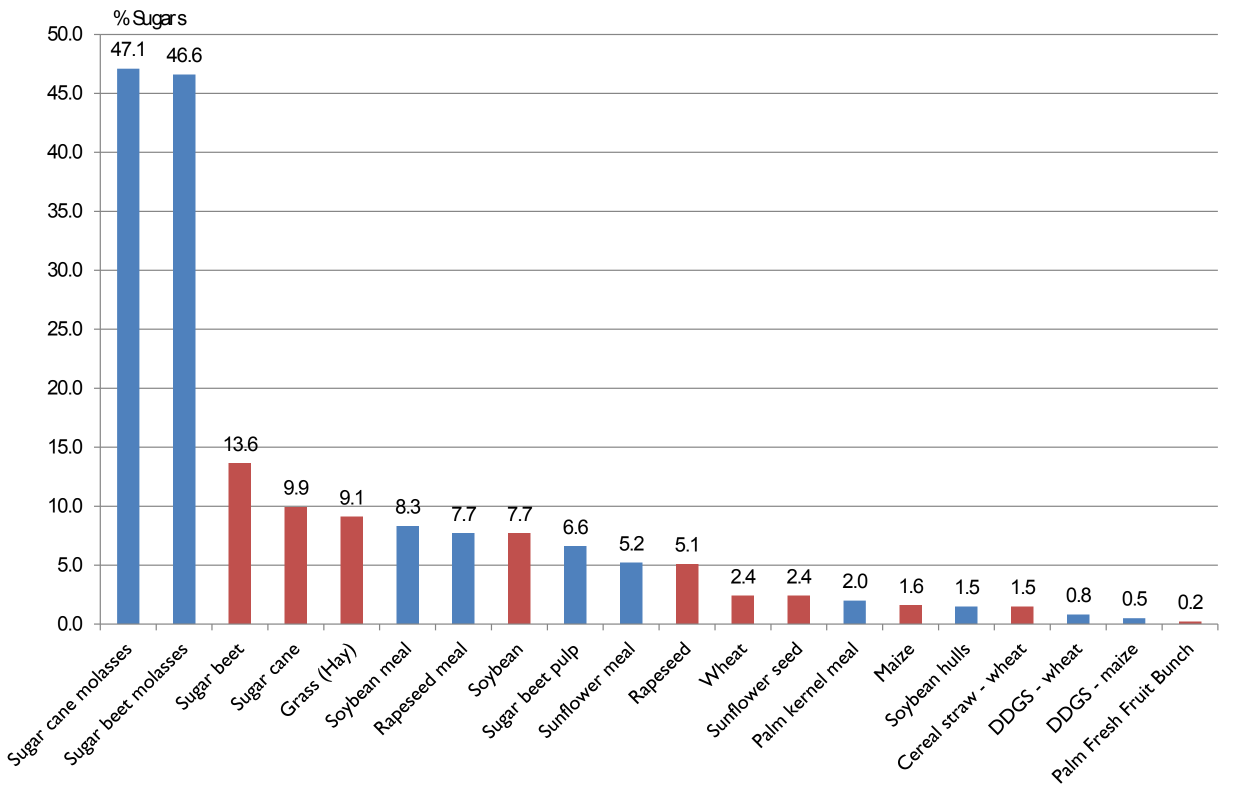

Figure 10: Sugars content of selected feedstock and potential substitutes (%)

Note: selected feedstocks which are the focus of this study are highlighted in red

Source: Agra CEAS Consulting

Figure 11 presents the starch content of selected feedstock products (as described in chapter 2.1.6) and compares these feedstocks to a number of close substitutes. In much the same way as for sugars above, factors which affect the substitutability of feedstocks as a source of starch include the ethanol yield and various geographical and technical factors.

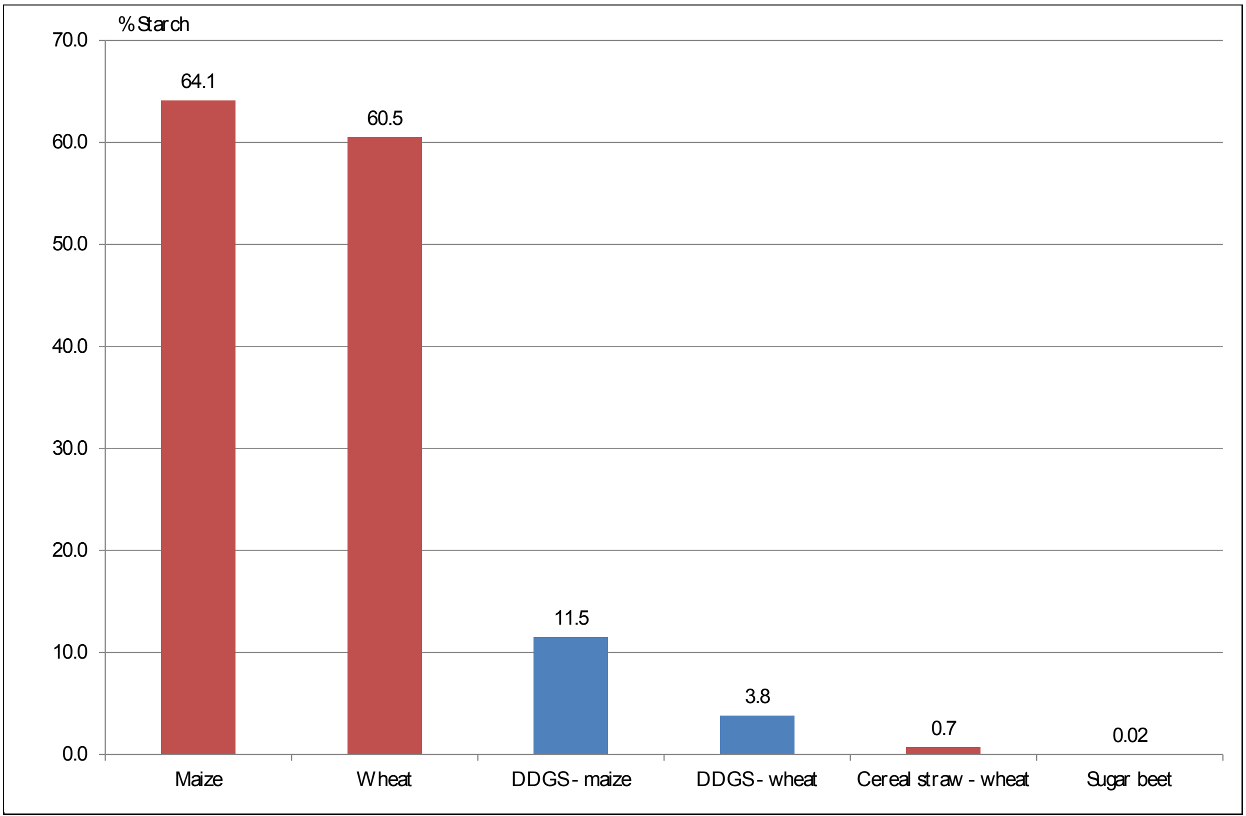

Figure 11: Starch content of selected feedstock and potential substitutes (%)

Note: selected feedstocks which are the focus of this study are highlighted in red

Source: Agra CEAS Consulting

Ethanol yield

In conjunction with the sugar and starch component composition wheat, maize grains, sugar beet and sugar cane, the relative ethanol yield from each feedstock is a relevant factor which affects the choice of feedstock and substitutability. Table 11 below provides typical ethanol conversion yields as well as sugar and starch content of ethanol feedstocks.

Table 11: Starch, sugar and ethanol yield of feedstock used for ethanol production (%)

		Wheat	Maize	Sugar beet	Sugar cane
Starch	%	60.5	64.1	0.0	0.0
Sugars	%	2.4	1.6	13.6	9.9
Ethanol yield	t/m^3	2.7	2.4	10	12.1

Note: ethanol yield given as tonnes of feedstock required to make $1m^3$ of ethanol.

Source: Agra CEAS Consulting

Logistics

Logistical factors such as the location of feedstock production affect feedstock substitutability. For example, sugar beet and sugar cane are not typically produced in the same regions, with sugar beet typically grown in temperate regions and sugar beet more suited to cultivation in the tropics. Given the bulky nature of both feedstocks, international transportation of feedstock for processing is not feasible and so there is little substitutability, despite both being used to manufacture the same sucrose product. This also applies to some degree to the wheat and maize, with for example the USA typically using maize as feedstock compared to wheat in the EU (historically, although this pattern varies by geography within the EU also), a pattern which is driven by prevailing agronomic conditions which favour the production of one or other feedstock type.

Technology

It is generally the case that starch milling plants, including both for native starch and ethanol production, are feedstock specific due to the process technologies employed (e.g. wet versus dry milling) and while there are nevertheless examples of multi-feedstock plants, the technical and logistical requirements of switching feedstocks can be complex. To a certain extent, this can be mitigated by plant design; however it is notable that a number of multi-feedstock ethanol plants in the EU have faced technical as well as economic difficulties. In addition to the technical issues affecting feedstock substitutability, in many cases the investment rationale for building the facility is also a factor, since many starch extraction and ethanol refining facilities are add-ons to existing grain milling facilities and are thus intended to operate most efficiently with the predominant feedstock supply at that facility.

In the case of native starch production, the products produced have differing technical specifications for specific applications and thus not only does starch extraction require specific technical processes and facilities to optimise output, economic factors relating to supplying a different product to different markets also affect the substitutability of feedstocks. For wheat and maize native starches, for example, it is the granule size and structure which affect the functionality of different starches. Grain size affects the gelatinisation and viscosity of the starch. Large granules have a higher viscosity but are more sensitive to shearing. According to Hegenbart (1996[17]), wheat starch has a bimodal grain structure, meaning that it has both large (22-36 microns in diameter) and small (2 to 3 microns); whereas maize has a more uniform structure with medium grain sizes (5-15 or 10-15 microns, depending on type). Another key factor is the amylose:amylopectin ratio, which affects the temperature and pressure required during processing to reach gelatinisation temperature. In general, the higher the amylose content, the higher the temperature required to achieve gelatinisation. Hegenbart (1996) states that wheat and common maize starch have an amylose content of around 25%; however the 3 other types of maize starch have varying composition, with waxy maize almost totally made up of amylopectin, while the 2 high-amylose corn starches have 55% and 70-75% amylose contents respectively.

3.2.4 Fibre

[17] Hegenbart, S. (1996). *Understanding Starch Functionality*. Food product design, Weeks Publishing 1996, Northbrook, IL, USA.

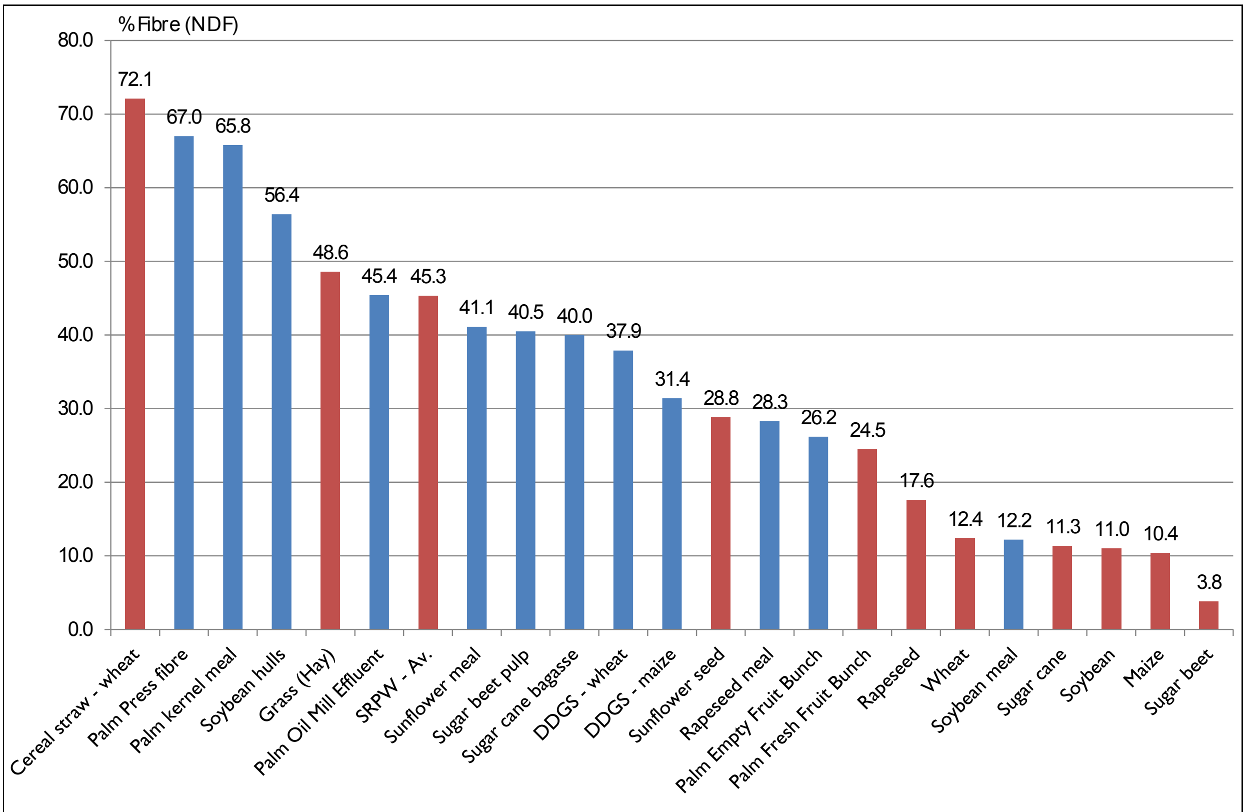

Figure 12Error! Reference source not found. presents the fibre content of selected feedstock products (as described in chapter 2.1.7) and compares these feedstocks to a number of close substitutes. Feedstock and co-products that contain the highest levels of fibre per tonne include wheat straw and grass hay, as well as various co-products from the vegetable oil and sugar processing sectors. Figure 13 presents the relative proportions of cellulose, hemicellulose and lignin within total fibre (NDF) of the selected feedstocks. Apart from component yield, factors which affect the substitutability of feedstocks as a source of fibre include the lignin-cellulose ratio, the hemicellulose fraction, organic matter digestibility and other technical and economic factors.

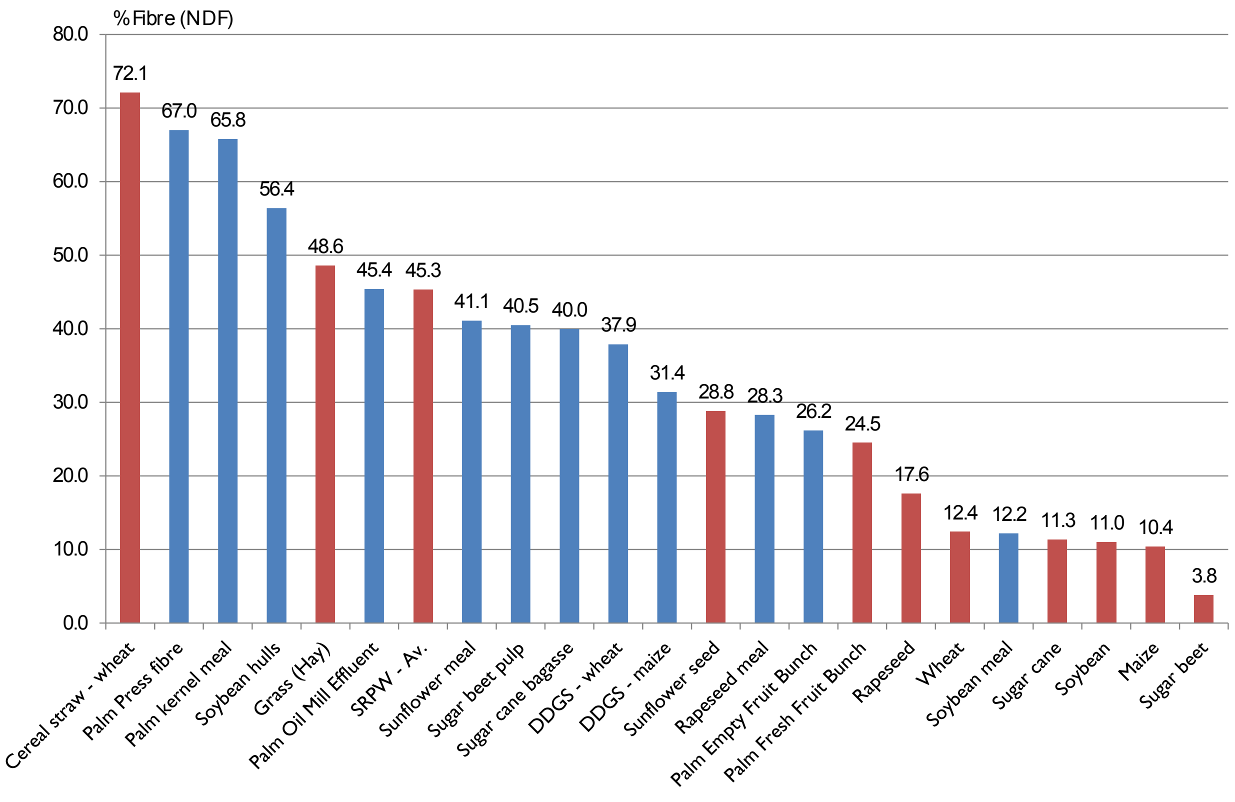

Figure 12: Fibre content of selected feedstock and potential substitutes (%)

Note: selected feedstocks which are the focus of this study are highlighted in red

Source: Agra CEAS Consulting

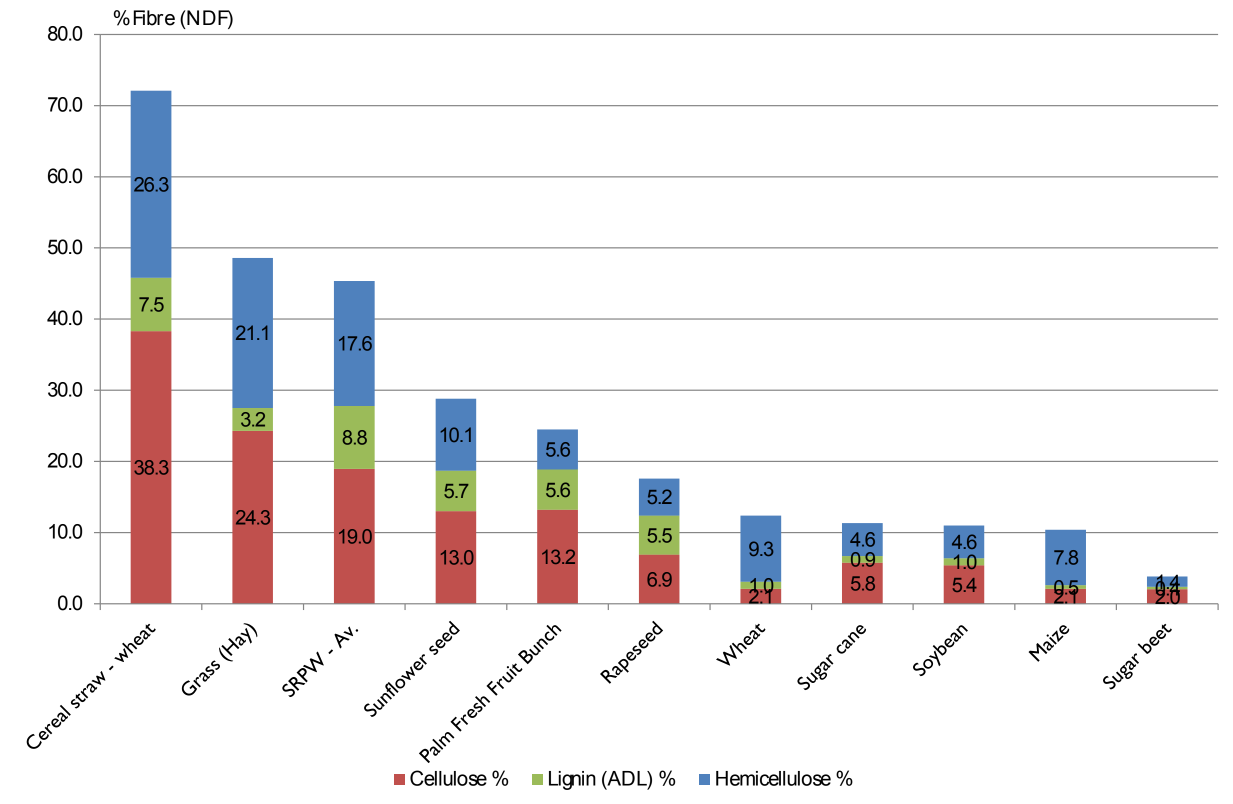

Figure 13: Fibre, cellulose, hemicellulose and lignin content of selected feedstock (%)

Source: Agra CEAS Consulting

Lignin-cellulose ratio

It is the cellulose within fibre which has the major value as a raw material and also as a source of energy. Since cellulose exists mostly in the form of ligno-cellulose, the presence of lignin presents a major challenge and affects the uses for and substitutability of feedstock products. For example:

- For the forest products industries, lignin is the major barrier to efficient extraction of cellulose fibres for pulp and paper production (Li et al., 2003[18]).

- For the bioenergy industries, lignin is a barrier to saccharification for production of liquid biofuel (Chen and Dixon, 2007[19]).

- Lignin content expressed as a ratio to cellulose – high ratio indicates low digestibility (Van Soest, 1994[20])

[18] Li, L., Zhou, .Y, Cheng, X., Sun, J., Marita, J., Ralph, J., Chiang, V. (2003). Combinatorial modification of multiple lignin traits in trees through multigene co-transformation. Proc Natl Acad Sci. USA 100: 4939–4944.

[19] Chen, F., Dixon, R.A. (2007) Lignin modification improves fermentable sugar yields for biofuel production. Nat Biotechnol 25: 759–761.

Figure 14 presents the ratio of lignin to cellulose within total ligno-cellulose as measured by the Acid Detergent Fibre (ADF) and Acid Detergent Lignin (ADL) methods (see chapter 2.1.7).

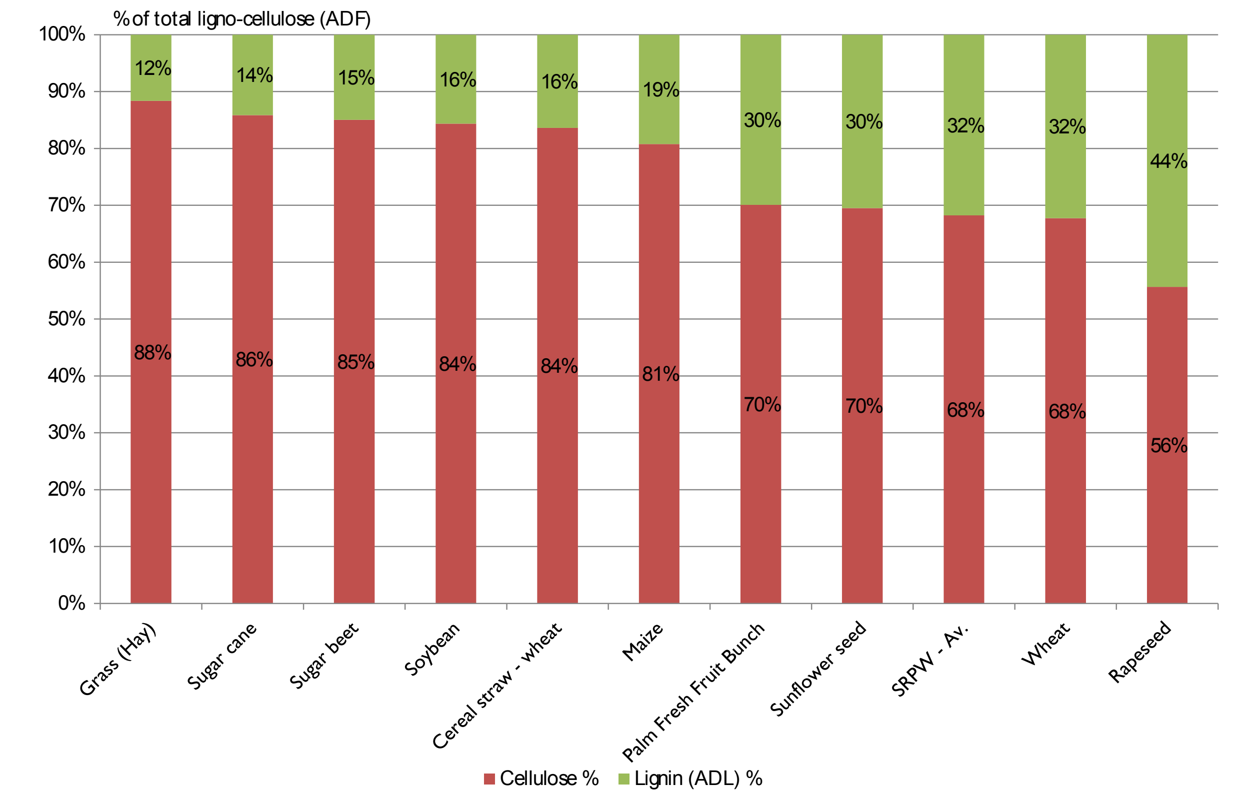

Figure 14: Lignin-cellulose ratio of selected feedstock (%)

Source: Agra CEAS Consulting

Hemicellulose

The other major component of fibre is hemicellulose (see chapter 2.1.7), the content of which is also presented in Figure 13 above.

Hemicellulose itself is an important component of bast fibres such as flax which are distinguished from other textile fibres such as cotton which has a very low hemicellulose but high true cellulose content (Müssig, J., 2010[21]). The hemicellulose content is thus an important factor for raw material substitutability in some textile industries and may have positive or negative attributes depending on product and use, e.g. increasing water absorption (in flax) or causing uneven dyeing (in cotton).

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[20] Van Soest, P. (1994). Nutritional Ecology of the Ruminant. Cornell University Press.

[21] Müssig, J. (2010). Industrial Applications of Natural Fibres: Structure, Properties and Technical Applications. John Wiley & Sons.

Hemicellulose content of fibre has a particular significance for the substitutability of livestock feed materials, as it affects the voluntary feed intake of animals. As the proportion of hemicellulose in animal feed increases the voluntary feed intake decreases, i.e. reducing overall feed quantity consumed and thus affecting performance unless the diet is carefully controlled.

Organic Matter digestibility

The fibre (cellulose, hemicellulose and lignin) content itself does not indicate the availability or efficiency of fibre utilisation by livestock. Therefore measures of digestibility, i.e. the ability of the animal to utilise components, such as Organic Matter digestibility (OMd - %) can provide an indicator of substitutability between feedstock types. Organic Matter digestibility (OMd - %) is a measure of the overall digestibility of biomass; however, as it is mostly based on the plant cell wall constituents, it gives a high level comparison of overall fibre digestibility. Table 12 below indicates the relative energy digestibility of the selected biofuel feedstock for which data are available. The data suggests the comparative availability of energy to livestock through feeding based on the relative digestibility of the energy containing material in different feedstocks. The values are given as a percentage which can be digested and therefore an indication of substitutability between feedstocks.

The presence of fibre may have adverse effects, particularly in pig diets, which are the main use for oilseed meals in the livestock sector. Feed blenders are aware that there is a limit to the volume of food a pig will eat, so fibre tends to add to the bulk of the food without providing much additional digestible energy. Furthermore, pigs digest fibre poorly, so it reduces the digestibility of the other components including proteins. Therefore the blender limits the amount of high-fibre protein feeds, such as sunflower meal, palm kernel meal and DDGS, and this reduces their value compared to the same quantity of crude protein in soybean meal. This issue is not relevant for other animal types [22].

[22] Based on correspondence between the authors and Robert Edwards, JRC, 2016.

Table 12: Organic matter digestibility (OMd) of biofuel feedstocks (%)

		Wheat	Maize	Sugar beet	Sugar cane	Rapeseed	Palm Fruit Bunch	Soybeans	Sunflower seed
Conventional biofuel feedstocks									
Pigs (growing)	%	90	84	n/a	n/a	81	n/a	79	69
Pigs (sows)	%	92	85	n/a	n/a	84	n/a	87	74
Ruminants	%	88	83	89.2	65.2	83	n/a	88	72
Advanced cellulosic and other biofuel feedstocks									
		Short Rotation Plantation Wood		Cereal straw		Grass (Hay)		Animal fats	
Pigs (growing)	%	n/a		12		43		85	
Pigs (sows)	%	n/a		18		51		85	
Ruminants	%	n/a		44		73		n/a	

Note: * Negative nitrogen balances occur when the animal excretes more nitrogen than it consumes. n/a = data not available.

Source: Agra CEAS Consulting

3.2.5 Cross-component factors

There are factors which affect the substitutability of feedstock due to a combination of multiple components with in a feedstock, most notably gross energy which derives from the sugar, starch, fat and protein content.

Gross energy

Gross Energy is a measure of the overall energy (calorific) content of feedstock materials, based on the proportions of carbohydrate (sugar and starch; as well as fibre for ruminants), fat, and protein present, since each of these components have different (and varying) energy content (Codex Alimentarius, 1991[23]), for example[24]:

- Fat – ~37 MJ/kg
- Carbohydrate – ~17 MJ/kg
- Protein – ~17 MJ/kg

[23] Codex Alimentarius Commission (CAC) (1991). *Codex Alimentarius*. FAO / WHO Food Standards Programme, Rome, Italy.

[24] Note that these values vary.

Energy is contained in the chemical bonds between organic compounds present in the feedstock material. This chemical energy is released as heat when these chemical bonds are broken and is termed *gross energy*. It is measured by burning a known quantity of material and recording the heat produced. Gross energy is therefore a universal indicator of the energy potential of biomass.

Figure 15 illustrates the gross energy content of selected feedstock products and compares them with a number of close substitutes. Here it can clearly be seen that the majority of feedstock and co-products have very similar gross energy values at between 15-20 MJ/kg; with the major oilseeds having a slightly higher gross energy at 20-27 MJ/kg; while vegetable oils and animal fats have the highest gross energy content at around 39 MJ/kg; in contrast to short rotation plantation wood at around 4 MJ/kg.

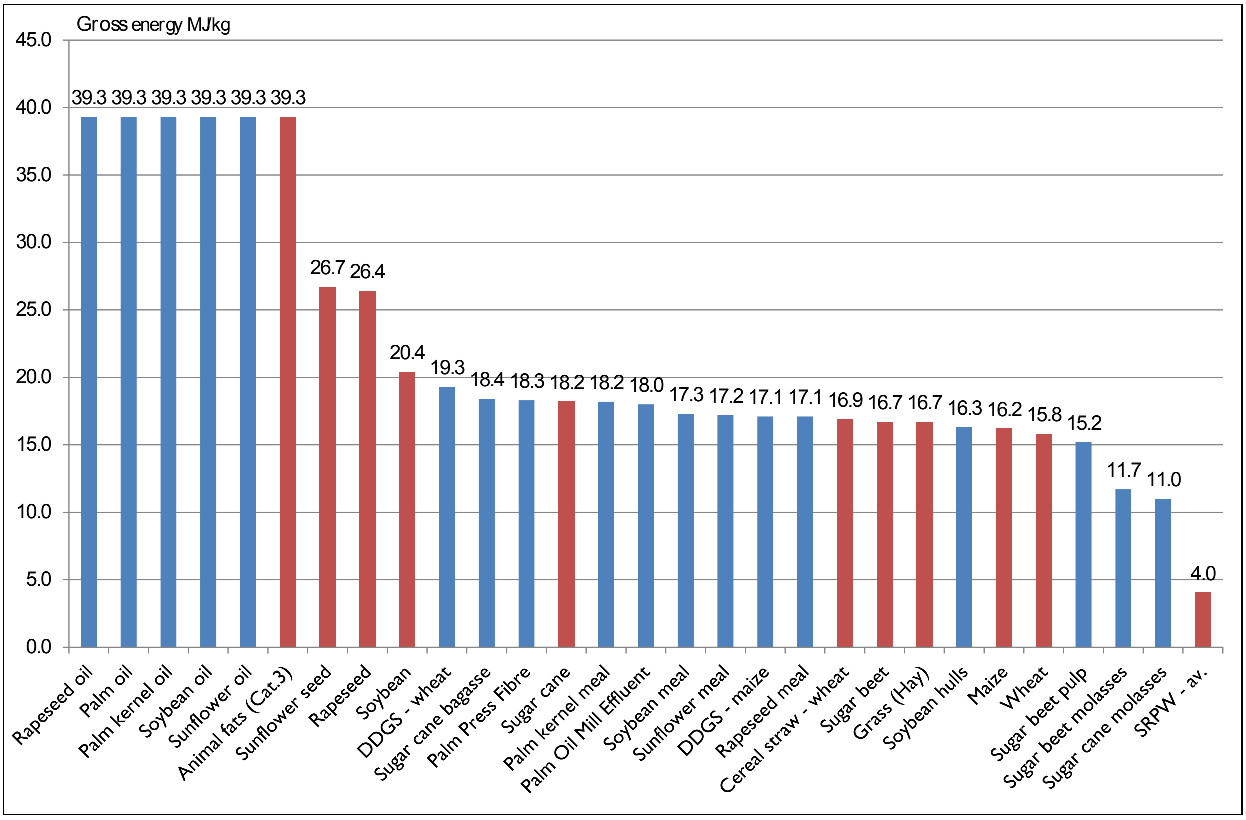

Figure 15: Gross energy content of selected feedstock and potential substitutes (MJ/kg)

Note: selected feedstocks which are the focus of this study are highlighted in red

Energy digestibility

This can be a useful high level indicator of energy, which can be applicable across market sectors. However, when comparing feedstocks and feed materials for livestock feeding specifically, gross energy does not take into account the efficiency of energy utilisation by livestock. Therefore measures of energy digestibility (Ed - %) can provide an indication of the actual amount of energy from a feed that can be available for use by the animal and therefore an alternative indicator of substitutability between feedstock types.

Table 13 below presents gross energy and energy digestibility data for the selected biofuel feedstock. The data shows the comparative availability of energy to livestock through feeding based on the relative digestibility of the feedstock. The values are given as a percentage which can be digested and therefore an indication of substitutability between feedstocks.

Table 13: Gross energy and energy digestibility (Ed) of biofuel feedstocks (MJ/kg; %)

		Wheat	**Maize**	**Sugar beet**	**Sugar cane**	**Rapeseed**	**Palm Fruit Bunch**	**Soybeans**	**Sunflower seed**
Conventional biofuel feedstocks									
Gross Energy	MJ/kg	15.8	16.2	16.7	18.2	26.4	n/a	20.4	26.7
Pigs (growing)	%	88	81	81	36.7	83	*n/a*	78	71
Pigs (sows)	%	89	83	*n/a*	*n/a*	85	*n/a*	85	74
Ruminants	%	86	81	84.6	62.4	87	*n/a*	90	77

Advanced cellulosic and other biofuel feedstocks

		Short Rotation Plantation Wood	**Cereal straw**	**Grass (Hay)**	**Animal fats**
Gross Energy	MJ/kg	4.1	16.9	16.7	39.3
Pigs (growing)	%	*n/a*	12	38	85
Pigs (sows)	%	*n/a*	19	46	85
Ruminants	%	*n/a*	41	70	88

Source: Agra CEAS Consulting

3.3 Price analysis

The assessment involves the collection and construction of historical time series data for each component category (i.e. protein, fats, sugars, starch and fibre) and assesses the correlation between component prices from different feedstocks (including co-products) and the correlation of selected feedstocks (including co-products) with similar component contents.

3.3.1 Data collection

Component price series have been collected where there is an identified market for each component, which mainly applies to fats in the form of vegetable oils, animal fats, crude tall oil and used cooking oil, as well as raw sugar.

For components where a price series was not available, the approach taken is to construct a time series based on the component composition of primary products (i.e. feedstock or co-products) which are most valued for that single component using the decomposition of feedstock products data from the previous task, as well as for additional co-products selected and decomposed for the purposes of this task. For this purpose, a minimum 20% component share[25] was specified for each primary product to determine the main uses of each primary product, although in practice component shares typically ranged from 22% to 99.9%.

In some specific cases where either component or feedstock price series data is available, price series data are estimated based on traded quantities and values. This applies specifically to starch (i.e. native starch from wheat, maize and/or potatoes) (see chapter 3.3.7.1) and fibre from short rotation plantation wood (see chapter 3.3.8.1). In the case of crude tall oil feedstock, price series data is calculated based on an industry approved formula (see chapter 3.3.5.1).

3.3.2 Data sources

Data were obtained from a number of sources, including *inter alia*:

- F.O. Licht;
- ISTA-Mielke;
- Eurostat, and
- DG Agriculture.

Feedstock and primary product prices are reported based on a series of pre-defined International Commercial Terms (INCOTERMS) published by the International Chamber of Commerce (ICC). It was

[25] This applies to the fibre (NDF) category, although the analysis then focuses on cellulose and lignin components of fibre.

determined that it was not necessary to adjust the price series to a uniform basis for a number of important reasons.

- Firstly, data on inter alia material transport, handling and storage costs are not typically available and therefore would have to be estimated.
- In addition, all of the price series selected represent availability of products within the EU (many of which at ports such as Amsterdam, Rotterdam, Antwerp, etc.), whereas there is no information regarding the location of the end user of those products or components.
- Furthermore the differences in component price on a per kg basis introduced by different price terms is small and therefore for modelling purposes it is considered that explain potential variance in price levels is likely to be sufficient.

The relevant terms are explained below.

CIF – Cost, Insurance & Freight (named port of destination): The seller pays for the carriage and insurance of the goods up to the named port of destination. The seller is required to obtain insurance for the goods while in transit to the named port of destination. Risk transfers to buyer when the goods have reached the named port of destination.

FOB – Free on Board (named port of shipment): The seller pays for and arranges delivery of goods to the vessel including loading and export clearance. The buyer pays cost of marine freight transportation, bill of lading fees, insurance, unloading and transportation cost from the arrival port to destination. Risk passes from the seller to the buyer when the goods are loaded aboard the vessel.

FOT – Free on Truck (named place of transport): Similar to FOB, but for road transport.

FCA – Free Carrier (named place of delivery): The seller delivers the goods, cleared for export as required, at a named place. If delivery occurs at the seller's premises, the seller is responsible for loading the goods on to the buyer's carrier. If delivery occurs at any other place, the buyer is responsible for both unloading the goods and loading them onto their own carrier.

EXW – Ex Works (named place of loading): The seller makes the goods available at their premises and the buyer incurs the risks for bringing the goods to their final destination. Loading onto a carrier (whether by the seller or the buyer) is at the buyer's risk and cost. Ex Works is therefore often used when making an initial quotation for the sale of goods without any costs included.

Dlvd. - Delivered (named place of destination): There are many variations, but essentially the seller is responsible for delivering the goods to the named place in the country of the buyer, and pays all costs in bringing the goods to the destination including import duties and taxes. The buyer is responsible for unloading.

3.3.3 Correlation of feedstock and component price series

Correlation of feedstock price series with similar component contents and correlation of component price series from different feedstocks is assessed using the Pearson product-moment correlation co-efficient method, which is a statistical measurement of the correlation (linear association) between two sets of values. This was selected as an indicator because the primary aim is to assess the extent to which there is association between sets of values, whereas other measures such as r-squared linear regression are used to test a deterministic relationship, or how much of the variance between two variables can be explained by the model.

The Pearson product-moment correlation coefficient for two sets of values, x and y, is given by the formula:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}}$$

where x and y are the sample means of the two arrays of values.

If the value of r is close to +1, this indicates a strong positive correlation, i.e. implies that a linear equation describes the association between X and Y perfectly, with all data points lying on a line for which Y increases as X increases.

If the value of r is close to -1, this indicates a strong negative correlation, i.e. implies that all data points lie on a line for which Y decreases as X increases.

If the value of r is close to 0, this implies that there is no linear correlation between the variables.

3.3.4 Protein

The average price for protein over the period is EUR 0.70/kg; ranging from a low of EUR 0.50/kg to a high of EUR 0.93/kg (Figure 16).

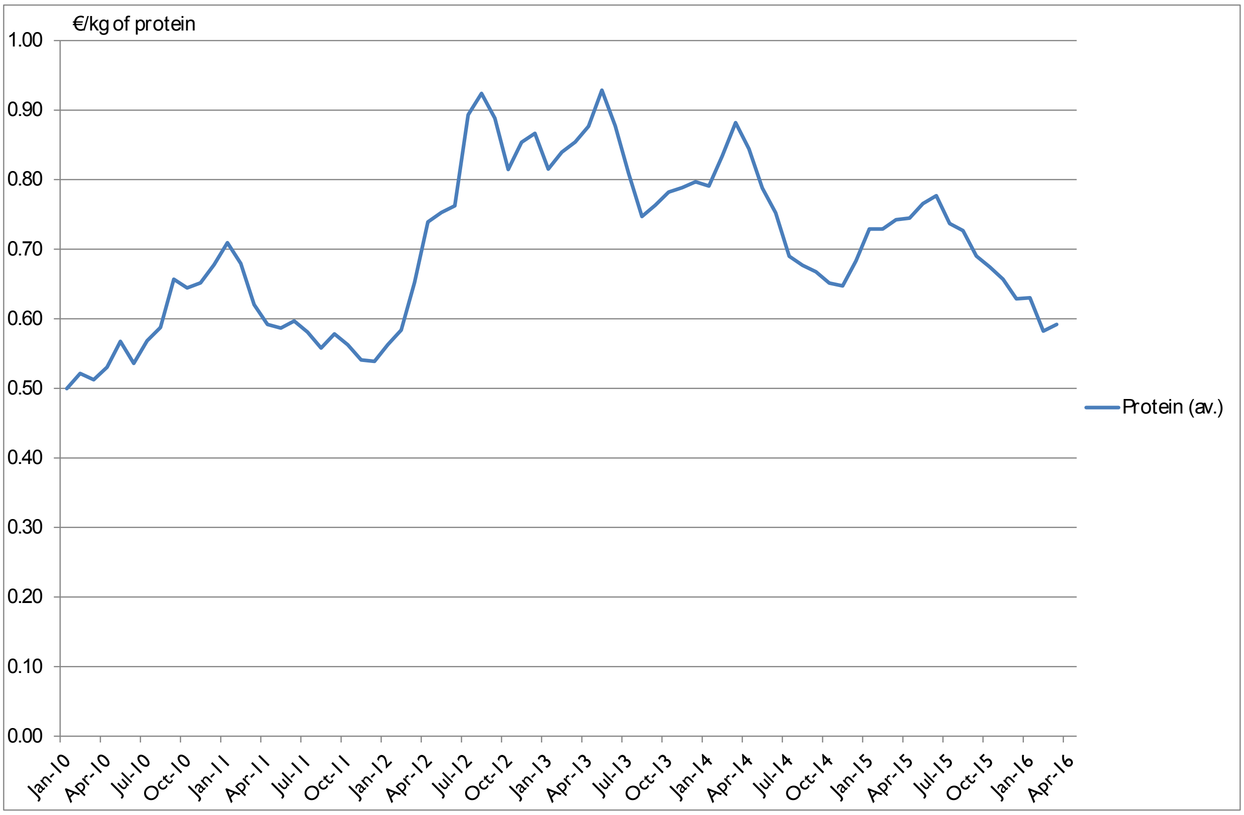

Figure 16: Derived protein price, 2010-16 (€/kg)

Source: Agra CEAS Consulting.

3.3.4.1 Calculation

There is no open market price reporting for protein specifically and therefore prices are calculated based on the component composition of primary products. The following primary products were selected based on a) the feedstocks being assessed by this project; and b) where market demand is determined to be primarily driven by the main component content. All of the primary products have a protein content of >22% and all of the price series are for European supplies. The primary products assessed are:

- **Rapeseed meal (34% protein)**
  - 34% protein, EU origin, Germany (Hamburg), ex-works.
  - 33.7% protein, EU origin, Germany (Hamburg), ex-works.
- **Sunflower meal (33% protein)**
  - 38% protein, Argentina origin, Netherlands (Rotterdam), cif.
  - 33% protein, Argentina origin, UK (Liverpool), cif.

- **Soybean meal (45% protein)**
  - 45% protein, Argentina origin, Netherlands (Rotterdam), cif.
- **Palm kernel meal (22% protein)**
  - 22% protein, Malaysia origin, Netherlands (Rotterdam), cif.
- **DDGS (wheat) (31% protein)**
  - 31% protein, EU origin, Belgium (Ghent), ex-works.

Analysis of the association between primary product price series over the period from 2010-2016 produces very strong Pearson correlation coefficients ranging from r=0.72 to r=0.95. *A priori*, this is to be expected given that each of these primary products is used as a source of protein for livestock feeding.

Based on the time series data for each primary product over the period from January 2010 to March 2016, the price of protein is calculated based on the respective protein content, e.g. for rapeseed meal with a protein content of 34% you can divide the primary product price (€226/t) by the protein content (34% protein): 224/340= 0.67€/kg protein. The protein component prices for each feedstock type are presented in Figure 17 below.

- **Rapeseed meal** - Average monthly price EUR 0.67/kg protein (ranging over the period from a low of EUR 0.45/kg to a high of EUR 0.91/kg).
- **Sunflower seed meal** - Average monthly price EUR 0.62/kg protein (ranging over the period from a low of EUR 0.43/kg to a high of EUR 0.96/kg).
- **Soybean meal** - Average monthly price EUR 0.79/kg protein (ranging over the period from a low of EUR 0.59/kg to a high of EUR 1.12/kg).
- **Palm kernel meal** - Average monthly EUR 0.68/kg protein (ranging over the period from a low of EUR 0.39/kg to a high of EUR 0.89/kg).
- **DDGS (wheat)** - Average monthly price EUR 0.77/kg protein (ranging over the period from a low of EUR 0.47/kg to a high of EUR 1.09/kg).

The **average price for protein over the period is EUR 0.70/kg** (ranging from a low of EUR 0.50/kg protein to a high of EUR 0.93/kg protein).

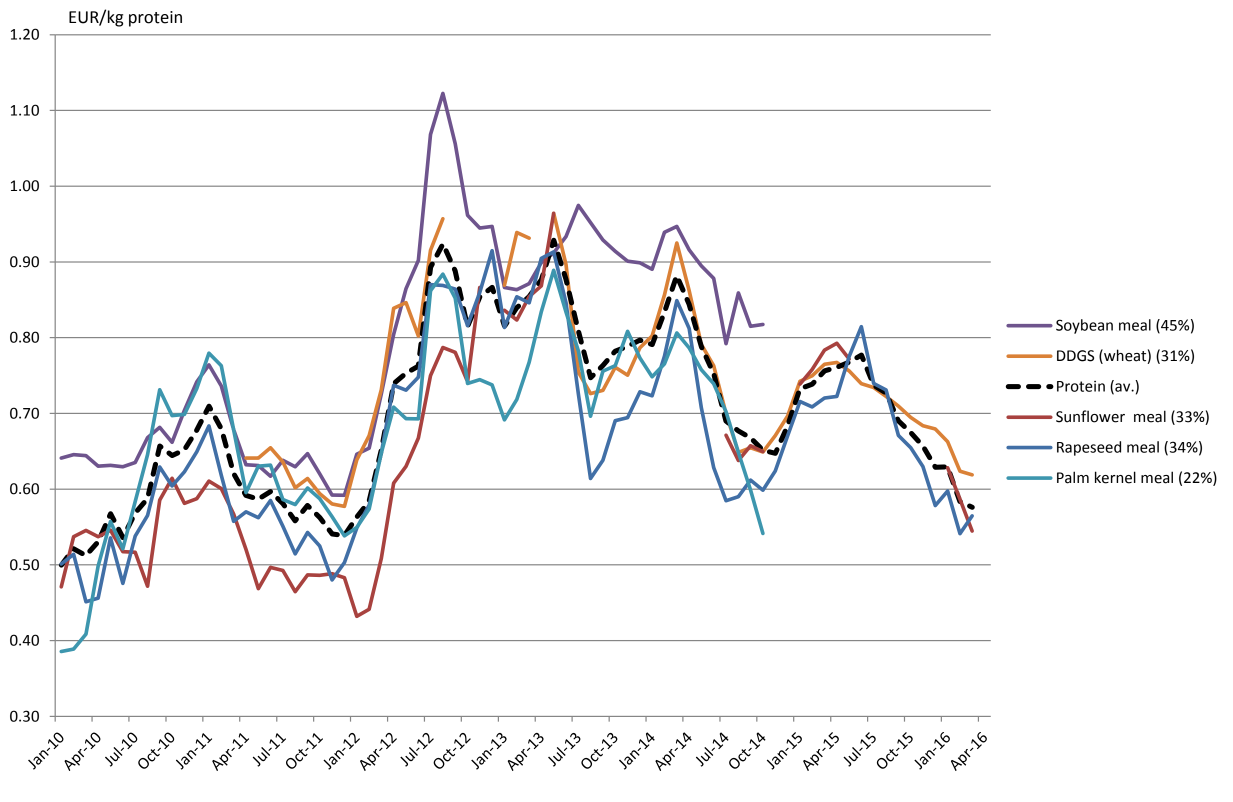

Figure 17: Derived protein prices, 2010-16 (€/kg protein)

Source: Agra CEAS Consulting.

As can be seen from the graph, the component prices are seen to have moved in concordance with each other over time. Analysis of the association between protein component price series between the various feedstock types over the period from 2010-2016 produces very strong Pearson correlation coefficients ranging from r=0.72 to r=0.94 (see Table 14). A priori, this would not be unexpected given the high degree of substitutability between the feedstocks as a source of protein (primarily for the livestock feed sector).

Table 14: Correlation of derived protein prices from selected primary products, 2010-16

	Rapeseed meal	Sunflower meal	Soybean meal	Palm kernel meal	DDGS (wheat)
Rapeseed meal	1.00	0.89	0.85	0.83	0.95
Sunflower seed meal		1.00	0.84	0.72	0.82
Soybean meal			1.00	0.79	0.80
Palm kernel meal				1.00	0.86
DDGS (wheat)					1.00

Source: Agra CEAS Consulting

3.3.5 Fats

The average price for fats over the period is EUR 0.69/kg; ranging from a low of EUR 0.51/kg to a high of EUR 0.89/kg (Figure 18).

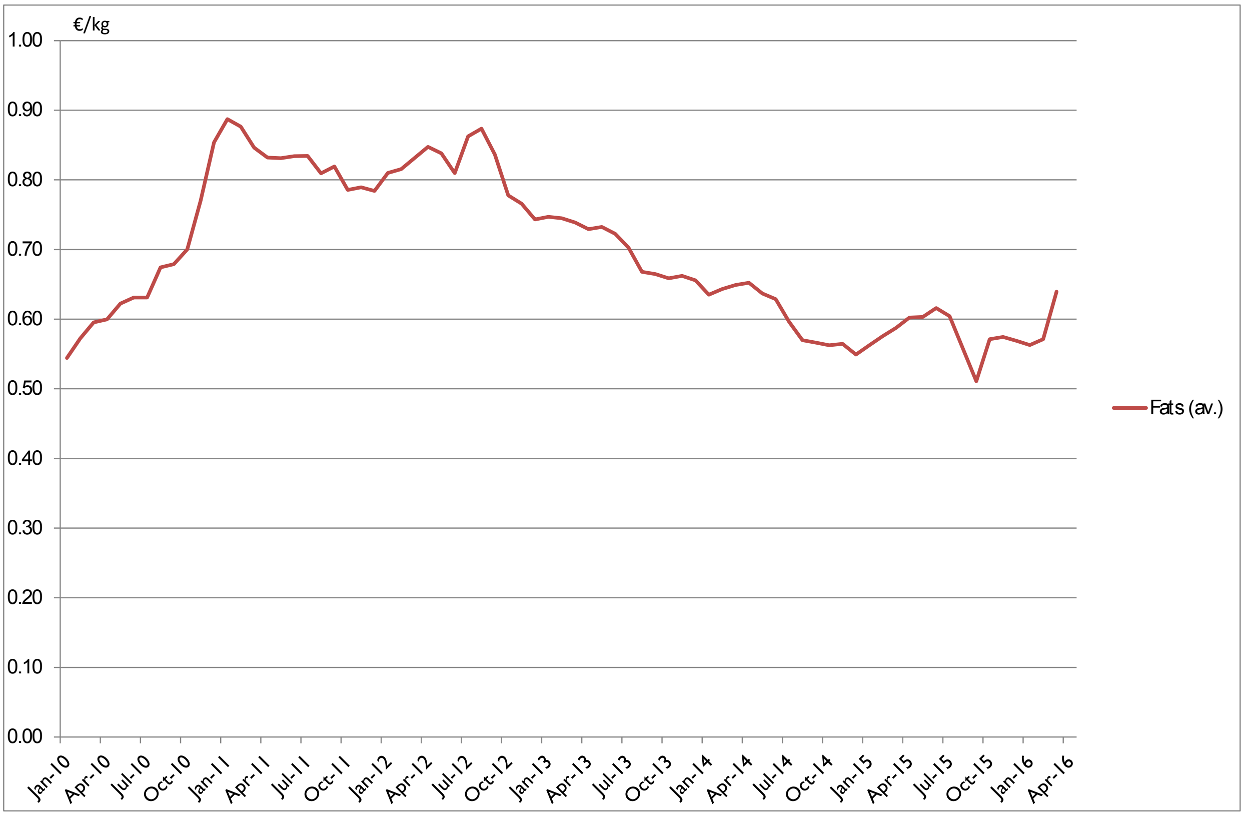

Figure 18: Derived fats price, 2010-16 (€/kg)

Source: Agra CEAS Consulting.

3.3.5.1 Calculation

There is de facto open market price reporting for fats by virtue of that fact vegetables oils extracted from oilseed meals, used cooking oil and animal fats from carcass rendering have component compositions of virtually 100% fat. The exception here is crude tall oil extracted from pine wood for which prices are estimated based on an industry approved formula (see below). The following primary products were therefore selected based on the feedstocks being assessed by this project:

- **Crude Palm Oil (99.9% fats)**
    - Netherlands (Rotterdam), front month, cif.
    - EU (NW ports), cif.
- **Rapeseed Oil (99.9% fats)**
    - EU origin, EU (ARA), nearby delivery, ex-mill.
    - EU origin, Netherlands, nearby delivery, ex-mill.
- **Soybean Oil (99.9% fats)**

  - EU origin, EU (ARA), nearby delivery, ex-mill.
  - EU origin, Netherlands, nearby delivery, ex-mill.
- **Sunflower Oil (99.9% fats)**
  - EU origin, EU (ARA), front month, cif.
  - EU origin, EU (NW ports), fob.
- **Crude Tall Oil (99.5% fats)**
  - EU, cif (constructed data series).
- **Animal Fats (99.8% fats)**
  - Animal fat (Tallow) (Cat. III), EU origin, EU (ARA), fob.
  - Animal fat (Cat. I and II), EU origin, Germany, ex-works.
  - Animal fat (Cat. III), EU origin, Germany, ex-works.
- **Used Cooking Oil (98.1% fats)**
  - EU origin, EU (ARA), fob.
  - EU origin, Germany, ex-works.
  - EU origin, EU (Southern), ex-works.

For crude tall oil (CTO), a price series was constructed based on a formula (validated by industry correspondence) incorporating Carbon Dioxide (CO_2) and Heavy Fuel Oil (1% Sulphur) prices:

$$\text{CTO price / tonne} = (0.9 \times \text{HFO price}) + 30\ \text{€/tonne} + (2.9 \times \text{CO2 price})$$

Analysis of the association between primary product price series over the period from 2010-2016 produces strong to very strong Pearson correlation coefficients ranging from r=0.49 to r=0.98. *A priori*, this is to be expected given the relative substitutability of the primary products as sources of fats for livestock feeding, energy and industrial uses.

Based on price data for each primary product over the period from January 2010 to March 2016, the price of fats is calculated based on the respective fats content, e.g. for rapeseed oil with a fats content of 100% you can divide the primary product price (€814/t) by the fats content (99.9% fats): 814/999= 0.81€/kg fats. The fats component price series for each feedstock type is presented in Figure 19 below.

- **Crude Palm Oil** - Average monthly price EUR 0.68/kg fats (ranging over the period from a low of EUR 0.47/kg fats to a high of EUR 0.96/kg fats.
- **Rapeseed Oil** - Average monthly price EUR 0.81/kg fats (ranging over the period from a low of EUR 0.64/kg fats to a high of EUR 1.08/kg fats).
- **Soybean Oil** - Average monthly price EUR 0.80/kg fats (ranging over the period from a low of EUR 0.64/kg fats to a high of EUR 1.03/kg fats).
- **Sunflower Oil** - Average monthly price EUR 0.84/kg fats (ranging over the period from a low of EUR 0.62/kg fats to a high of EUR 1.12/kg fats).
- **Crude Tall Oil** - Average monthly price EUR 0.42/kg fats (ranging over the period from a low of EUR 0.17/kg fats to a high of EUR 0.57/kg fats).
- **Animal Fats** - Average monthly price EUR 0.62/kg fats (ranging over the period from a low of EUR 0.22/kg fats to a high of EUR 0.88/kg fats).
- **Used Cooking Oil** - Average monthly price EUR 0.69/kg fats (ranging over the period from a low of EUR 0.40/kg fats to a high of EUR 0.85/kg fats).

The **average price for fats over the period is EUR 0.69/kg** (ranging from a low of EUR 0.51/kg to a high of EUR 0.89/kg). It should be noted that these are extracted component/product price series and therefore the price includes an implicit production cost.

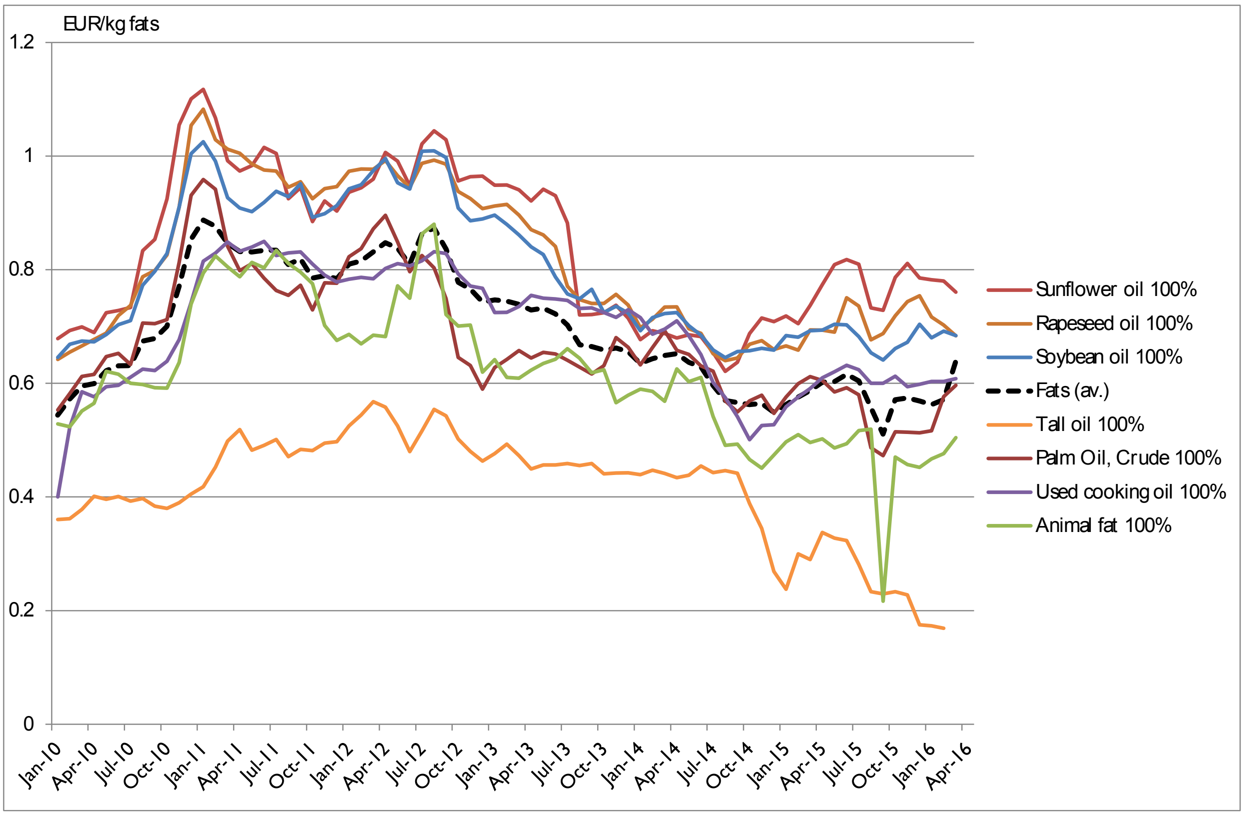

Figure 19: Derived fats prices, 2010-16 (€/kg fats)

Source: Agra CEAS Consulting.

As can be seen from the graph, the component prices are seen to have generally moved in concordance with each other over time (Table 15). The price of crude tall oil trends below that of other oils, as it is arguably less influenced by agricultural (food, livestock feed) market factors. This reflects the relative substitutability between feedstocks for different markets, as well as origins of the various feedstock products. Looking at the Pearson correlation coefficient values between the fats price series,

- there is very strong correlation between all of the vegetable oils, palm oil, animal fats and used cooking oil (r=0.74 to r-0.98);
- there is very strong correlation between animal fats, used cooking oil and crude tall oil (r=0.73 to r=0.76);
- there is strong correlation between crude tall oil and sunflower oil (r=0.49).

Table 15: Correlation of derived fats prices from selected primary products

Correlation	Crude palm oil	Rapeseed oil	Soybean oil	Sunflower oil	Crude Tall Oil	Animal fats	Used cooking oil
Crude palm oil	1.00	0.85	0.87	0.76	0.69	0.83	0.76
Rapeseed oil		1.00	0.98	0.95	0.65	0.84	0.88
Soybean oil			1.00	0.93	0.70	0.86	0.87
Sunflower oil				1.00	0.49	0.74	0.77
Crude Tall Oil					1.00	0.76	0.73
Animal fats						1.00	0.85
Used cooking oil							1.00

Source: Agra CEAS Consulting

3.3.6 Sugars

The average monthly price of sugars over the period is EUR 0.32/kg; ranging from a low of EUR 0.28/kg to a high of EUR 0.37/kg (Figure 20).

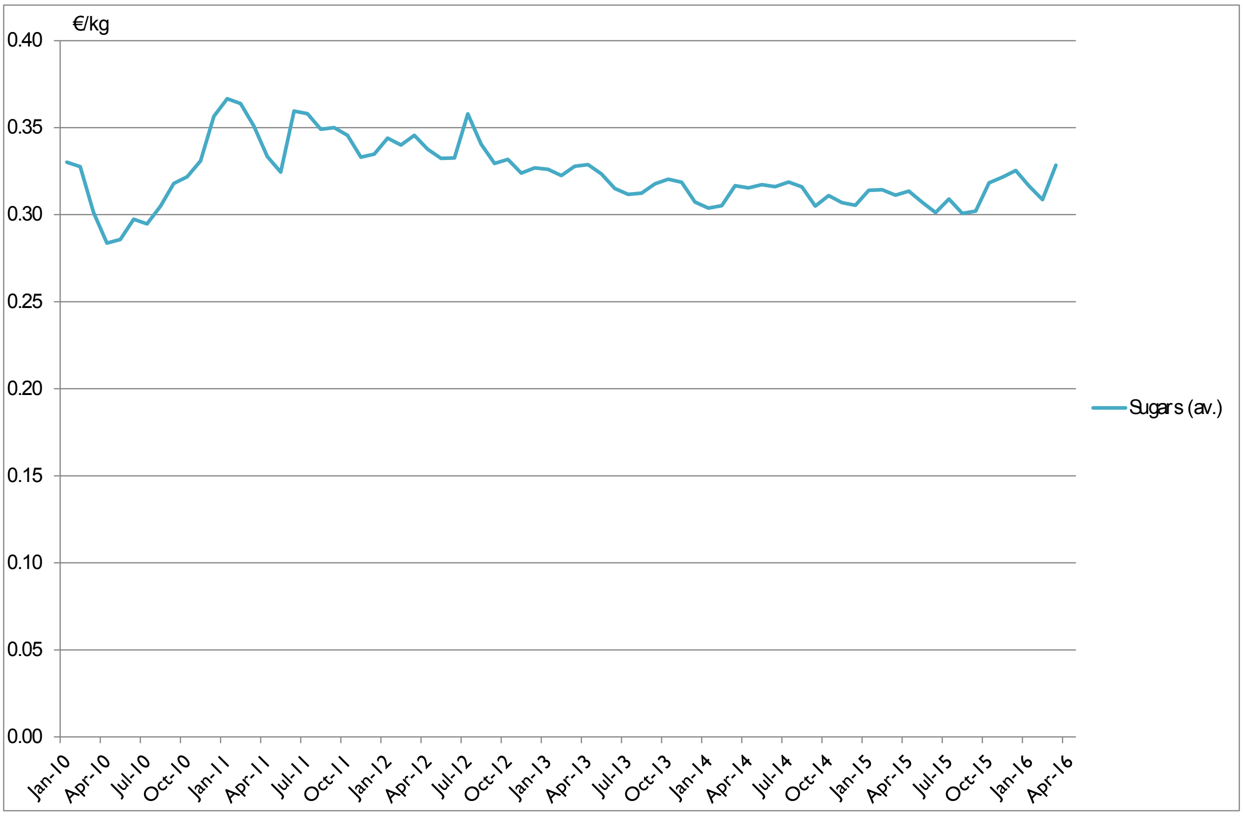

Figure 20: Derived sugars price, 2010-16 (€/kg)

Source: Agra CEAS Consulting.

3.3.6.1 Calculation

There is open market price reporting for sugars in the form or raw and white sugar (sucrose) as well as beet and cane molasses. The following primary products were therefore selected based on the feedstocks being assessed by this project:

- **Sugar beet molasses (45% sugar)**
  - EU origin, Austria, ex-works.
  - EU origin, EU, ex-works (EU representative market price[26]).
  - 42% sugars, EU origin, Germany, fca.
  - 47% sugars, EU origin, Italy (Bologna), fca.
  - 48% sugars, EU origin, Poland, fca.
  - 48% sugars, Russia origin, Russia (Black Sea), fob.
- **Sugar cane molasses (47% sugar)**
  - EU origin, Belgium (Roeselare), Dlvd.
  - EU origin, EU, ex-works (EU representative market price).
  - EU origin, Spain (Barcelona), cif.
- **Raw sugar (99% sugar)**
  - ISA, fob.

Analysis of the association between primary product price series over the period from 2010-2016 produces very strong Pearson correlation coefficients for cane molasses and ISA raw sugar (r=0.76), but weak correlation between beet and cane molasses (r-0.25) and negligible correlation between beet molasses and ISA raw sugar (r=-0.10). *A priori*, this is to be expected given the different geographies of cane and beet production as well as the relative quantities of cane and beet sugar contributing to the ISA raw sugar price. Nevertheless, despite the weak statistical association, the actual spread between beet and cane molasses on the European market over the period from 2010-2016 averaged just EU €13/t.

Based on price data for each primary product over the period from January 2010 to March 2016, the price of sugars is calculated based on the respective sugars content, e.g. for beet molasses with a sugar content of 47% you can divide the primary product price (€129/t) by the sugars content (47% sugars): 129/470= 0.28€/kg sugar. The sugars component price series for each feedstock type is presented in Figure 21 below.

- **Sugar beet molasses** - Average monthly price EUR 0.31/kg sugars (ranging over the period from a low of EUR 0.26/kg sugars to a high of EUR 0.35/kg sugars).
- **Sugar cane molasses** - Average monthly price EUR 0.33/kg sugars (ranging over the period from a low of EUR 0.29/kg sugars to a high of EUR 0.36/kg sugars).
- **Raw sugar** - Average monthly price EUR 0.33/kg sugars (ranging over the period from a low of EUR 0.23/kg sugars to a high of EUR 0.49/kg sugars).

[26] European Commission, DG Agriculture.

The **average monthly price of sugars over the period is EUR 0.32/kg** (ranging from a low of EUR 0.28/kg to a high of EUR 0.37/kg). It should be noted that the ISA raw sugar price is an extracted component/product price series and therefore includes an implicit production cost.

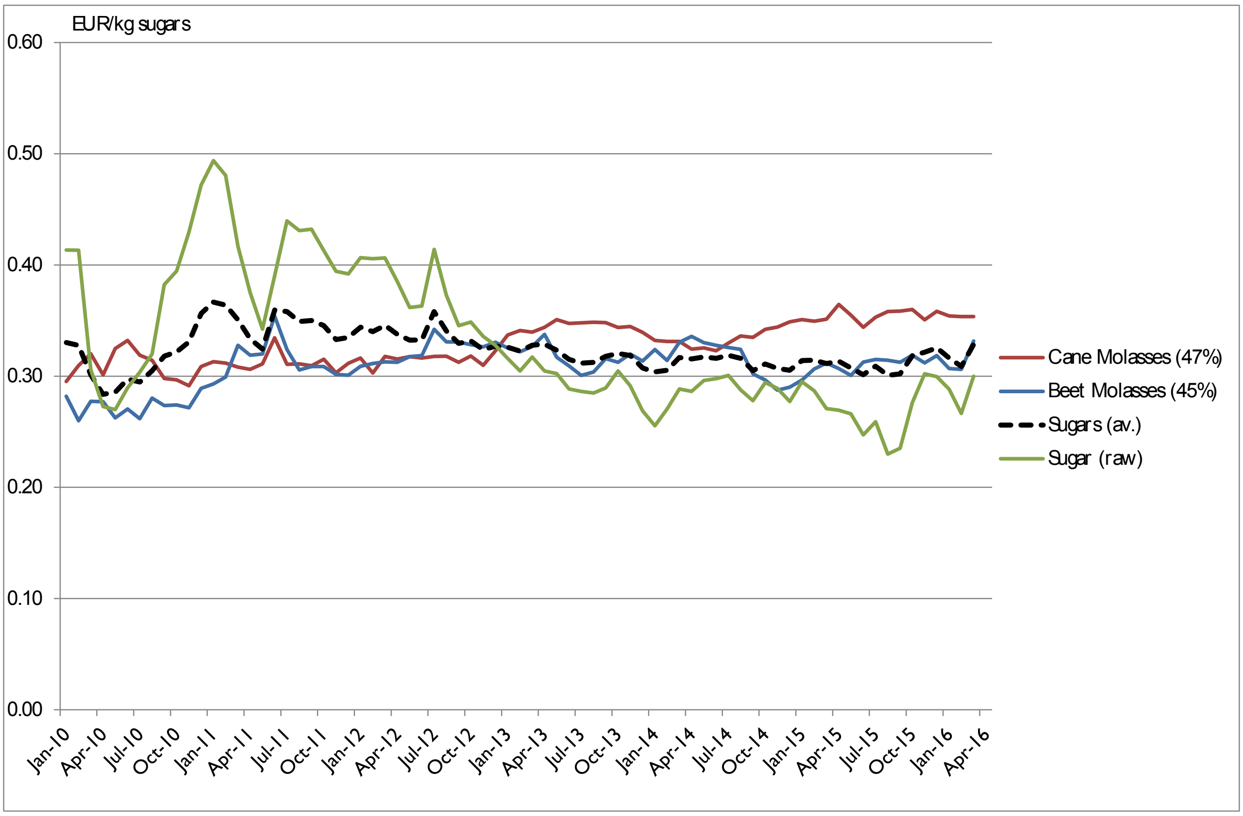

Figure 21: Derived sugars prices, 2010-16 (€/kg sugars)

Source: Agra CEAS Consulting.

As can be seen from the graph, the component prices are seen to have generally moved in concordance with each other over time (Table 16). Looking at the Pearson correlation coefficient values between the sugar component price series:

- there is a very strong negative correlation between cane molasses and raw sugar (r=-0.76);
- there is weak correlation between beet molasses and cane molasses (r=0.25); and
- there is no or negligible correlation between beet molasses and raw sugar (r=-0.10). This reflects key differences in the beet sugar and cane sugar markets, their respective geographies and the relative quantities of cane and beet sugar production contributing to the ISA raw sugar price. Nevertheless, despite the weak statistical association, the actual spread between sugar component prices from beet and cane molasses primary product on the European market over the period from 2010-2016 averaged just EU €0.02/kg.

Table 16: Correlation of derived sugars prices from selected primary products

Correlation	Beet Molasses	Cane Molasses	Sugar (raw)
Beet Molasses	1.00	0.25	-0.10
Cane Molasses		1.00	-0.76
Sugar (raw)			1.00

Source: Agra CEAS Consulting

3.3.7 Starch

The average monthly price of starch over the period is EUR 0.40/kg; ranging from a low of EUR 0.30/kg to a high of EUR 0.50/kg (Figure 22).

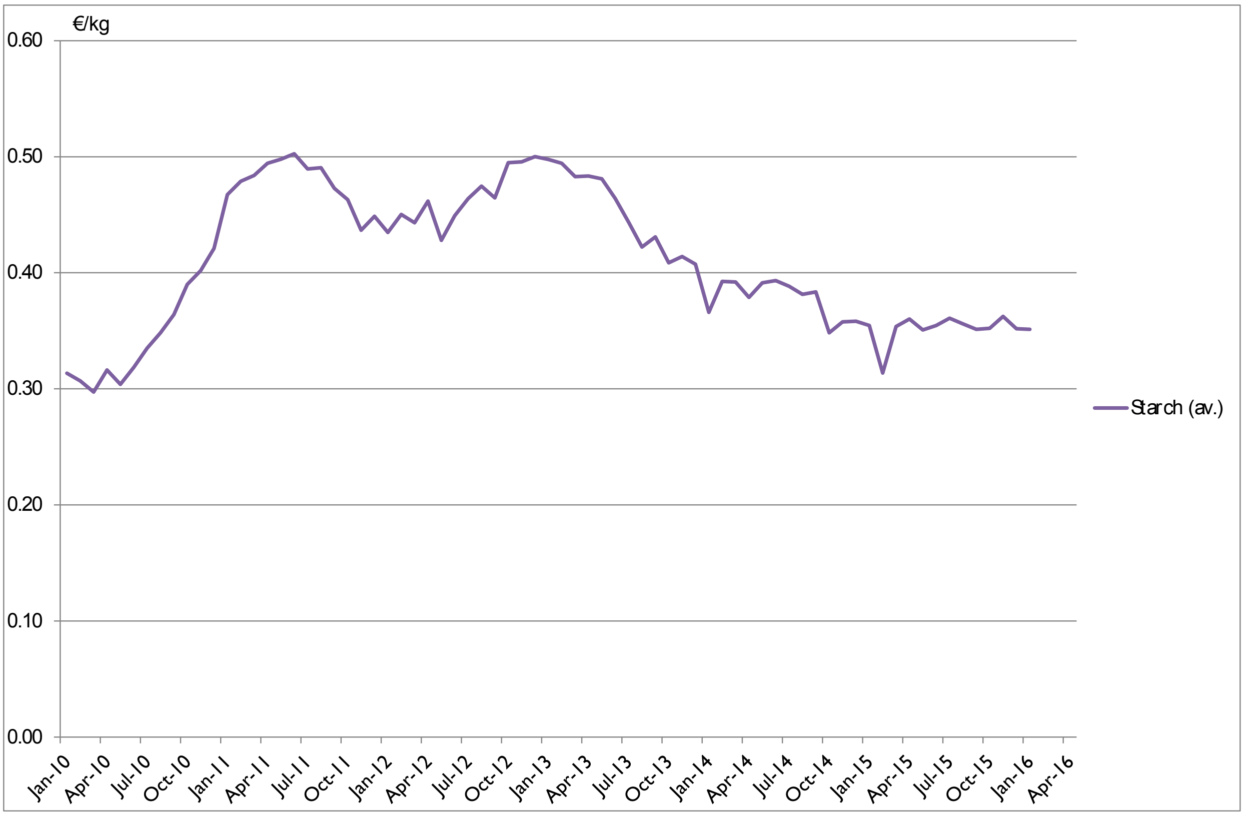

Figure 22: Derived starch price, 2010-16 (€/kg)

Source: Agra CEAS Consulting.

3.3.7.1 Calculation

There is no open market price reporting for starch specifically and therefore prices are calculated based on the component composition of primary products. The following primary products were selected based on a) the feedstocks being assessed by this project and b) where market demand is determined to be primarily driven by the main component content. All of the primary products have a starch content of >61%. The primary products assessed are:

- **Wheat native starch (87% starch)**
  - EU origin, EU, cif (constructed data series).
- **Wheat grain (61% starch)**
  - EU origin, EU, ex-works (EU representative market price[27])
- **Maize native starch (84% starch)**
  - EU origin, EU, cif (constructed data series).
- **Maize grain (64% starch)**
  - EU origin, EU, ex-works (EU representative market price).

Analysis of the association between primary product price series over the period from 2010-2016 produces strong and very strong Pearson correlation coefficients between wheat and maize native starches and their grain feedstocks (r=0.67 to r=0.87). *A priori*, this is to be expected given that feedstock costs contribute the largest share of total production costs for native starch products.

Based on price data for each primary product over the period from January 2010 to March 2016, the price of starch is calculated based on the respective starch content, e.g. for wheat grain with a starch content of 61% you can divide the primary product price (€183/t) by the starch content (61% starch): 183/610= 0.30€/kg starch.

Wheat and maize native starch are extracted components for which open market price data are not available due to the low liquidity in the market which means that most starch is traded by direct contract between buyer and seller, rather than offered on the open market. Prices for wheat and maize native starch are estimated based on reported trade data (Eurostat). The methodology used is to first establish the net trade flow from import and export data. On the assumption that net imports will be priced at import parity and net exports would be priced at export parity, the price per tonne of product is estimated. The component price series is then calculated based on the major component share (as described above).

The starch component price series for each feedstock type is presented in Figure 23.

- **Wheat native starch** - Average monthly price EUR 0.44/kg starch (ranging over the period from a low of 0.31/kg starch to a high of EUR 0.57/kg starch). It should be noted that this is an extracted component/product price series and therefore the price includes an implicit production cost.
- **Wheat grain** - Average monthly price EUR 0.30/kg starch (ranging over the period from a low of EUR 0.19/kg starch to a high of EUR 0.42/kg starch).
- **Maize native starch** - Average monthly price EUR 0.60/kg starch (ranging over the period from a low of 0.38/kg starch to a high of EUR 0.72/kg starch). It should be noted that this is an extracted component/product price series and therefore the price includes an implicit production cost.
- **Maize grain** - Average monthly price EUR 0.29/kg starch (ranging over the period from a low of EUR 0.21/kg starch to a high of EUR 0.39/kg starch).

[27] European Commission, DG Agriculture.

The **average monthly price of starch over the period is EUR 0.41/kg** (ranging from a low of EUR 0.30/kg to a high of EUR 0.50/kg). It should be noted that this includes extracted component/product price series and therefore the price includes an implicit production cost. It should be noted that the native starch component/product price series are for extracted starch products and therefore the price includes an implicit production cost, whereas the component price series for the wheat and maize grain do not.

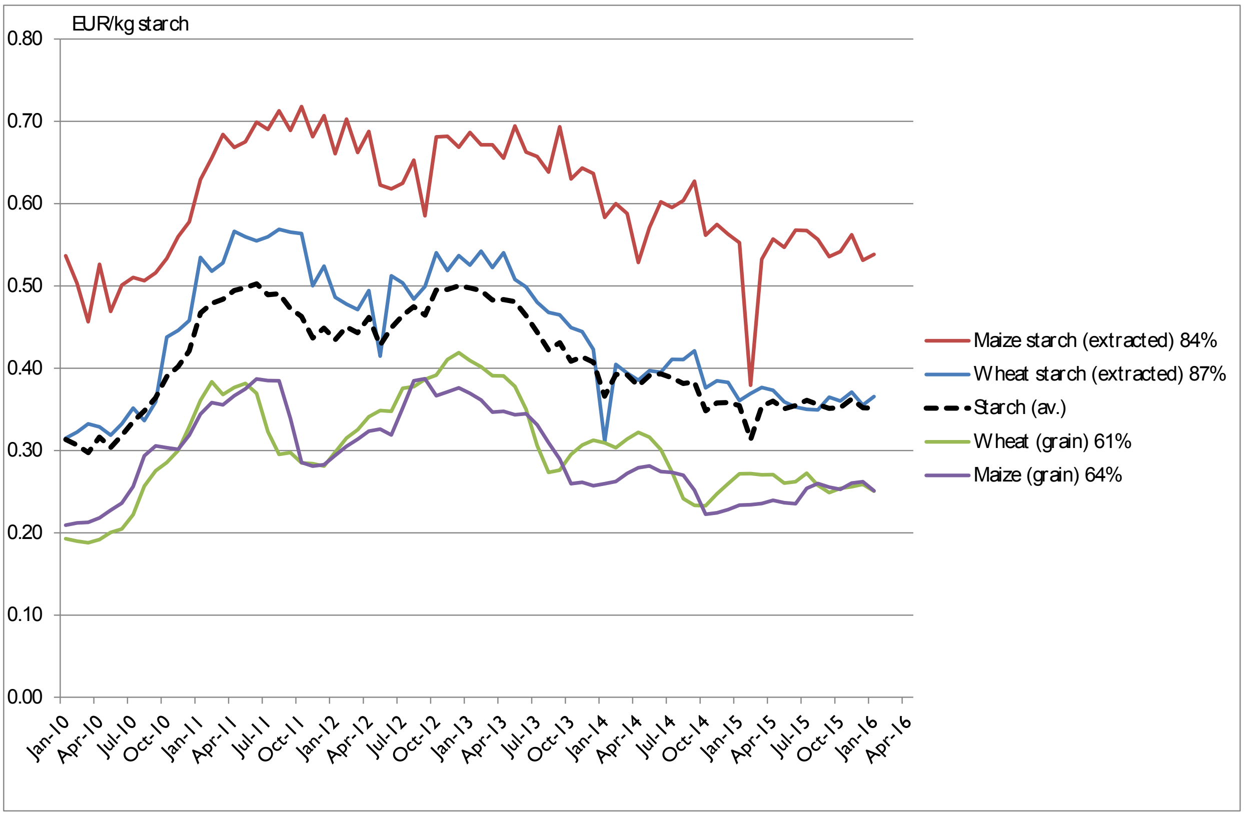

Figure 23: Derived starch prices, 2010-16 (€/kg starch)

Source: Agra CEAS Consulting.

As can be seen from the graph, the component prices are seen to have moved in concordance with each other over time. Looking at the Pearson correlation coefficient values (see Table 17 below) between the starch price series:

- There is very strong correlation between wheat native starch product prices and the price of the starch component in wheat grain (r=0.78);
- There is very strong correlation between maize native starch product prices and the price of the starch component in maize grain (r=0.87);
- There is a very strong correlation between wheat and maize starch component prices (r=0.87); and
- There is a very strong correlation between wheat and maize native starch prices (r=0.86)

Table 17: Correlation of derived starch prices from selected primary products

Correlation	Wheat native starch	Maize native starch	Wheat	Maize
Wheat native starch	1.00	0.86	0.78	0.87
Maize native starch		1.00	0.67	0.71
Wheat			1.00	0.87
Maize				1.00

Source: Agra CEAS Consulting

3.3.8 Fibre - Cellulose

The average price for cellulose over the period is EUR 0.34/kg fibre; ranging from a low of EUR 0.27/kg fibre to a high of EUR 0.47/kg fibre (Figure 24).

Figure 24: Derived cellulose price, 2010-16 (€/kg)

Source: Agra CEAS Consulting.

3.3.8.1 Calculation

There is no open market price reporting for cellulose and therefore prices are calculated based on the component composition of the three ligno-cellulosic feedstocks which are the focus of this study, namely grass hay, cereal straw and short rotation plantation wood, which have cellulose component contents of between 19.0% and 38.3%. Non-coniferous wood chips are analysed as a proxy for short rotation plantation wood since it is a traded commodity based on the same types of tree species which comprise short rotation plantation wood, i.e. deciduous hardwood (non-coniferous) tree species including inter alia Alder, Ash, Birch, Poplar, Willow, etc.

- **Grass hay (49% fibre (NDF); 24.3% cellulose)**
  - EU origin, UK, ex-works.
- **Cereal straw (72% fibre (NDF); 38.3% cellulose)**
  - EU market, cif (constructed data series).
- **Non-coniferous wood chips (45% fibre (NDF); 19.0% cellulose)**
  - EU market, cif (constructed data series).

Analysis of the association between primary product price series over the period from 2010-2016 produces moderate Pearson correlation coefficients between grass hay and cereal straw (r=0.39), but negligible association between cereal straw and non-coniferous wood chip (r=0.13). *A priori*, this is to be expected given that each of these feedstock products are used as a source of fibre for the livestock sector, whereas one of the main uses of wood chip is in the bio-energy sector.

Based on price data for grass hay over the period from January 2010 to March 2016, the price of cellulose per tonne is calculated based on the respective starch content, e.g. for grass hay with a cellulose content of 24.3%, divide the hay price (€87/t) by the cellulose content (24.3%): 87/243 = 0.36€/kg cellulose.

Open market prices for cereal straw are available for some market, (e.g. the UK), but not for all or for the EU as a whole. The situation for non-coniferous wood chip is similar. Prices are therefore estimated based on reported trade data (Eurostat). The methodology used is to first establish the net trade flow from import and export data. On the assumption that net imports will be priced at import parity and net exports would be priced at export parity, the price per tonne of product is estimated. The component price series is then calculated based on the major component share (as described above). Note that the cereal straw price estimates were cross checked with annual data from DG Agriculture and found to correspond closely, however annual data is insufficient for the purposes of this study.

The cellulose component price series for each feedstock type is presented in Figure 25.

- **Grass hay** - Average monthly price EUR 0.36/kg fibre (ranging over the period from a low of EUR 0.23/kg fibre to a high of EUR 0.66/kg fibre).
- **Cereal straw** - Average monthly price EUR 0.28/kg fibre (ranging over the period from a low of EUR 0.20/kg fibre to a high of EUR 0.37/kg fibre).
- **Non-coniferous wood chips** - Average monthly price EUR 0.40/kg fibre (ranging over the period from a low of EUR 0.32/kg fibre to a high of EUR 0.46/kg fibre).

The **average price for cellulose over the period is EUR 0.34/kg** (ranging from a low of EUR 0.27/kg to a high of EUR 0.47/kg).

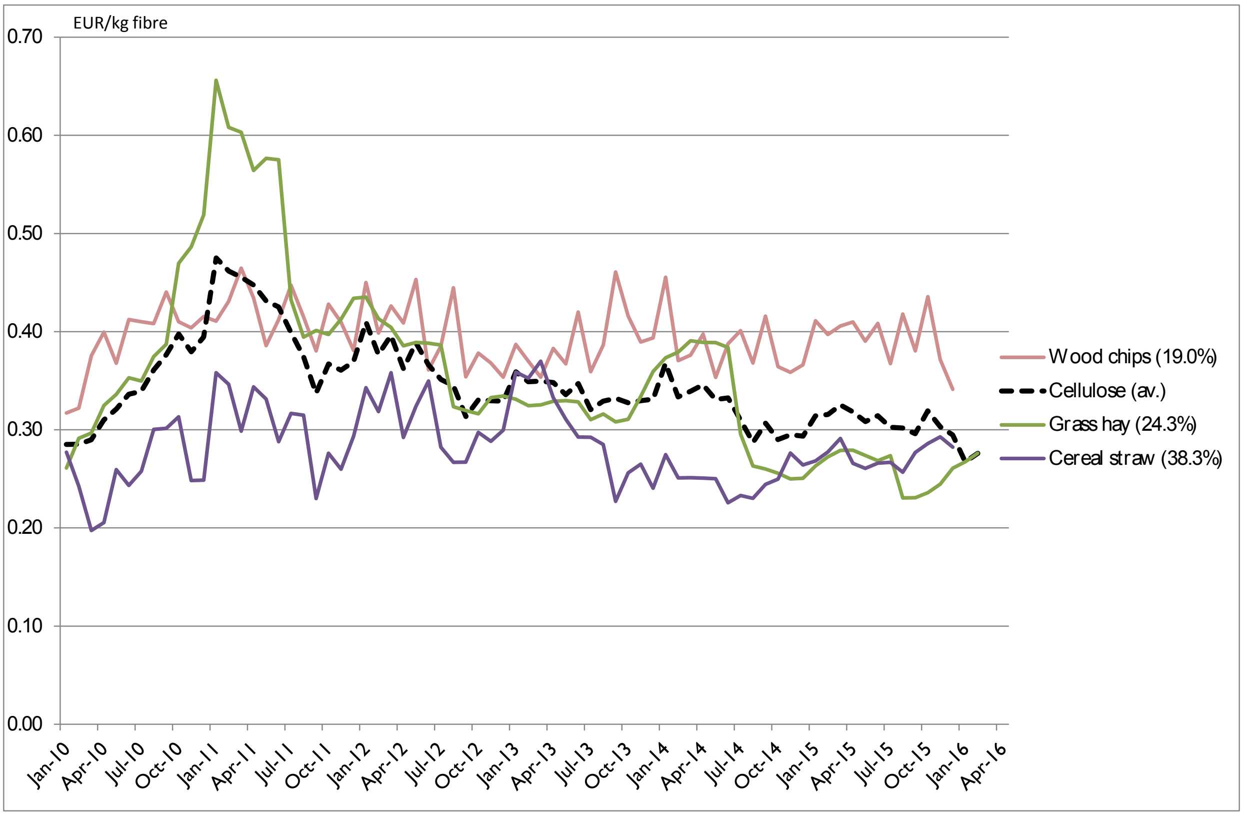

Figure 25: Derived cellulose prices, 2010-16 (€/kg cellulose)

Source: Agra CEAS Consulting

As can be seen from the graph, the price of cellulose from biomass-type feedstocks such as grass hay, cereal straw and non-coniferous wood chips fall within a comparatively close range. Looking at the Pearson correlation coefficient values (see Table 18):

- There is moderate to strong correlation between grass hay and both cereal straw and non-coniferous wood chips (r=0.39);
- There is moderate to strong correlation between grass hay and non-coniferous wood chips (r=0.39);
- There is negligible correlation between cereal straw and non-coniferous wood chips (r=0.13).

Table 18: Correlation of derived cellulose prices from selected feedstock

Correlation	Grass hay (24.3%)	Cereal straw (38.3%)	Wood chips (19.0%)
Grass hay (24.3%)	1.00	0.39	0.39
Cereal straw (38.3%)		1.00	0.13
Wood chips (19.0%)			1.00

Source: Agra CEAS Consulting

3.3.9 Component prices - Summary

Figure 26 below presents the derived monthly component prices over the period from 2010 to 2016 in euros per kg of component:

- **Protein**: average EUR 0.70/kg (low EUR 0.50/kg; high EUR 0.93/kg) (see chapter 3.3.4).
- **Fats**: average EUR 0.69/kg (low EUR 0.51/kg; high EUR 0.89/kg) (see chapter 3.3.5).
- **Sugars**: average EUR 0.32/kg (low EUR 0.28/kg; high EUR 0.37/kg) (see chapter 3.3.6).
- **Starch**: average EUR 0.41/kg (low EUR 0.30/kg; high EUR 0.50/kg) (see chapter 3.3.7).
- **Cellulose** fibre: av. EUR 0.34/kg (low EUR 0.27/kg; high EUR 0.47/kg) (see chapter 3.3.8).

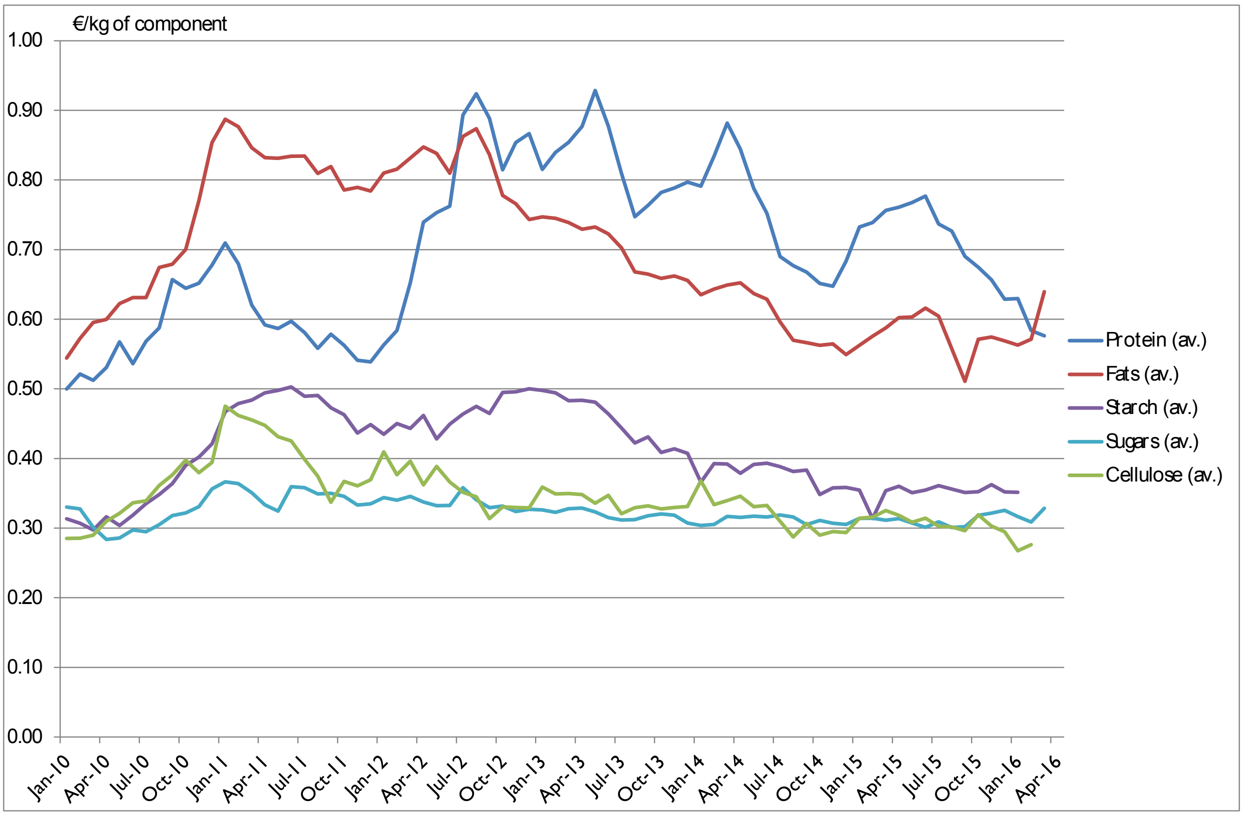

Figure 26: Derived component prices, 2010-16 (€/kg)

Source: Agra CEAS Consulting.

4 Conclusions Task 1-2

Tasks 1 and 2 aim to decompose biomass feedstock crops into various separate crop components, to value components and assess the extent to which components from different crops can be substituted. Initial component categories are based on 3 macro-nutrients contained in biomass materials. Macro-nutrients are based on nutritional requirements for food and livestock feed, but are also key component categories for bio-energy. The three main macro-nutrients are protein (containing *inter alia* amino acids), fats (containing *inter alia* fatty acids and glycerol) and carbohydrates (containing *inter alia* sugars, starch and cellulose). Of particular relevance to current and future biofuel technologies, it was decided that the three main components within the carbohydrate category should be analysed as distinct components, i.e. sugars, starch and fibre (of which cellulose, hemicellulose and lignin).

The disaggregation of components within biomass is based on proximate and sequential analysis in laboratories, which has been developed over a considerable period of time to approximate the digestive process of livestock. This process separates compounds in a feedstock into six categories (water, ash, crude protein, crude fat, crude fibre and nitrogen-free extracts (digestible carbohydrates) based on the chemical properties of the compounds. The results are a categorisation of components based upon common chemical properties. We identified protein, fats, sugar, starch and fibre (further decomposed into cellulose, hemicellulose and lignin) to be the most relevant component categories.

Component price series have been collected where there is an identified market for each component. This mainly applies to fats extracted from raw materials in the form of vegetable oils, crude tall oil, animal fats and used cooking oil; starch; and raw sugar. For these primary products, it is noted that the prices are for 'extracted components' and therefore an element of production cost is also included.

For components where a price series was not available, the approach taken is to construct a time series based on the price of key primary products which are determined to be valued mainly on the basis of a single component. Primary products were selected based on two criteria, i) that the primary product is, or is derived from, one of the bio-energy feedstocks under consideration within the scope of this study; and ii) that the minimum component content within each primary product should be>20% (in practice component shares typically ranged from 22% to 99.9%). Based on the price series for a selected primary product with known component composition, the price of the main component on a per kg basis is calculated.

Where no open market price series exists for a primary product valued primarily for a single component, a price series for both the primary product and main constituent component was constructed. Two methods were used: i) a price calculation based on customs data on trade quantity and value; and ii) in the specific case of crude tall oil, a price series was constructed based on a formula (validated by industry correspondence) incorporating Carbon Dioxide (CO_2) and Heavy Fuel Oil (<1% Sulphur) prices. For these primary products, it is noted that the prices are for 'extracted components' and therefore an element of production cost is also included.

The primary products selected for the analysis of component prices are listed as follows:

- **Protein**
  - Rapeseed meal (34% protein)
  - Sunflower meal (33% protein)
  - Soybean meal (45% protein)
  - Palm kernel meal (22% protein)
  - DDGS (wheat) (31% protein)

- **Fats**
  - Crude Palm Oil (99.9% fats)
  - Rapeseed Oil (99.9% fats)
  - Soybean Oil (99.9% fats)
  - Sunflower Oil (99.9% fats)
  - Crude Tall Oil (99.5% fats)
  - Animal Fats (99.8% fats)
  - Used Cooking Oil (98.1% fats)

- **Sugars**
  - Sugar beet molasses (45% sugar)
  - Sugar cane molasses (47% sugar)
  - Raw sugar (99% sugar)

- **Starch**
  - Wheat native starch (87% starch)
  - Wheat grain (61% starch)
  - Maize native starch (84% starch)
  - Maize grain (64% starch)

- **Fibre**
  - Grass hay (49% fibre (NDF); 24.3% cellulose)
  - Cereal straw (72% fibre (NDF); 38.3% cellulose)
  - Non-coniferous wood chips (45% fibre (NDF); 19.0% cellulose)

An average price series over the period 2010-2014 for each primary product was calculated and from this an average price series for each component category was calculated.

The results are as follows:

- The average price for **protein** over the period is **EUR 0.70/kg** (ranging from a low of EUR 0.50/kg protein to a high of EUR 0.93/kg protein).

- The average price for **fats** over the period is **EUR 0.69/kg** (ranging from a low of EUR 0.51/kg to a high of EUR 0.89/kg).

- The average monthly price of **sugars** over the period is **EUR 0.32/kg** (ranging from a low of EUR 0.28/kg to a high of EUR 0.37/kg).

- The average monthly price of **starch** over the period is **EUR 0.41/kg** (ranging from a low of EUR 0.30/kg to a high of EUR 0.50/kg).

- The average price for **cellulose (fibre)** over the period is **EUR 0.34/kg** (ranging from a low of EUR 0.27/kg to a high of EUR 0.47/kg).

The constructed component price data is taken as a proxy for the economic value of components, although it is noted that component values are affected by factors which affect the substitutability of components from different feedstocks, such as gross energy content, digestibility, amino acid content, fatty acid content, lignin-cellulose ratio, etc. as noted in section 3.2.

Discussion on assessment of economic value of crop component categories

Our component category valuation is based on historical price series of products most valued for the component that is assessed and thus reflects the cost of sourcing protein from various feedstocks and coproducts. For example, we assume that rapeseed meal is mostly valued for its protein content and the protein value is then based on the protein content of rapeseed meal. We trust that both the most important quality aspects of components and the relative supply and demand are captured in these market prices. However, we recommend that further research takes place to determine whether it is possible to treat the same components from different feedstocks as single categories in the calculation of estimated ILUC values; as well as to assess the impact of certain quality aspects on component values [28], such as energy content and digestibility (see section 3.2.5) that potentially affect the economic value of proteins and fats; the amino acid balance and protein damage (see section 3.2.1) are important factors for protein values (notably in DDGS); and the effect of fibre content on protein intake in pigs (the largest overall user of protein-rich feed materials such as oilseed meals) (see section 3.2.4).

We recognise that *inter alia* energy has a value and provide data on this and other factors in the context of qualitative discussion of their effect on substitutability between components from different sources. However, we did not consider the isolation of energy from other components in this analysis (i.e. it was not selected as one of the components for decomposition in Task 1). There are undoubtedly potential alternative component valuation methods such as Pearson square, simultaneous equations, matrices and least-cost formulations based on linear programming and regression analysis; however, all have their specific limitations for this application, ranging from only being able to balance one nutrient at a time, only being valid for one type of livestock at a time, complex mathematics, or requiring detailed scientific nutritional knowledge. On balance it was decided that a simplified methodology based on identifying market price series for feedstocks and co-products which are valued primarily for single components was a pragmatic approach to deriving component prices which reflect the cost of sourcing components from various feedstocks and coproducts (despite the additional unavoidable presence of other components such as energy which may affect the component values).

[28] Based on correspondence between the authors and Robert Edwards, JRC, 2016.

5 Estimating ILUC effects of crop components

Indirect land use change associated with bioenergy production has been assessed so far by type of crop feedstock, such as wheat, maize, sugar beet, sugar cane for ethanol, or rapeseed, soybean, sunflower, palm fruit for biodiesel (see IFPRI and GLOBIOM studies). However, these different materials are not consumed entirely for the production of bioenergy, only a part of their components is converted to biofuel. Other components are fed back to the market as coproducts and consumed for different purposes.

Task 1 of this study has been looking at what the different components constituting the most fundamental uses of the different crops and materials used for bioenergy are. Most important components identified have been: starch, sugar, proteins, lipids and fibres. These components are present in all crops and constitute the basis for the different uses of these crops. Starch and sugar can be metabolised by the living organisms into energy, fat are both used for their biophysical and energy carrying properties, and proteins are used as the elementary bricks of living organisms.

Moving from a feedstock-based approach to a component-based approach of indirect land use change quantification would mean for instance that the previously investigated question – "what is the impact on land use of producing 1 MJ from wheat (starch)?" – would be changed into "what is the impact on land use of producing 1 MJ from starch". For these questions to be completely equivalent, a fluid starch market would be required, where the different type of starch would be perfectly substitutable. Under this condition, the land use change effect of bioenergy could be directly analysed at the level of feedstock component.

In this task, we look at what the implications could be of estimating ILUC at the component level using the GLOBIOM modelling framework that was previously used to calculate ILUC at the feedstock level. The model can be used to capture some of the component markets through its optimisation framework. The different questions we are looking at are the following:

a) What are the total land use change impacts of crops when capturing all their various components?
b) How do the component ILUC effect compare across feedstock when using GLOBIOM?

To answer these questions, we will use a series of GLOBIOM runs applied to six feedstocks for which components are partly separated, as explained in more details in section 2. We will answer question a) in Section 3 where ILUC crop level results will be analysed. Section 4 will look at the results of component ILUC factors estimation from GLOBIOM through shocks on the different coproducts to answer question b).

5.1 Methodological approach

In order to determine the ILUC of components, two main approaches can be envisaged:

A. **An attributional approach at crop level:** one part of the complexity of the ILUC calculation by component categories is that components are always produced jointly and therefore, mandating a given quantity of component is likely to affect demand for several products at the same time. For instance, implementing an ethanol mandate leads to the production of wheat starch but also wheat dried distiller's grains with solubles (DDGS), which therefore affects the livestock feeding sector. Because land use impact starts at the crop level, one way of going around this problem is to look at the impact of a full crop product itself, i.e. what would be the impact of consuming more wheat. In the usual ILUC calculation for biofuels, other coproducts, such as DDGS, are also sent to the market, therefore the ILUC effect is only partial (see Figure 27). Because the crops contain all the components at the same time, determining the ILUC associated with the full crop could allow to know the full extent of land use impact. This impact could then be distributed across components (starch, DDGS proteins, etc.) on the basis of their mass or their economic value, as usually assumed in an attributional life cycle analysis.

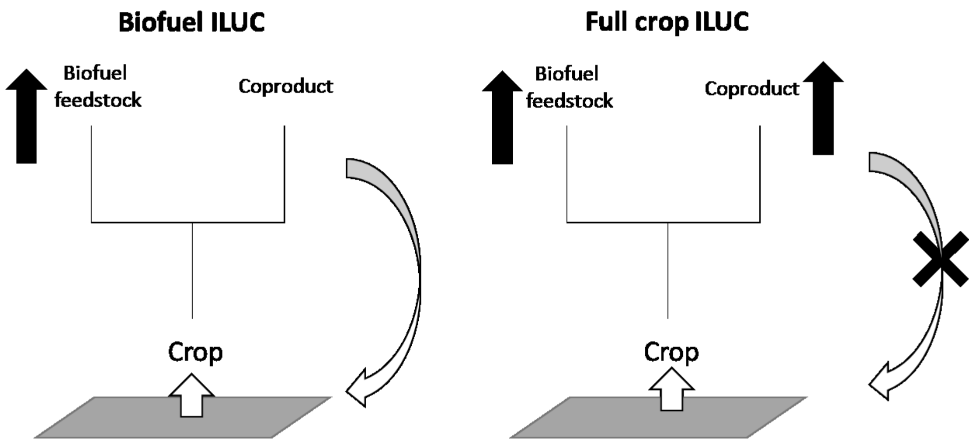

Figure 27. Difference in land use impact of mandating biofuel feedstock (left) versus all crop products (right)

B. **A consequential approach at the component level**: this more comprehensive approach fully relies on a modelling framework and looks at the impact of mandating a certain amount of a particular component (wheat starch). In the case of components used as ILUC feedstocks, this is equivalent to the analysis performed in the GLOBIOM ILUC quantification study of biofuels[29]. However, the discussion of ILUC results in the previous study was not conducted from the perspective of components themselves, but only from the one of energy content. The present analysis can correct for this by expressing all results in tCO_2 per tonne product, instead of tCO_2 per MJ. Additionally, many components were not covered by that

[29] Project ENER/C1/428-2012, LOT 2.

study, because they are not used as biofuel feedstocks. This is the case of proteins, mostly found in the DDGS and oilseed meals coproducts, and fibres present in notable amount in sugar beet pulp.

In order to compare the results from the two approaches A and B above, we focus our analysis on six crops that have been also analysed in the GLOBIOM ILUC study of biofuels. These crops and their coproducts are presented in Table 19. Their composition thanks to Task 1 and through GLOBIOM previous development.

Table 19:- List of products and their components analysed in this report.

Primary product	Biofuel feedstock component	Biofuel co-product (main component)
Wheat grain	Wheat starch	Wheat DDGS (proteins)
Maize grain	Maize starch	Maize DDGS (proteins)
Sugar beet	Beet sugar	Sugar beet pulp (fibre)
Soya bean	Soybean oil	Soybean meal (proteins)
Rapeseed	Rapeseed oil	Rapeseed meal (proteins)
Sunflower seed	Sunflower oil	Sunflower meal (proteins)

Approach A requires the calculation of the full impact of mandating the crop product, as listed in the first column of Table 19. For each of these products, we shock the full crop in GLOBIOM by the amount of product necessary to produce the equivalent of 1% of transportation fuel consumption in the EU as biofuel. The shock is therefore exactly similar to the one performed in the GLOBIOM ILUC study for biofuels, except that the coproducts are not sent to the animal feed markets. This shock is run on the same baseline as in the first ILUC study and results can then be compared to the results obtained at that time with coproducts sent to the feed markets.

Approach B requires to shock the individual components of the crops. These components and their markets are not all represented explicitly in GLOBIOM, in which only products are traded. However, some transformed products, such as cereals starch, sugar or vegetable oils, consist in fact of one single component, such as. Therefore we assume that the calculated ILUC of a biofuel feedstock (second column of Table 19) is equivalent to the ILUC of the components included in the feedstock. . Following this, we use the results from the ILUC quantification study of biofuels for starch, sugar and oil, and convert the results into different metrics from tCO_2 per MJ to tCO_2 per tonne component to ensure comparability with other components. The shock therefore corresponds here to requirements to produce of 1% of transportation fuel consumption in the EU as biofuel, but this time with all other coproducts and their components being sent to their respective markets and consumed.

However, the biofuel shocks cannot provide estimates for all the components required for approach B. For proteins and fibres, we use the biofuel coproducts, which are listed in the third column of Table 19. We perform now a shock on the coproducts of exactly the same magnitude as produced when biofuel are demanded for a 1% shock. Therefore, the quantity shocked is the same as the quantity of coproducts sent to the feed market for the biofuels scenario above, and the quantity shocked for the biofuels and their coproducts separately in approach B, are directly sum up to the quantities shocked in the approach A for the full crop product. In order to calculate the ILUC of the targeted component of each coproduct, we assume like in Task 2 that the main component determines the product use, and derive the component ILUC directly from its concentration in the coproduct.

Box 1. Applying approaches A and B on bioenergy crop: the example of wheat

Wheat can be used to produce ethanol from starch, and other output of the wheat transformation process include dried distillers grains with solubles. Producing 1% of the EU transportation fuel consumption by 2020 (123 PJ) requires approximately 13.6 million tonnes of dry matter wheat to be processed, and more specifically 8.9 million tonnes of starch. This also leads in parallel to the production of 4.7 million tonnes of wheat DDGS. Approach A is implemented by shocking the model by taking out of the market the 13.6 million tonnes of wheat as a whole and looking at the impacts. Approach B only removes the 8.9 million tonnes of starch, in which case the 4.7 million tonnes of wheat DDGS go to the livestock feed market (biofuel shock); and it looks at the opposite case, by removing from the market 4.7 million tonnes of wheat and sending to the fuel market 8.9 million tonnes of starch processed as ethanol (123 PJ). Note that because this last amount is larger than the total quantity of ethanol mandated in 2020 under the baseline scenario, we will analyse in practice the effect of a shock twice lower when shocking the DDGS (2.35 million tonnes) to avoid a saturation of the EU ethanol market.

In total, approach A relies on 6 scenario runs (first column of Table 19), whereas approach B requires 12 scenarios results from GLOBIOM (second and third columns). Their results are presented and analysed in the two following sections, and compared in section 5.

6 Crop component ILUC: attributional approach

In this section, we present an overview of results from the attributional approach (approach A), where crop components are shocked all together, which is equivalent to a bioenergy shock without coproduct feedbacks.

6.1 Crop land use change effect

Results from the 1% shock on the six feedstocks are presented in Figure 28 with the emissions for the full crops on the left, compared to the emissions from the biofuel part of the crop on the right, when the coproducts are sent to the animal feed market.

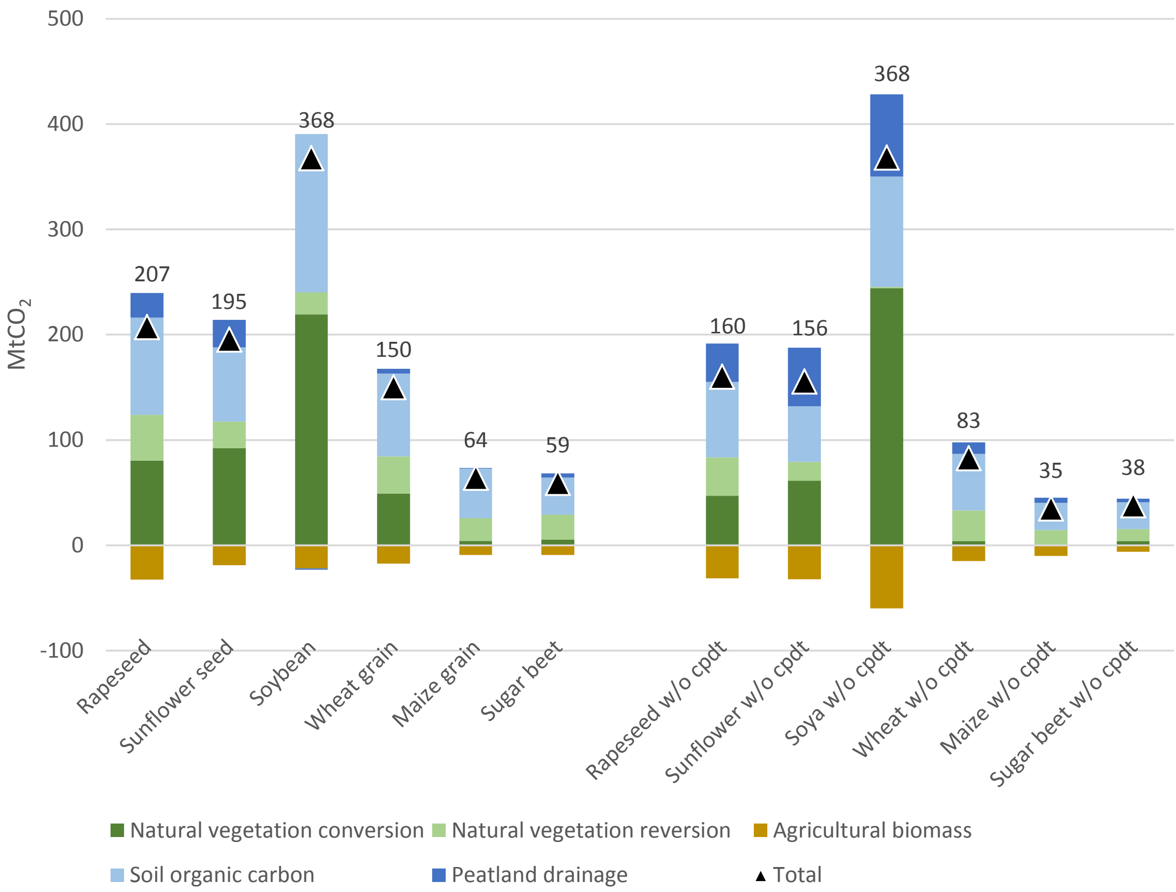

Figure 28. Cumulated emissions over 20 years for the six different selected crops with their coproducts (full LUC, left side) and without these coproducts (partial LUC, right side). Colours correspond to the different sources of emissions, and the black triangle represent the total across sources (positive minus negative emissions).

Most salient findings from these results are:

- The total LUC emissions of the crop appear to follow the same hierarchy as observed in the case of bioenergy feedstock land use change. Soybean land use impact is higher than for rapeseed and sunflower seed, these latter being higher than cereals and sugar beet. Wheat appears to generate significantly higher emissions than corn, due to the difference in yield.
- For all the crops tested, removing all the components from the market has more impact than removing only the bioenergy components, except in the case of soybean for which the results are equivalent for both cases. For this latter, this can be explained by the large amount of soybean meal produced compared to oil, generates a higher shortage of oil in EU markets and is compensated by larger palm plantation expansion in Southeast Asia.
- In the case of ethanol feedstocks (cereals and sugar beet), removing simultaneously from the market bioenergy components and coproducts mitigate to a large extent the transmissions of the effects to the palm oil markets (peatland emissions close to zero). No substitution through DDGS or sugar beet pulp occurs that would in turn call for palm oil production; residual responses through palm oil and peatland emissions are only the results of variation in feed prices that impact level of protein meals consumption.
- In the case of biodiesel feedstocks, removing all components simultaneously keeps having an impact on the other oilseeds markets, because higher vegetable oil prices drive some substitution. However, this effect is lower than when oilseed meals are sent to the animal feed market, because this leads to a decrease in price of meals and a further increase in price of oils that stimulates palm oil demand.

These emission results can also be expressed in other metrics, per tonne of crop or per hectare of crop per year, as presented in Table 20. As it can be seen, effects measured per hectare are much more homogeneous as when expressed per ton of crop. This confirms a well-known effect that LUC impacts are much larger for low yielding crops, and it will have important implications for the values of component LUC values as well.

Table 20. LUC results per main crop product expressed in annual tCO_2 per t crop, and annual tCO_2 per ha.

	Emissions 20 years	Shock (Mt)	$tCO_2/t/yr$	Avg yield	$tCO_2/ha/yr$
Rapeseed	207	8.2	1.26	3.5	4.4
Sunflower seed	195	7.9	1.24	1.7	2.1
Soybean	368	19.4	0.95	3.1	2.9
Wheat grain	150	16	0.47	5.5	2.6
Maize grain	64	14.1	0.23	7.3	1.7
Sugar beet	59	57.8	0.05	69.6	3.6

Box 2. Understanding the effect of biofuel coproducts on land use and GHG emissions

Instead of total greenhouse gas emissions results, we can use the scenario of this report to better understand the partial LUC effect versus total LUC effect of bioenergy crops by looking at the change in land use in the same scenarios (Figure 29).

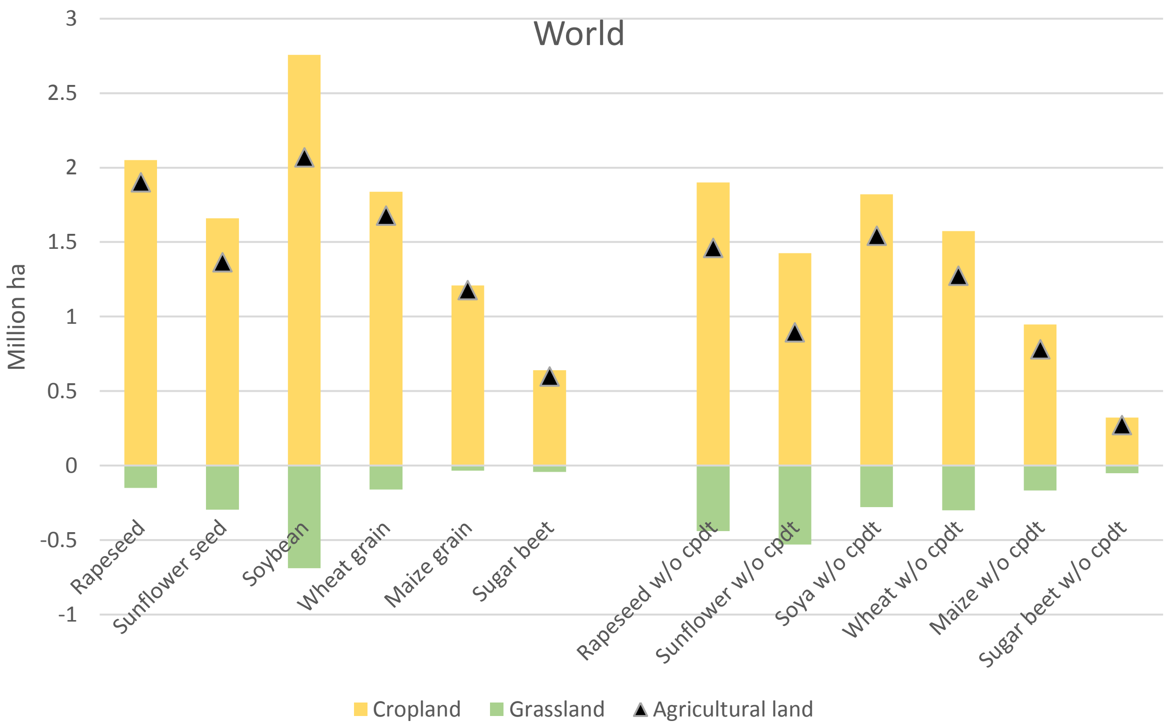

Figure 29**. Change in global cropland, grassland and agricultural land by 2020 for the six different selected crops with their coproducts (full LUC, left side) and without these coproducts (partial LUC, right side).**

At global level, the findings on land use are consistent with the GHG emissions results, but with more systematicity. In particular, partial LUC effects, corresponding to the case where coproducts are sent to the feed market, are systematically lower than total LUC effect, where all crop components are removed from the markets. This also applies to the case of soybeans that had shown a more ambiguous response on GHG emissions results, due to the contribution of peatland emissions.

The aggregated global patterns however hide the strong difference in patterns between global and partial LUC scenarios, at regional level. As illustrated in Figure 30, the effect of removing all components on deforestation is rather limited, except in the case of soybeans where expansion of cropland drives, for a fraction of it, additional land clearing in forest. However, when only bioenergy components are used and other components are sent back to the market, deforestation is decreased in Latin America (less soybean meals, and cheaper feed driving intensification of the livestock sector), whereas it increases in Southeast Asia due to the extra demand of palm oil to compensate for the soybean oil disappearance.

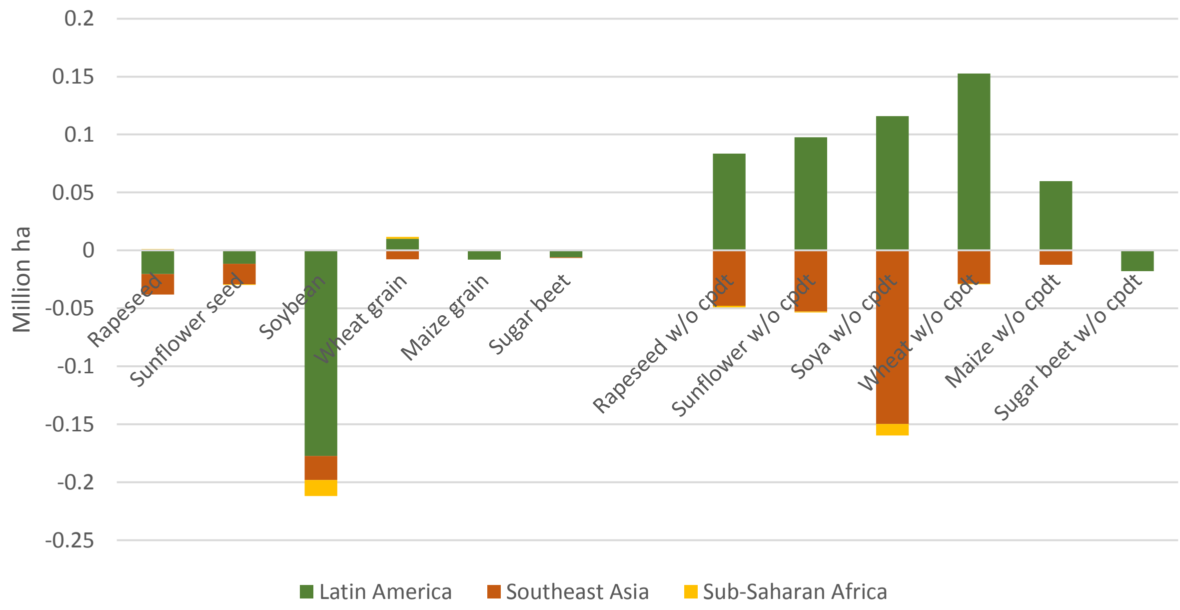

Figure 30. Change in tropical deforestation by 2020 for the six different selected crops with their coproducts (full LUC, left side) and without these coproducts (partial LUC, right side).

6.2 Decomposition of the LUC value through attributional approach

Using the analysis from Task 1 and 2, it is possible to use the component composition of the crops to allocate the total land use change impact. Two distribution keys can be used: allocation on the basis of mass composition or on the basis of economic value of component fractions. The first approach has the advantage of being independent from prices, but the second one reflects better the causalities behind the use of the materials (the most expensive components are the ones for which the full crop is produced).

Mass and value composition for the main crop components are displayed in Table 21 for the six crops of interest here. For ethanol feedstocks, the main difference between the two distribution keys the share of protein versus fibre, whereas the fraction used for bioenergy keeps always the same importance at about 70%. In the case of oilseeds, share of fat and protein is higher when looking at value, and both can represent 85% of the crop total value, to be compared with 66-74% for the share of total mass.

Table 21. Mass and value composition of the selected crops across component categories

		Wheat		Maize		Sugar beet	
	Price (€/t)	*% d.m.*	*% value*	*% d.m.*	*% value*	*% d.m.*	*% value*
Protein	710	12.0	19.5	9.2	14.7	7.7	15.9
Fats	720	1.7	2.8	4.2	6.8	0.5	1.0
Fibre	240	14.2	7.8	11.8	6.4	20.1	14.1
Starch	430	69.3	67.9	72.9	70.7	0.1	0.1
Sugars	330	2.7	2.1	1.8	1.4	71.6	68.8
		Rapeseed		**Soybean**		**Sunflower seed**	
	Price (€/t)	*% d.m.*	*% value*	*% d.m.*	*% value*	*% d.m.*	*% value*
Protein	710	22.8	27.3	48.7	57.8	17.4	22.2
Fats	720	50.1	60.8	25.1	30.1	48.6	62.7
Fibre	240	21.0	8.5	15.4	6.2	31.4	13.5
Starch	430	0.0	0.0	0.0	0.0	0.0	0.0
Sugars	330	6.1	3.4	10.8	5.9	2.6	1.5

We can apply the shares from the Table 21 above to the values previously calculated in Section 6.1. The resulting LUC values per component are presented in the Table 22 below. The first lines indicates what the crop value is per fresh or dry matter tonne. The blocks in grey show how this LUC value per tonne of crop is attributed to the different components using the distribution keys by mass (upper part of the table), or by economic value (lower part of the table). The resulting LUC value per tonne of component is displayed in the two other blocks in white, for the component mass distribution and the economic value distribution. In the case of the former, all values are identical for the components because the distribution of LUC and of mass is the same. An illustration with the case of wheat is provided in Box 3.

Box 3. Attributional LUC decomposition: the example of wheat

According to section 6.1, the LUC value for wheat using GLOBIOM is 0.47 tCO_2 per tonne of fresh matter wheat. At an average 15% moisture content, this corresponds to 0.54 per tonne of dry matter wheat. According to Table 21, wheat is mainly composed of 69.3% of starch, 14.2% of fibre and 12% of proteins. If we apply this shares to the LUC value of wheat, we then allocate 0.37 tCO_2 of the wheat impact to starch, 0.08 tCO_2 to fibres and 0.06 tCO_2 to wheat proteins. If we express these results per tonne of component, using the shares again of 69.3% of starch, 14.2% of fibre and 12% of proteins, we come to the conclusion that for starch, fibre and proteins, the LUC value per tonne of component (and not crop) is 0.54 tCO_2.

Results are more differentiated if we follow the economic value distribution key. Starch share of the wheat economic value is 67.9%, fibre only 7.8% and proteins 19.5% (see Table 21). Applying this new distribution key, we find that the 0.54 tCO_2 now split into 0.37 tCO_2 for starch, 0.04 tCO_2 for fibres and 0.11 tCO_2 for proteins. Scaled per tonne of component, this leads now to 0.53 tCO_2 for starch, 0.30 tCO_2 for fibre and 0.87 tCO_2 for proteins. Starch value has little varied, but the relatively lower price of fibre and higher price of proteins has led to a decrease of the LUC value for the former and an increase for the latter.

The following remarks can be made on these results:

- The component LUC values differ across crops when using the attributional approach with the same hierarchy as the initial crop LUC values. They are strictly identical for the mass distribution key but this is also observed for the economic value key. For instance, protein LUC value are around 1.27-1.69 tCO_2/t when using the component value with oilseeds, whereas they are only in the range 0.42-0.87 tCO_2/t for cereals and sugar crops.
- When focusing on major components of the crop, one can note that ethanol feedstocks provide consistent values across the two keys of distribution. Maize starch and beet sugar have a LUC value of 0.26-0.27 tCO_2/t. Wheat starch has a higher value with 0.53-0.54 tCO_2/t, a results that can be explained by the lower average yield of wheat in the EU28, compared to maize.
- Rapeseed and sunflower protein and fat also show consistent values, but these are higher with the component value distribution key with 1.66-1.72 tCO_2/t for fats and 1.64-1.69 tCO_2/t for proteins. With the component mass distribution key, the lower values are due to the fibre component that is attributed a larger part of the crop LUC. For soybean, the protein and oil LUC are lower in comparison 1.27-1.28 or 1.08 tCO_2/t depending on the key of distribution.

Table 22. Component LUC per crop using an attributional approach. Bold values are for bioenergy fractions (tCO_2/t)

	Rapeseed	Sunflower	Soybean	Wheat	Maize	Sugar beet
Crop LUC value by t crop						
Fresh matter	1.26	1.24	0.95	0.47	0.23	0.05
Dry matter	1.37	1.33	1.08	0.54	0.26	0.27
Mass distribution key – crop LUC split by t crop						
Protein	0.31	0.23	0.52	0.06	0.02	0.02
Fats	0.69	0.65	0.27	0.01	0.01	0.00
Fibre	0.29	0.42	0.17	0.08	0.03	0.05
Starch				0.37	0.19	0.00
Sugars	0.08	0.03	0.12	0.01	0.00	0.19
Mass distribution key – LUC value by t component						
All components	**1.37**	**1.33**	**1.08**	**0.54**	**0.26**	**0.27**
Value distribution key – crop LUC split by t crop						
Protein	0.37	0.30	0.62	0.11	0.04	0.04
Fats	0.83	0.83	0.32	0.02	0.02	0.00
Fibre	0.12	0.18	0.07	0.04	0.02	0.04
Starch				0.37	0.19	0.00
Sugars	0.05	0.02	0.06	0.01	0.00	0.19
Value distribution key – LUC value by t component						
Protein	1.64	1.69	1.27	0.87	0.42	0.56
Fats	**1.66**	**1.72**	**1.29**	0.89	0.43	0.57
Fibre	0.55	0.57	0.43	0.30	0.14	0.19
Starch				**0.53**	**0.26**	0.34
Sugars	0.76	0.79	0.59	0.41	0.20	**0.26**

To conclude, it is possible to develop an attributional analysis to derive an ILUC estimate for each crop using consistent distribution keys based on the crop composition. The advantage of this approach is that component LUC values can be easily added up to the crop LUC value. However, this approach leads to some LUC estimates for the components that are relatively similar (or equal with a distribution key by mass) to the initial crop values. Additionally, the distribution key used to attribute the LUC value can notably change the results, at least in the case of oilseeds. In order to solve these limitations, one can try to directly shock the components themselves, or their most approaching products, directly in the model, which we present in the next section.

7 Crop component ILUC: consequential approach using GLOBIOM

In this section, we depart from the attributional approach presented above to directly look at the impact of removing specific components using GLOBIOM, accordingly with the consequential approach (approach B) presented in section 5.1. The components we target are approached through the following model products (with their component shares):

- Starch: ethanol from wheat starch (100%), ethanol from maize starch (100%)
- Proteins: wheat DDGS (36.6%), maize DDGS (31.2%), rapeseed meal (40.6%), soybean meal (49.9%), sunflower meal (49.8%)
- Sugar: ethanol from beet sugar (100%)
- Fats: rapeseed oil (100%), soybean oil (100%), sunflower oil (100%)
- Fibres: sugar beet pulp (45.5%)

7.1 Scenario results for LUC values of products containing components

To derive the LUC values of components we run the scenarios corresponding to the products above. The size of the shock performed is equivalent to those performed in Section 6.1 where the full crop was shocked by an amount equivalent to the biofuel requirement for an incorporation of 1% in transportation fuel consumed in the EU. This means that non-biofuel feedstocks are shocked by the equivalent of the amount generated as co-product when producing 1% biofuel from the main feedstock (see Box 1 for the example of wheat).

An overview of the cumulated emissions over 20 years associated to these scenarios is presented in Figure 31. Products are grouped by category of their main components. By construction, the results for wheat and corn starch, beet sugar and the three categories of oil are the same as for the ethanol and biodiesel scenarios from the previous ILUC study using GLOBIOM, as also used in Section 6.1 for the partial LUC values. The new categories are for proteins and fibres. For these categories, the biofuel coproducts have been shocked, and they generated some by-products themselves, which are vegetable oil for oilseeds, or ethanol for DDGS. These coproducts are feedback to the market and consumed by other sectors, as were the meals and DDGS in the case of bioenergy shocks. In the case of ethanol however, it should be noted that the level of ethanol consumed in the baseline by 2020 is only 0.5% of total fuel consumption,[30] which means the EU cannot absorb all the ethanol coproduced with the DDGS for a shock at 1%. In order to accommodate this issue, we decrease for the ethanol coproduct scenario the size of the shock at 0.5% as well.

[30] For more details on the baseline, see Chapter 2 of the GLOBIOM ILUC quantification study of biofuels.

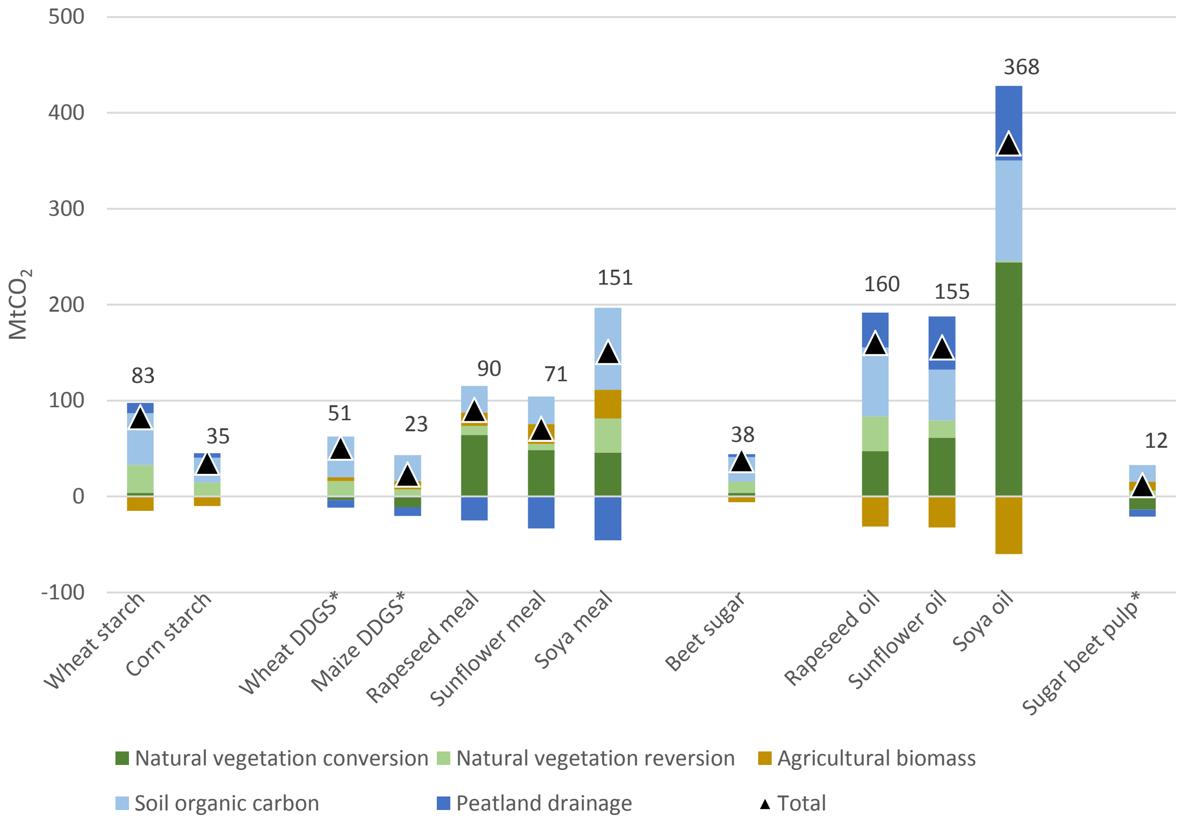

Figure 31. GHG emissions over 20 years of scenarios targeting products containing main coproducts. Starred scenario are runs on a 0.5% target.

7.2 From products to components LUC values

Using the results of the scenarios above, we can calculate the LUC values obtained by component. For products containing multiple components, we use the component value shares in the different products, as indicated in the Table 23 below and apply the coefficients in bold to attribute the LUC of the product to the component. Due to the high value of proteins, oilseed meals and DDGS have half of their effect associated to proteins, and even more than 80% for sunflower and soybean meal. For sugar beet pulp, 53% of the economic value can be associated to fibre. For products not in this table, only one component is present and all the LUC value is associated to this component.

Table 23. Composition and economic value shares of the components assumed for the different products. Italic values are those adjusted to fit GLOBIOM assumptions. Bold values indicate the main component economic shares used for the analysis.

[%]		Wheat DDGS	Maize DDGS	Rapeseed meal	Sunflower meal	Soya meal	Sugar beet pulp
	d.m. content	90	88.2	88.7	88.7	87.8	89.1
Protein		*36.6*	*31.2*	*40.6*	*45.3*	*49.9*	9.1
Fats		7.2	4.4	2.6	1.9	2.2	1.0
Fibre		42.1	35.6	31.9	*12.2*	13.9	45.5
Starch		4.2	13.0	0.0	0.0	0.0	0.0
Sugars		0.9	0.6	8.7	5.9	9.5	7.4
Economic value share	*Price (€/t)*						
Protein	710	**59.9**	**55.8**	**69.9**	**83.8**	**81.6**	31.4
Fats	720	12.0	8.0	4.5	3.6	3.6	3.5
Fibre	240	23.3	21.5	18.6	7.6	7.7	**53.1**
Starch	430	4.2	14.1	0.0	0.0	0.0	0.0
Sugars	330	0.7	0.5	7.0	5.0	7.2	11.9

The shares above and the shock size can be used to calculate the LUC values associated to each component-product pair, as illustrated in the Table 24 below. The cumulated emissions of each scenarios are divided by 20 and by the shock size. This provides the LUC values of the products, and as explained in section 0, provide directly the component LUC values under a mass distribution key. If one wants to correct by the economic values, information from Table 23 needs to be used. As it appears in the case of starch, values determined through the consequential analysis are primarily influenced by the crop yield and starch value for wheat is higher than for corn, with a range 0.2-0.46 tCO_2 per tonne starch. Results for proteins are higher, with a range 0.48-1.09 tCO_2 per tonne protein if using a mass distribution key and even higher at 0.79-1.78 tCO_2 per tonne protein when correcting by the economic value. Once again the results are strongly influenced by crop yield and composition. The crops with the higher protein yield, soybean and maize, get the lower ILUC in this range. Sugar has a relatively low LUC value at 0.2 tCO_2/t, whereas vegetable oils all show the highest LUC values from 2.3 to 5.3 tCO_2/t.

This is due in particular to the linkage with the palm oil market and the impact on tropical deforestation and peatland drainage in Southeast Asia. Soya oil has the highest value because of its small share in composition of soya bean (18%). Last, fibres also has a LUC effect that is estimated in this approach to be around 0.37-0.43 tCO_2/t product.

Table 24. Calculation of component LUC values using the consequential analysis with GLOBIOM

	Emissions 20 years ($MtCO_2$)	Shock size (Mt)	Component economic value share (%)	Component LUC (tCO2 per tonne, by mass)	Component LUC (tCO2 per tonne by economic value)
Starch					
Wheat starch	83	8.9	100	0.46	0.46
Maize starch	35	8.9	100	0.20	0.20
Proteins					
Wheat DDGS*	51	2.4	59.9	1.09	1.78
Maize DDGS*	23	2.1	55.8	0.55	0.98
Rapeseed meal	90	4.6	69.9	0.98	1.69
Sunflower meal	71	4.3	84.5	0.82	1.53
Soya meal	151	15.6	81.6	0.48	0.79
Sugar					
Beet sugar	38	9.2	100	0.21	0.21
Vegetable oil					
Rapeseed oil	160	3.5	100	2.29	2.29
Sunflower oil	155	3.5	100	2.22	2.22
Soya oil	368	3.5	100	5.26	5.26
Fibre					
Sugar beet pulp*	12	1.6	53.1	0.37	0.43

* Shock adjusted to 0.5% to accommodate the baseline.

Box 4. Consequential LUC decomposition: the example of wheat

To determine the component LUC of wheat under the consequential approach, two products are shocked separately in GLOBIOM: wheat starch and wheat coproducts, with shock sizes determined according to Box 1. For wheat starch, cumulated emissions of 83 $MtCO_2$ are divided by 20 years and by the shock size, which directly provides the emissions per tonne of product, i.e. emissions per ton of starch component. Wheat starch LUC value obtained is 0.46 tCO_2 per tonne starch. In the case of wheat DDGS, the same calculation on the scenario results provides a LUC value per tonne of DDGS, which is equivalent to the LUC value per tonne of component as long as distribution key by mass is used (see section 0). We then obtain a value of 1.09 tCO_2 per tonne protein from wheat DDGS. Using an economic value distribution key require to use values from Table 23 on wheat DDGS composition. We can see that protein content represents 36.6% of the dry matter mass but 59.9% of the economic value of the DDGS, due to the high price of proteins compared to other DDGS components. This leads to a much higher LUC estimate, by 64% (=59.9/36.6) for proteins from wheat DDGS, at 1.78 tCO_2 per tonne protein.

It clearly appears from the results above that consequential approaches expands the spread of the component LUC estimates with values as high as 5.3 tCO_2 per tonne of component for the case of soybean oil. This is due to the fact that vegetable oils can generate much more land use change impact than their share in the whole crop would let expect, due to their interaction with the palm oil market and land related GHG emissions in Southeast Asia. However, this approach also has some drawbacks because the additionality across feedstocks is not fully preserved, i.e. aggregated LUC values at crop level do not come to be the weighted average of the LUC value of their different components. In other terms, shocking a crop with components A and B do not lead to the same effect as shocking A alone, and B alone, and summing the results together. This is illustrated by the comparison of the scenario results in Figure 32. This non-additivity is due to a certain number of non-linear responses in the model that affect marginally the results when different crop products are shocked at the same time.

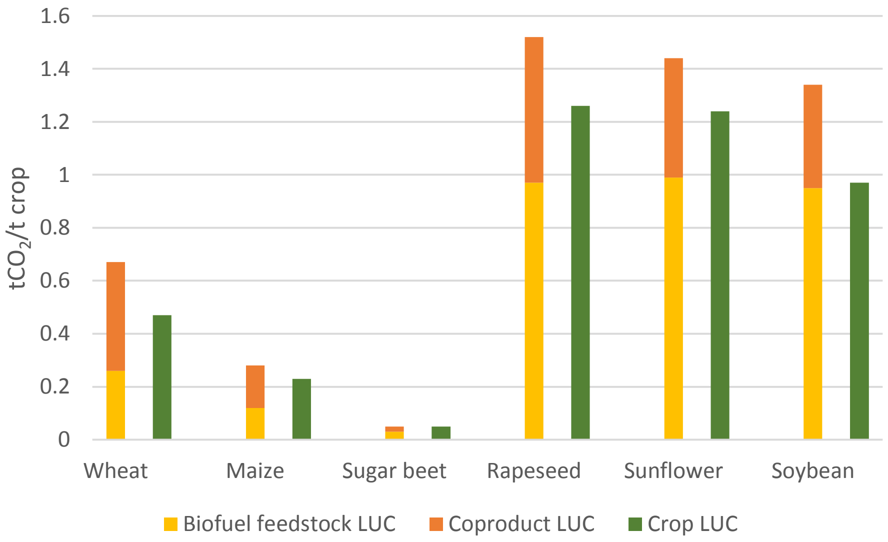

Figure 32. Additionality performance of the consequential approach across feedstocks using GLOBIOM

8 Conclusions Task 3

In this study, we have estimated the component LUC values associated to starch, protein, fats, sugar and fibre following two different methods, an attributional analysis and a consequential analysis. The results from these two approaches are summarised in the Table 25.

Table 25. Summary of results for component LUC value for the attributional and consequential approaches.

[tCO_2/t component]	Attributional		Consequential	
	Mass	Value	Mass	Value
Starch				
Wheat starch	0.54	0.53	0.46	0.46
Maize starch	0.26	0.26	0.20	0.20
Proteins				
Wheat DDGS	0.54	0.87	1.09	1.78
Maize DDGS	0.26	0.42	0.55	0.98
Rapeseed meal	1.37	1.64	0.98	1.69
Sunflower meal	1.33	1.69	0.82	1.53
Soya meal	1.08	1.27	0.48	0.79
Sugar				
Beet sugar	0.27	0.26	0.21	0.21
Vegetable oil				
Rapeseed oil	1.37	1.66	2.29	2.29
Sunflower oil	1.33	1.72	2.22	2.22
Soya oil	1.08	1.29	5.26	5.26
Fibre				
Sugar beet pulp	0.27	0.19	0.37	0.43

The following conclusions can be drawn from of our analysis:

- Component LUC values differ for the same component across various feedstocks. This is due to the fact that components in the modelling framework that we use are not perfectly substitutable. In some cases, though, values can be close, such as for vegetable oil from rapeseed or sunflower. In some others however, values are different due to imperfect substitution across regions and products, as well as amount of coproduct generated, e.g. with soybean oil.
- Attributional and consequential approaches lead to relatively comparable results for ethanol feedstocks, but results are very different for oilseeds used for biodiesel. This is because the consequential approach allocates much more GHG emission to vegetable oil than does the attributional approach. Conversely, the attributional approach appear to overestimate the LUC value of protein meals from oilseeds for a given distribution keys, mass or economic value. The attributional method has the advantage of its transparency, but the modelling

findings seriously question its relevance when coming to allocate GHG emissions from land use. Indeed, the consequential approach is the only one that allows to represent the complex combinations of effects between the joint products across regions and markets, as well as the heterogeneity in yields and emission factors.

- A hierarchy of ILUC values for various feedstocks seems to robustly emerge out of the analysis, with some convergence between the two approaches. Vegetable oils appear as the components with the highest LUC values, followed by proteins. Starch come next and sugar and fibre are the components with the lowest LUC values. This is consistent with the findings from the previous GLOBIOM ILUC quantification study.
- It should be kept in mind that the results above:
    - depend on the overall modelling framework chosen, even for the attributional method that primarily use GLOBIOM input at crop level. Substitution assumptions in GLOBIOM could gain to be revised according to finding of Task 2 of this project, when relevant.
    - do not factor in any uncertainty analysis. The GLOBIOM ILUC quantification study showed that feedstock results are sensitive to change in various parameters. The hierarchy presented above across components is based on mean value estimates and do not reflect uncertainty bounds.

The analysis performed in this study explored the feasibility of interpreting the results of ILUC modelling in terms of component instead of feedstocks to allow more comparability across crops and be able to compare bioenergy pathways. The results appear mixed because, although a hierarchy of LUC values emerge across component categories, the feasibility of a precise ILUC for each component however depends on the final understanding of level of substitutions on the markets and the calibration of the modelling framework to these. This is also the reason why a LUC value Evaluation Tool has been designed in the framework of this same task, to allow exploration of full implication of this role of substitutability.

APPENDIX: DETAILED TASK 3 SCENARIO RESULTS

This appendix presents the detailed results of 18 scenarios used for this analysis. These different feedstocks are shocked as presented in Table 26.

Table 26. List of feedstocks analysed in this section

Main crop product	Biofuel feedstock	Main coproduct
Wheat grain	Wheat ethanol	Wheat DDGS
Maize grain	Maize ethanol	Maize DDGS
Sugar beet	Sugar beet ethanol	Sugar beet pulp
Rapeseed	Rapeseed oil	Rapeseed meal
Sunflower seed	Sunflower oil	Sunflower meal
Soybean	Soybean oil	Soybean meal

For each feedstock, a shock was performed in the EU to calculate the effect of removing a given quantity on the market. For biofuel feedstocks, the size of the shock corresponds to 1% incorporation of ethanol or FAME in EU transportation fuel, on an energy basis. For the co-products, the shock size is aligned on the same amount as the coproducts associated to a 1% shock of bioenergy. The only exception are the ethanol coproducts that are shocked at 0.5% because ethanol demand in the baseline in the EU is too low to absorb extra demand of biofuel. For the main crop product, the shock is also aligned with the biofuel shock. The biofuel feedstocks and the coproducts are shocked simultaneously, which corresponds to a demand for the main product for a shock of 1% incorporation of the corresponding biofuel, but with removal of the coproduct from the market.

Wheat grain

Shock size:	16 million tonnes wheat (wheat req. for 123 PJ i.e. 1% biofuel)
Land Use Factor:	0.47 tCO_2 per t crop

Additional demand of 1% ethanol (123 PJ) and its coproducts are produced from 16 million tons (Mt) of wheat, taking place for 59% in the European Union. This shock leads to a price increase of 2.4% at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (7.7 Mt), North America (2.2 Mt), Latin America (1.4 Mt), Russia and satellites (0.7 Mt) and rest of Eastern Europe (0.5 Mt). This new production requires an acreage of 1.6 million ha (Mha) in the European Union, 380 kha in North America, 300 kha in Latin America, 200 kha in Russia and satellites and 100 kha in rest of Eastern Europe.

Overall agricultural production is affected by the expansion of wheat demand, and total demand for cereals decreases by 2.5 Mt, due to higher prices. Demand for protein meals and DDGS decreases by 0.2 Mt.

Land use change effects

Land expansion requires 1.8 Mha of additional cropland globally. In the European Union, cropland expands by 1.4 Mha of which 630 kha are sourced from abandoned land by 2020 and 800 kha from grassland and other natural vegetation. Other regions where cropland expands are rest of Eastern Europe (90 kha), North America (50 kha), sub-Saharan Africa and Southeast Asia (70 kha each).

Land use change emissions

GHG emissions are mainly associated to soil organic carbon emissions (78 MtCO2eq), conversion of natural vegetation (49 MtCO2eq) and the foregone carbon sequestration of abandoned land in the European Union (35 MtCO2eq). Additional carbon sequestration in crop biomass decreases emissions by 18 MtCO2eq.

Total land use emissions of 16 million tonnes additional wheat are found to be 150 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.47 tCO2eq/t wheat.

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Wheat DDGS

Shock size:	2.35 million tonnes DDGS wheat (req. 8 million wheat)
Land Use Factor:	0.41 tCO_2 per t crop.

Additional demand of 0.5% ethanol (123 PJ) is produced from 8 million tons (Mt) of wheat, taking place for 41% in the European Union. This shock leads to a price increase of wheat of 0.6% at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (2.9 Mt), North America (0.7 Mt) and Latin America (0.5 Mt). This new production requires an acreage of 590 kha in the European Union, 170 kha in North America and 110 kha in North America.

Overall agricultural production is affected by the expansion of wheat DDGS demand, and total demand for cereals increases by 0.1 Mt, whereas demand for protein meals and DDGS decrease by 1 Mt.

Land use change effects

Land expansion requires 0.7 Mha of additional cropland globally. In the European Union, cropland expands by 550 kha of which 270 kha are sourced from abandoned land by 2020 and 310 kha from grassland and other natural vegetation. Oil palm plantation decrease globally by 30 kha, mainly in Southeast Asia.

Land use change emissions

Land use emissions are mainly associated to soil organic carbon emissions with 43 MtCO2eq. Foregone carbon sequestration of abandoned land in the European Union increases by 16 MtCO2eq following the shock due to expansion of cropland. Peatland emissions decrease by 8 MtCO2eq while decrease of carbon sequestration in crop biomass increases emissions by 4 MtCO2eq.

Total land use emissions of 123 PJ additional wheat ethanol are found to be 51 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 1.08 tCO2eq/ t wheat DDGS, i.e. 0.41 tCO2eq/ t wheat.

Wheat ethanol

Shock size:	16 million tonnes wheat (123 PJ)
Land Use Factor:	0.26 tCO_2 per t crop (34 gCO_2/MJ)

Additional demand of 1% ethanol (123 PJ) is produced from 16 million tons (Mt) of wheat, with 57.5% of additional production taking place in the EU. This shock leads to a price increase of wheat of 12% in the EU and 1.8% at the global level.

Adjustments to the shock

The additional feedstock supply is achieved 15% through a decrease in feed and, to a lesser extent, food demand; 26% by displacement of purpose-grown feed by co-product of ethanol; and 59% by extra production, with yield increase contributing 10% and area 49%. At the total cropland level, due in part to the impact on the livestock sector, feed demand declines even further (26%) and only 46% additional supply is required.

Additional feedstock production is located in the EU (7.2 Mt), North America (2.3 Mt), Latin America (1.5 Mt), and Russia, Ukraine and rest of Europe (1.2 Mt). This new production requires an acreage of 1.5 million ha (Mha) in the EU, 340 kha in North America, 310 kha in Latin America and 310 kha in Russia, Ukraine and rest of Europe.

Overall agricultural production is affected by the expansion of wheat demand and total demand for cereals decreases by 3.6 Mt due to higher prices. Demand for protein meals (incl. DDGS) increases by 2.8 Mt as a result of the extra supply of biofuel co-products on the market.

Land Use Change effect

Land expansion requires conversion of 1.7 Mha of land globally, of which 1.6 Mha becomes new cropland. In the EU, cropland expands by 1.2 Mha, of which 490 kha is sourced from abandoned land by 2020 and 750 kha from other natural vegetation. North America and Latin America, extra wheat is produced on the current cropland, whereas in Ukraine and the rest of Europe, cropland expands at the expense of other natural vegetation (-100 kha). Oil palm plantation expands globally, because when DDGS displaces protein meals, it also decreases the production of their vegetable oil co-products and this triggers an increase in palm oil production (34 kha in Indonesia and Malaysia).

Land use change emissions

Land use emissions are mainly associated to soil organic carbon emissions with 54 $MtCO_2e$. Foregone carbon sequestration of abandoned land in the EU also increases by 29 $MtCO_2e$ following the shock due to expansion of cropland while additional carbon sequestration in crop biomass decreases emissions by 15 $MtCO_2e$.

Total land use emissions are found to be 83 $MtCO_2e$ for 123 PJ wheat ethanol. With an assumed 20 year amortisation this results in an LUC emissions factor of 0.26 tCO2/t wheat or 34 gCO_2e/MJ ethanol.

Maize grain

Shock size:	14.1 million tonnes maize
Land Use Factor:	0.23 tCO_2 per t crop.

Additional demand of 1% ethanol (123 PJ) is produced from 14.1 million tons (Mt) of maize, taking place for 95% in the European Union. This shock leads to a price increase of 0.4% at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (12.1 Mt), and Latin America (0.7 Mt). This new production requires an acreage of 1.5 million ha (Mha) in the European Union, and 70 kha in Latin America.

Overall agricultural production is affected by the expansion of maize demand, and total demand for cereals decreases by 1 Mt, due to higher prices. Demand for protein meals and DDGS remains stable.

Land Use Change effect

Land expansion requires 1.2 Mha of additional cropland globally, which fully takes place in the European Union. Cropland expansion is sourced from abandoned land for 400 kha and from grassland and other natural vegetation for 750 kha.

Land use change emissions

Land use emissions are mainly associated to the soil organic carbon (47 MtCO2eq) and the foregone sequestration in abandoned land in the European Union (21 MtCO2eq). Conversion of natural land only represents 4 MtCO2eq and carbon in agricultural biomass corresponds to -9 MtCO2eq.

Total land use emissions of 14.1 Mt additional maize are found to be 64 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.23 t CO2eq/t maize.

Maize DDGS

Shock size:	2.1 million tonnes maize DDGS (7.1 million tonnes maize)
Land Use Factor:	0.16tCO_2 per t crop.

Additional demand of maize DDGS is produced from 7.1 million tons (Mt) of maize, which corresponds to 0.5% ethanol (123 PJ). Demand for DDGS takes place for 96% in the European Union. This shock leads to a price increase of 0.3% at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (6.4 Mt), and Latin America (0.3 Mt). This new production requires an acreage of 790 kha in the European Union, and 70 kha in Latin America.

Overall agricultural production is affected by the expansion of wheat demand, and total demand for cereals increases by 1.0 Mt, due to lower cereal prices, whereas demand for protein meals and DDGS decreases by 0.9 Mt.

Land Use Change effect

Land expansion requires 0.4 Mha of additional cropland globally. In the European Union, cropland expands by 500 kha of which 100 kha are sourced from abandoned land by 2020 and 400 kha from grassland and other natural vegetation. Oil palm plantation decrease globally by 30 kha, mainly in Southeast Asia.

Land use change emissions

Land use emissions are mainly associated to the soil organic carbon emissions with 27 MtCO2eq. Foregone carbon sequestration of abandoned land in the European Union represents 7 MtCO2eq, while lower additional carbon sequestration in crop biomass increase emissions by 8 MtCO2eq. Land conversion emissions decrease on their side by 11 MtCO2eq and peatland emissions by 9 MtCO2eq.

Total land use emissions of 123 PJ additional wheat ethanol are found to be 23 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.55 t CO2eq/ t maize DDGS, i.e. 0.16 tCO2eq / t maize grain.

Maize ethanol

Shock size:	14.1 million tonnes maize
Land Use Factor:	0.12 tCO_2 per t crop. (14 gCO_2/MJj)

Additional demand of 1% ethanol (123 PJ) is produced from 14.1 Mt of corn, with 82% of additional production taking place in Europe. The shock leads to a price increase of 4% in the EU and 0.4% at the global level.

Adjustments to the shock

The additional feedstock supply is achieved 18% through a decrease in feed, with food demand hardly impacted, 26% by displacement of feed by co-products of ethanol, and 56% by extra production, where yield increases account for 11%.

Additional feedstock production is located in Europe (9.6 Mt), and Latin America (1 Mt). This new production requires acreage of 1.2 Mha in the EU, and 130 kha in Latin America.

Overall agricultural production is affected by maize acreage expansion and grain demand decreases of 2.8 Mt, while demand for protein meals (including DDGS) increases by 3.1 Mt.

Land use change effect

Land expansion requires 950 kha of additional land globally for cropland, most of it coming from the EU. In the EU, cropland expands 700 kha into other natural vegetation, whereas 250 kha are sourced from abandoned land. In Latin America, extra corn production substitutes soybean production, which is substituted by corn DDGS, and no cropland expansion is necessary. In North America, production of soybean meal is also decreased and the decreased price of protein meals leads to more substitution for grain-based production systems, and 110 kha of grassland is returned to other natural vegetation. Palm oil production increases to replace displaced soybean oil due to protein meal substitution and palm plantations expand globally by 10 kha.

Land use change emissions

Land use emissions are mainly associated with soil carbon changes on cropland (26 $MtCO_2$), most of it taking place in the EU, and emissions from foregone sequestration (14 $MtCO_2$). Carbon sequestration in agricultural crops decreases emissions by 10 $MtCO_2$.

Total land use emissions of maize ethanol are found to be 35 $MtCO_2e$. With an assumed 20 year amortisation this results in an LUC emissions factor of 14 gCO_2e/MJ or 0.12 t CO2eq/ t maize.

Sugar beet

Shock size:	57.8 million tonnes sugar beet
Land Use Factor:	0.05 tCO_2 per t crop.

Additional demand of 1% ethanol (123 PJ) is produced from 57.8 million tons (Mt) of sugar beet, taking place for 100% in the European Union. This shock leads to a price increase of 7% at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (54.7 Mt). This new production requires an acreage of 840 kha in the European Union.

Overall agricultural production is affected globally and total demand for sugar crops decreases by 3.2 Mt, due to higher prices and demand for cereals by 0.2 Mt. Demand for protein meals and DDGS decreases by 0.2 Mt.

Land use change effect

Land expansion requires 640 kha of additional cropland globally. In the European Union, cropland expands by 540 kha of which 430 kha are sourced from abandoned land by 2020 and only 110 kha from grassland and other natural vegetation.

Land use change emissions

Land use emissions are mainly associated to soil carbon emissions (35 MtCO2eq) and the foregone carbon sequestration in abandoned land in the European Union (24 MtCO2eq).

Total land use emissions of 57.8 Mt sugar beet, equivalent to a 1% biofuel shock magnitude) are found to be 59 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.05 t CO2eq/t sugar beet.

Sugar beet pulp

Shock size:	1.6 million tonnes sugar beet pulp (28.9 million tonnes sugar beet)
Land Use Factor:	0.02 tCO_2 per t crop.

Additional demand of sugar beet pulp is produced from 28.9 million tons (Mt) of sugar beet sourced for 100% from the European Union. This shock is equivalent to an ethanol demand of 0.5% and leads to a price increase of 2.1% at the global level.

Adjustments to the shock

Additional feedstock production is located fully in the European Union (19.8 Mt). This new production requires an acreage of 300 kha in the European Union.

Overall agricultural production is affected by the expansion of sugar beet pulp demand, and total demand for cereals increases by 1.2 Mt, due to lower prices. Demand for protein meals and DDGS decreases by 1 Mt.

Land use change effect

Land expansion requires 70 kha of additional cropland in the European Union mostly sourced from grassland and other natural vegetation. Oil palm plantation decreases by 30 kha mainly in Southeast Asia and sub-Saharan Africa.

Land use change emissions

Land use emissions are mainly associated to the soil organic carbon emissions with 18 MtCO2eq. Foregone carbon sequestration of abandoned land in the European Union increase by 6 MtCO2eq following the shock due to expansion of cropland, while land use conversion emissions decrease by 14 MtCO2eq and peatland emissions by 7 MtCO2eq. Lower carbon sequestration in crop biomass increases emissions by 9 MtCO2eq.

Total land use emissions of 123 PJ additional wheat ethanol are found to be 12 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.37 t CO2eq/ t sugar beet pulp, i.e. 0.02 tCO2eq/t sugar beet.

Sugar beet ethanol

Shock size:	57.8 million tonnes sugar beet
Land Use Factor:	0.03 tCO_2 per t crop.

Additional demand of 1% ethanol (123 PJ) is produced from 58 Mt of sugar beet, with 100% of additional production taking place in the EU. This shock leads to a price increase of 7.4% at the European level.

Adjustments to the shock

The additional feedstock is achieved 4% through a decrease in food and feed demand, 19% by displacement of feed by co-product of ethanol and 77% by extra production, which occurs fully through expansion. Slightly lower yield in the newly producing land contributes negatively to the adjustments (-6%).

Additional feedstock production is exclusively located in Europe (55 Mt) and requires acreage of 860 kha.

Overall agricultural production is also affected by the additional sugar beet demand and global demand for grains. Beside the decrease in sugar crop demand of 3.0 Mt, cereals demand decreases by 3.2 Mt. Protein meals and DDGS increase by 3.0 Mt, while vegetable oil demand is barely impacted (-0.1 Mt).

Land use change effect

Land expansion leads to 320 kha of additional cropland globally, which expands mostly into abandoned land. Cropland expands by 220 kha, of which 200 kha are sourced from abandoned landand other natural vegetation and 20 kha is sourced from grassland.

Land use change emissions

Land use emissions are mainly associated with soil carbon changes in cropland (26 $MtCO_2$). Reversion in natural vegetation accounts for 11 $MtCO_2$ and carbon sequestration in agricultural crops decreases emissions by 6 $MtCO_2$.

Total LUC emissions of sugar beet ethanol are found to be 38 $MtCO_2e$. With an assumed 20 year amortisation this results in an LUC emissions factor of 15 gCO_2e/MJ, i.e. 0.03 tCO2e / t sugar beet.

Rapeseed

Shock size:	8.2 million tonnes rapeseed
Land Use Factor:	1.26 tCO_2 per t rapeseed.

Additional demand of 1% biodiesel (123 PJ) is produced from 8.2 million tons (Mt) of rapeseed, taking place for 43% in the European Union. This shock leads to a price increase of rapeseed of 6.1% at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (3.2 Mt), North America (2.3 Mt) and Oceania (0.5 Mt). This new production requires an acreage of 850 kha in the European Union, 680 kha in North America and 370 kha in Oceania.

Overall agricultural production is affected globally and total demand for cereals decreases by 0.6 Mt, due to higher prices. Demand for protein meals and DDGS decreases by 0.6 Mt.

Land use change effect

Land expansion requires 2.1 Mha of additional cropland globally. In the European Union, cropland expands by 1.3 Mha of which 730 kha are sourced from abandoned land by 2020 and 560 kha from grassland and other natural vegetation. In North America, 200 kha cropland expands at the expense of other natural vegetation and in Oceania, 250 kha of cropland replace abandoned land. Oil palm plantation expands globally by 70 kha mainly allocated in Southeast Asia.

Land use change emissions

Land use emissions are mainly associated to the soil organic carbon (92 MtCO2eq) and conversion of natural vegetation in Latin America and in Southeast Asia (80 MtCO2eq). Foregone carbon sequestration of abandoned land increases by 44 MtCO2eq. Peatland emissions increase by 24 MtCO2eq. However, agricultural biomass sequesters 33 MtCO2eq.

Total land use emissions of 8.2 million tonnes of rapesed are found to be 207 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 1.26 t CO2eq/t rapeseed.

Rapeseed meal

Shock size:	4.6 million tonnes rapeseed meals
Land Use Factor:	0.55 tCO_2 per t rapeseed.

Additional demand of 4.6 million tonnes rapeseed meal is requiring 8.2 million tons (Mt) of rapeseed. This shock leads to a price increase of 0.4% of rapeseed at the global level.

Adjustments to the shock

Additional feedstock production is relatively limited with 0.3 Mt in the European Union and and 0.2 Mt in Canada. This new production requires an acreage of 90 thousands ha (kha) in the European Union, and 80 kha in Canada.

Overall agricultural production is affected globally and total demand for cereals decreases by 2.5 Mt, due to higher prices. Demand for protein meals and DDGS decreases by 2.2 Mt.

Land use change effect

Land expansion requires 0.3 Mha of additional cropland globally. In the European Union, cropland expands by 170 kha into abandoned land by 2020. In North America, crop land expands by 50 kha and in Middle East North Africa, by 70 kha. Oil palm plantation decrease globally by 100 kha mainly in Southeast Asia (70 kha), and to a lesser extent in sub-Saharan Africa (-20 kha).

Land use change emissions

Land use emissions are mainly associated to land use conversion with 64 MtCO2eq emitted. Soil organic carbon emissions increase by 28 MtCO2eq following the shock due to expansion of cropland. Peatland emissions decrease by 25 MtCO2eq and reduced carbon sequestration in crop biomass increases emissions by 14 MtCO2eq. Foregone carbon sequestration of abandoned land in the European Union adds 9 MtCO2eq.

Total land use emissions of 4.6 million tonnes rapeseed cakes are found to be 90 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.98 t CO2eq/t cakes, i.e. 0.55 t CO2eq per tonne rapeseed.

Rapeseed oil

Shock size:	3.5 million tonnes rapeseed oil (equiv. 8.2 million tonnes rapeseed)
Land Use Factor:	0.97 tCO_2 per t rapeseed.

Additional demand of 1% FAME (123 PJ) is produced from 3.5 Mt of rapeseed oil, with 41% of additional production taking place inside the EU. This shock leads to a price increase of 25% for the price of rapeseed and 28% for the price of rapeseed oil in the EU. At the global level, impacts on seed and oil prices are 5.3% and 7%, respectively.

Adjustments to the shock

The additional feedstock is achieved 13% through a decrease in food and feed demand, 32% by displacement of feed by co-product of biodiesel and 54% by extra production.

Additional feedstock production corresponds to 6.2 Mt of rapeseed, mainly located in the EU (3.0 Mt), North America (2.6 Mt) and Oceania (0.5 Mt). This requires acreage of 790 kha in the EU, 780 kha in North America and 350 kha in Oceania.

Overall agricultural production is also affected globally by an increase in consumption of protein meal of 2.3 Mt and the decrease of 720 kt in vegetable oil demand. Grain demand increases by 1.1 Mt to serve as feed complement to newly consumed protein meals, whereassugar crops demand decreases by 1.7 Mt. The livestock sector benefits from the extra feed production and meat and milk production increase globally by 130 kt and 330 kt, respectively.

Land use change effect

Land expansion requires 1.9 Mha of additional cropland globally. In the EU, cropland expands by 1.1 Mha, of which 630 kha is into abandoned land and 470 kha is into other natural vegetation. Global grassland decreases by 440 kha as protein meal availability favors grain-based production systems over grass-based ones, in particular in Latin America (-140 kha) and North America (-180 kha). At the same time, palm oil plantation expands by 110 kha in Southeast Asia, which leads to 50 kha of extra deforestation in the region. Deforestation, however, decreases in Latin America by 80 kha, due to lower expansion of grassland.

Land use change emissions

Land use emissions are mainly associated with soil carbon changes (72 $MtCO_2e$), peatland emissions (36 $MtCO_2e$) and foregone sequestration (36 $MtCO_2e$). Carbon sequestration in palm plantations decreases emissions by 31 $MtCO_2e$.

Total land use emissions of rapeseed FAME is found to be 160 $MtCO_2e$. With an assumed 20 year amortisation, this results in an LUC emissions factor of 65 gCO_2e/MJ, i.e. 2.29 tCO2e/t rapeseed oil, or 0.97 tCO2e/t rapeseed.

Sunflower seed

Shock size:	7.9 million tonnes sunflower seed
Land Use Factor:	1.24 tCO_2 per t sunflower seed.

Additional demand of 1% ethanol (123 PJ) is produced from 7.9 million tons (Mt) of sunflower, taking place for 36% in the European Union. This shock leads to a price increase of sunflower seed of 5.7% at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (2.4 Mt), rest of Eastern Europe (1.6 Mt), Russia and its satellites (1.6 Mt) and Latin America (0.7 Mt). This new production requires an acreage of 1.3 million ha (Mha) in the European Union, 660 kha in rest of Eastern Europe and 1.1 Mha in Russia and satellites and 350 kha in Latin America.

Overall agricultural production is affected by the expansion of sunflower seed demand, and total demand for cereals decreases by 3.4 Mt, due to higher prices. Demand for protein meals and DDGS increases by 0.2 Mt.

Land expansion requires 1.7 Mha of additional cropland globally. In the European Union, cropland expands by 790 kha of which 520 kha are sourced from abandoned land by 2020 and only 270 kha from grassland and other natural vegetation. In the rest of Eastern Europe, cropland expands at the expense of other natural vegetation (-250 kha) and in Russia at the expense of grassland mainly (-120 kha for 200 kha expansion). Oil palm plantation expands globally by 70 kha mainly allocated in Southeast Asia.

Land use emissions are mainly associated to conversion of natural vegetation in Latin America and Southeast Asia (92 MtCO2) as well as soil organic carbon emissions (70 MtCO2eq) following the shock due to expansion of cropland. Peatland emissions increase by 26 MtCO2eq. Foregone carbon sequestration of abandoned land in the European Union represents 25 MtCO2eq, while additional carbon sequestration in crop biomass decreases emissions by 19 MtCO2eq.

Total land use emissions of 7.9 million tonnes of sunflower seed are found to be 195 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 1.24 t CO2eq/t sunflower seed.

Sunflower meal

Shock size:	4.3 million tonnes sunflower meals
Land Use Factor:	0.45 tCO_2 per t rapeseed.

Additional demand of 4.3 million tons (Mt) of sunflower meals corresponds to 7.9 million tonnes of sunflower seed, taking place for 100% in the European Union. This shock leads to a price increase of 1.5% for sunflower at the global level.

Adjustments to the shock

Additional feedstock production is located in the European Union (0.7 Mt), and Russia and satellites (0.5 Mt) whereas it reduces in rest of Eastern Europe (-0.8 Mt). This new production requires an acreage of 400 kha in the European Union, 310 kha in Russia and satellites, whereas harvested areas decrease by -340 kha in rest of Eastern Europe.

Overall agricultural production is affected globally and total demand for cereals decreases by 3.3 Mt, due to higher prices. Demand for protein meals and DDGS decreases by 1.6 Mt.

Land use change effect

Land expansion requires 230 kha of additional cropland globally. In the European Union, cropland expands by 150 kha, sourced from abandoned land by 2020. In Russia and satellites, and in the rest of Eastern Europe, cropland remains stable, but it expands in North America by 50 kha at the expense of other natural vegetation. Oil palm plantation are reduced globally by 120 kha mainly in Southeast Asia (-90 kha) and sub-Saharan Africa (-20 kha).

Land use change emissions

Land use emissions are mainly associated to land use conversion with 49 MtCO2eq emitted. Soil organic carbon emissions increase by 29 MtCO2eq following the shock due to expansion of cropland. Peatland emissions decrease by 33 MtCO2eq and reduced carbon sequestration in crop biomass increases emissions by 20 MtCO2eq. Foregone carbon sequestration of abandoned land in the European Union adds 6 MtCO2eq.

Total land use emissions of 4.6 million tonnes rapeseed cakes are found to be 71 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.83 t CO2eq/t sunflower meals, i.e. 0.45 t CO2eq per tonne rapeseed.

Sunflower oil

Shock size:	3.5 million tonnes sunflower oil (7.9 million tonnes sunflower seed)
Land Use Factor:	0.99 tCO_2 per t sunflower seed.

Additional demand of 1% FAME (123 PJ) is produced from 3.5 Mt of sunflower oil, with 28% of additional production taking place in the EU. This shock leads to a price increase of 8.1% on sunflower seeds, and 16.7% on sunflower oil in Europe. At the global level, the price impacts are 5.2% and 8.3% for sunflower seed and oil, respectively.

Adjustments to the shock

The additional feedstock is achieved 12% through a decrease in food and feed demand, 32% by displacement of feed by sunflower meal and 57% by extra production, of which 52% is from area expansion and 4% from yield increase.

Additional feedstock production requires 6.1 Mt of sunflower globally, located in the EU (1.7 Mt), Ukraine and rest of Europe (1.7 Mt), in Russia and its neighbouring countries formerly part of the USSR (1.3 Mt) and in Latin America (0.9 Mt). This new production requires 870 kha in the EU, 660 kha in Ukraine and rest of Europe, 860 kha in Russia and its neighbors and 450 kha in Latin America.

Overall agricultural production is also affected globally by an increase in consumption of 2.1 Mt of protein meals and the displacement of 530 kt of vegetable oils on the demand side. Extra availability of protein meals leads to increased feed consumption. Meat production increases by 130 kt globally and milk by 120 kt.

Land use change effect

Land expansion leads to 1.5 Mha of additional land conversion globally, mainly for cropland. In the EU, cropland expands by 625 kha of which 290 kha are sourced from abandoned land and 290 kha from other natural vegetation. In Ukraine and rest of Europe, cropland expands by 270 kha mainly into other natural vegetation. Global grassland also decreases by 530 kha as protein meals availability favors grain-based production systems instead of grass-based ones, in particular in Latin America (-140 kha). At the same time, palm oil plantation expands by 160 kha in Southeast Asia, which leads to 50 kha of extra deforestation in the region. Deforestation however decreases in Latin America by 100 kha, due to lower expansion of grassland.

Land use change emissions

Land use emissions are mainly associated to soil carbon changes in cropland (53 $MtCO_2$), natural vegetation conversion emissions (61 $MtCO_2e$) and peatland emissions (56 $MtCO_2e$). Carbon sequestration in agricultural crops decreases emissions by 32 $MtCO_2$.

Total land use emissions of sunflower FAME are found to be 155 $MtCO_2e$. With an assumed 20 year amortisation this results in a resulting LUC emissions factor of 63 gCO_2e/MJ, i.e. 2.21 tCO2e/ t sunflower oil, and 0.99 t CO2e/ t sunflower seed.

Soybean

Shock size:	19.4 million tonnes soybean
Land Use Factor:	0.97 tCO_2 per t soybean.

Additional demand of 1% biodiesel (123 PJ) is produced from 19.4 million tons (Mt) of soybean, taking place for 4% in the European Union. This shock leads to a price increase of soybean of 5.1% at the global level.

Adjustments to the shock

Additional feedstock production is located in the North America (9.0 Mt), in Latin America (4.8 Mt) and to a smaller extent in the Europnean Union (0.7 Mt). This new production requires an acreage of 2.3 Mha in North America, 1.8 Mha in Latin America, and 0.3 Mha in the European Union.

Overall agricultural production is affected globally and total demand for cereals decreases by 6.8 Mt, due to higher prices. Demand for protein meals and DDGS decreases by 1.9 Mt.

Land use change effect

Land expansion requires 2.8 Mha of additional cropland globally. In North America, cropland expands by 420 kha whereas in Latin America, expansion reaches 860 kha of which 180 kha are at the expense of forest, 540 kha are sourced from other natural vegetation and 150 kha from grassland. In the European Union, 420 kha cropland expands at the expense of abandoned land since 2000 (-330 kha) and other natural land (-90 kha). Oil palm plantations are unchanged under this scenario.

Land use change emissions

Land use emissions are mainly associated to the conversion of natural vegetation (219 MtCO2eq) and in Latin America and in Southeast Asia, and to soil organic carbon emissions (151 MtCO2eq). Foregone carbon sequestration of abandoned land increases by 21 MtCO2eq. However, agricultural biomass sequesters 22 MtCO2eq.

Total land use emissions of 19.4 million tonnes of soybean are found to be 368 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.97 t CO2eq/t soybean.

Soybean meal

Shock size:	15.6 million tonnes soybean
Land Use Factor:	0.39 tCO_2 per t soybean.

Additional demand of 15.6 million tons (Mt) of soybean meals corresponds to 19.4 million tonnes of soybean, taking place for 99% outside of the European Union. This shock leads to a price increase of 2.5% for soybean at the global level.

Adjustments to the shock

Additional feedstock production is located in the North America (6.8 Mt), and Latin America (4.0 Mt) whereas South Asia provides an extra 0.9 Mt soybean. This new production requires an acreage of 1.7 Mha in North America, 1.4 Mha in Latin America, and 0.6 Mha in South Asia.

Overall agricultural production is affected globally and total demand for cereals decreases by 10.8 Mt, due to higher prices. Demand for protein meals and DDGS decreases by 5.5 Mt.

Land use change effect

Land expansion requires 1 Mha of additional cropland globally. In North America, cropland expands by 280 kha whereas in Latin America, expansion reaches 330 kha at the expense of grassland and natural forest. In the European Union, 300 kha cropland expands at the expense of land abandoned since 2000. Oil palm plantations decrease globally by 210 kha mainly in Southeast Asia (-150 kha) and in sub-Saharan Africa (-60 kha).

Land use change emissions

Land use emissions are mainly associated to land use conversion with 46 MtCO2eq emitted. Soil organic carbon emissions increase by 85 MtCO2eq following the shock due to expansion of cropland. Peatland emissions decrease by 46 MtCO2eq and reduced carbon sequestration in crop biomass increases emissions by 30 MtCO2eq. Foregone carbon sequestration of abandoned land in the European Union adds 35 MtCO2eq.

Total land use emissions of 4.6 million tonnes rapeseed cakes are found to be 151 MtCO2eq. With an assumed 20 year amortisation this results in an ILUC emissions factor of 0.48 t CO2eq/t soybean meal, i.e. 0.39 t CO2eq per tonne soybean.

Soybean oil

Shock size:	3.5 million tonnes soybean
Land Use Factor:	0.95 tCO_2 per t soybean.

Additional demand of 1% FAME (123 PJ) is produced from 3.5 Mt of soybean oil, with 9.8% of additional production taking place inside the EU. This shock leads to a price increase of 2.3% for soybean and 10.8% for soybean oil at the global level.

Adjustments to the shock

The additional feedstock is achieved 18% through a decrease in food and feed demand, 38% by displacement of feed by soybean meal and 44% by extra production, in which area expansion accounts for 36% and yield increase for 8%.

Additional feedstock production requires 7.3 Mt of extra soybeans, mainly located in North America (4 Mt) and Latin America (2.7 Mt). This requires an area of 960 kha in North America and 860 kha in Latin America. Inside the EU, soybean production increases by 570 kt, which corresponds to 250 kha.

Overall agricultural production is also affected globally by an increase in consumption of protein meal by 5.9 Mt and the decrease of 1.4 Mt in demand for vegetable oils. Grain demand increases by 1 Mt to serve as feed complement to newly consumed protein meals, whereas sugar crops demand decreases by 0.9 Mt. The livestock sector benefits notably from the extra feed production and meat and milk production increase globally by 620 kt and 1,280 kt, respectively.

Land use change effect

Land expansion leads to 2.0 Mha of land conversion globally, 1.8 Mha of which corresponds to additional cropland. In Latin America, cropland expands (500 kha) mainly into other natural vegetation (420 kha), whereas grassland decrease (-190 kha) due to protein meal availability, which favors grain-based production systems instead of grass-based ones. As a consequence, deforestation decreases by 120 kha. The same effect is observed North America, where cropland expansion (190 kha) partly benefits from grassland decrease (-100 kha) and expands into other natural vegetation for only 90 kha. At the same time, palm oil plantation expands by 240 kha in Southeast Asia and cereal production also grows to provide more animal feed. This leads to 560 kha of cropland expansion in the region, replacing 160 kha of grassland, 150 kha of forest and 260 kha of other natural vegetation.

Land use change emissions

Land use emissions are mainly associated with LUC emissions (244 $MtCO_2e$), soil carbon changes (105 $MtCO_2e$) and peatland emissions (78 $MtCO_2e$). Carbon sequestration in biomass decreases emissions by 60 $MtCO_2e$.

Total land use emissions of soybean FAME are found to be 368 $MtCO_2e$. With an assumed 20 year amortisation, this results in an LUC emissions factor of 149 gCO_2e/MJ, i.e. 5.26 tCO2 per t soybean oil, which corresponds to 0.95 tCO2 per t soybean.

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