


POTENTIAL DANISH BIOMASS PRODUCTION AND UTILIZATION IN 2030

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Potential Danish biomass production and utilization in 2030

Advisory report from DCA – Danish Centre for Food and Agriculture

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Data sheet

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presented and discussed. The final composition of scenarios and choices of calculation methods were decided on within the project group.

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Preface

This report summarises the work of the project ”Effekter ved fremtidig arealanvendelse og alternativ anvendelse af biomasse”, which was requested by the Ministry of Food, Agriculture and Fisheries. The request was based on the acknowledgement of the large impact of the current and future utilization of land and sea and of the extraction, conversion and use of biomass resources on Denmark's CO_2-emissions.

In their report "Direction and measures for the next 10 years climate action in Denmark" The Danish Council on Climate Change (2020) described a land-use related CO_2 reduction potential of 1.4 M tonnes from reduction of agricultural land-use and of 0.4 M tonnes from changes in agricultural land-use on 100,000 ha. To achieve these reductions, the council stipulated a need for improving the existing regulations for land use change or setting land aside, so that they can play a larger role in the transition, and for achieving more knowledge on emission factors and effects of land-use changes.

Furthermore, there is need for knowledge on what should be grown on the land that is not permanently set aside or rewetted – is it forest, grassland or other biomass crops that are better, seen from the combined considerations for climate, environment, biodiversity, and businesses? As well as the potential for harvesting biomass from the sea?

Finally, the optimal uses of the biomass produced within the bioeconomy needs further investigation. There are many technology routes under development, and they compete for the same biomass. These considerations and questions were the backdrop of the project and the analyses conducted.

The following organisations were invited to participate in two webinars to discuss the aims of the projects as well as the proposed scenario set-ups and preconditions: SEGES, Landbrug & Fødevarer, Bæredygtigt Landbrug, DN, ARLA, DLG, Danish Crown, Energistyrelsen, Dansk Skovforening, Danske halmleverandører, Biogas Danmark, Dansk fiskeri, Dansk Akvakultur, Musholm Laks, WWF, DTU Aqua, Frøavlerforeningen, SDU Kemi-, Bio- og Miljøteknologi, DAKOFA, DAKOFO, Sukkerroedyrkerne, Danske Maskinstationer og Entreprenører, Drivkraft Danmark, AAU Kemi og Biovidenskab, DI fødevarer, 3F, Teknologisk Institut, Rådet for Grøn Omstilling, Danish Agro, Food & Biocluster DK, DI Bioenergi, Ørsted, Miljø- og Fødevareministeriet, Klima-, Energi- og Forsyningsministeriet, Danish Marine Proteins, Vestjyllands Andel, Dansk Miljøteknologi, Novozymes, Novo, Bio2Oil and Daka.

The authors want to express their great gratitude to the project coordinator Morten Gylling who sadly passed away during the project. This report is in his memory.

Content

Summary

The bioeconomy is expected to take over significant parts of the fossil economy during the green transition of our society over the coming decades. However, the biomass resources that can be sustainably sourced are limited and uncertain. They depend on a combination of productivity parameters as well as on the sustainability of the production, and on its effects on society, climate, environment, and biodiversity. This makes projections of the realistic contribution of biomass for the green transition uncertain, and the development of a suitable supporting political framework challenging.

The current analysis includes these aspects with the aim of providing updated scenarios for the potential use of land and sea for the provision of biomass, and possible effects on climate, environment, and the economy. The latter effects, however, are only analysed for agriculture – the sector providing the largest amount of biomass in Denmark.

The analysis is based on scenarios for the future land-use development in agriculture and forestry, as well as the future use of marine resources. The newest knowledge on production methods that are re-source efficient in order to maximize carbon capture by photosynthesis, and to utilize nutrients efficiently to reduce eutrophication of the environment, have been used to frame the scenarios. Political decisions and strategies agreed upon before July 2021 were used to frame the scenarios.

Some of the technologies we have implemented in the scenarios are 1) Increased use of perennial grass-legume mixtures that cover the soil year-round. The longer growing season compared to annual crops increases the capture of solar radiation, which in turn increases carbon capture and biomass yield. 2) Green biorefining of fresh green leaves from grass, clover, lucerne, beetroots etc. has been highly optimized over the last five years, providing a protein concentrate with quality similar to that of soybean meal as well as cattle feed, biomaterials (packaging, textiles, insulation etc.), colorants, and fermentation into chemicals for production of plastic and other biobased products. 3) Increases in low-trophic regenerative aquaculture of mussels and seaweeds as Nature-based Solutions for mitigating coastal eutrophication and climate change, while producing biomass for food, feed, or blue biorefineries, with focus on i.e. protein, lipids, and hydrocolloids.

Three fundamental scenarios were analyzed, each with different implications for agriculture, forestry, and marine biomass. The three scenarios are 1) Business-as-usual, which mimics a continuation of the current conditions for production of biomass. 2) Biomass, which assumes sustainable intensification of the biomass production to provide a high output of biomass. 3) Extensification, which takes into account significant environmental, climate and nature concerns. For the agricultural scenarios, also the effects of +/- 20 % change in animal production were analysed.

For agriculture, the BAU-scenario for 2030 resulted in an increase of approx. 4.5 M tonnes DM biomass compared to the baseline (2015-2019) by increased utilization of already known sources and technologies. The optimized Biomass scenario for 2030 resulted in an increase of close to 11 M tonnes of biomass DM. When reducing the animal production by 20 %, where some of the roughage area is turned into grass-clover for biorefining, biomass potential was increased to 13 M tonnes, while a 20 % increase in the animal production resulted in approx. 10 M tonnes biomass compared to the baseline. The Extensification scenario resulted in up to 11 % of agricultural land set aside for nature protection, while still increasing biomass availability by more than 8 M tonnes DM compared to the baseline. If animal production is reduced by 20 % in the Extensification scenario, biomass availability was slightly lower due to a lower quantity of manure available, while areas not needed for production of roughage was set aside for natural succession and extensive grazing instead of being used for crops for biorefining as in the Biomass scenario. If animal production is increased by 20 % in the Extensification scenario, the biomass production available for biorefining was slightly less than 7.5 M tonnes DM. The biomass production in the two scenarios with increased animal production was still relatively high, which was sustained by an increased grain import in these scenarios.

The forestry scenarios had implications for both the production of biomass as well as the build-up of forest carbon stocks. Contrary to the other sectors the application of various instruments are slow to manifest in differences in biomass production owing to the slow growth and late maturing of the forest resource. Consequently, there were no significant differences in biomass harvest by 2030, and production was reported over a 100-year period. In the Biomass and Extensification scenarios the forest area was expanded to 1.079 M hectares in 2120, while it was expanded to 0.793 M hectares in the BAU scenario within the 100 years of simulation. The three scenarios differed considerably in terms of the tree species distribution: fast growing conifers made up 85 % of the forest area in the Biomass scenario after 100 years whereas broadleaves made up 87 % in the Extensification scenario. The increased afforestation in the Biomass and Extensification scenarios increases the biomass stocks relative to the BAU scenario. However, increased focus on production in the Biomass scenario resulted in a faster build-up of biomass owing to the larger share of fast-growing tree species. Oppositely, in the Extensification scenario, use of natural succession and a large share of broadleaves in the afforestation resulted in a slower and lower build-up of biomass resources.

Marine biomass in the form of blue mussels, starfish, sugar kelp, sea lettuce, discard as well as landings of other species of invertebrates and non-quota fin fish, was calculated to contribute with 26 ktonnes dry matter in 2030 in the BAU scenario. The contribution was increased to 32, and 58 ktonnes DM in the Biomass and Extensification scenarios, assuming implementation in future water area plans of LTA of mussels and seaweed as a tool to mitigate coastal eutrophication. This is equivalent to a total annual supply of 6, 8, and 18 ktonnes of crude marine protein. In the Biomass and Extensification scenarios, most of the marine crude protein, 32 % or 62 % respectively, will derive from mussels produced in LTA. Realization of the marine Biomass and Extensification scenarios will require use of 2,902 or 13,124 ha, respectively. This is equivalent to only 0.02 or 0.09 % of the Danish Exclusive Economic Zone of 105,000 km^2. Expanding the Extensification scenario to include the North Sea will double the estimated LTA biomass production in 2030 but requires development of robust cultivation technology to withstand the forces of wind and waves in the more exposed environment.

The waste and by-products from households and industry are difficult to estimate, and much of the industrial by-products are already used for e.g., animal feed. With large uncertainty, it was estimated that approx. 1.6 M tonnes of DM industrial by-products are available to the bioindustry annually, and an organic waste fraction from households of approx. 0.4 M tonnes of DM.

The biomass from the scenarios coming from agriculture, forestry, marine sources, and industrial side-streams was converted through biorefining. Each biomass type was divided into its primary structural and biochemical components. These components are proteins/amino acids, lipids, carbohydrates (cellulose, hemicellulose, and simple carbohydrates), lignin, and inorganic matter. The most significant differences between the biomass potential in the Biomass and Extensification scenarios was the amount of green biomass and the amount of wood available for biorefining (excl. timber and industry wood). The increase in green biomass resulted in an additional production of especially protein that went from 1.62 M tonnes in the Extensification scenario to 2.08 M tonnes in the Biomass scenario, as well as a significant increase in carbohydrates, which was 1.03 M tonnes/year higher for cellulose, 0.74 M tonnes for hemicellulose, and 0.89 M tonnes for simple carbohydrates. The large difference in simple carbohydrates was because the Biomass scenario includes a yield of 0.84 M tonnes/year of sugar beet for biorefining, where the Extensification scenario does not include beets, and that the green biomass has a relatively high content of free sugars. The larger contributions of biomass came from agriculture and forestry. The biomass contribution from side-streams and especially from the sea was in comparison very limited. However, many high value and readily available sources of protein, carbohydrates, and lipids are coming from sea and side-stream biomass. The projected biomass resources are so large and so diverse that several biorefining systems can be established to produce both food, feed, chemicals, materials, liquid fuels, power, and heat. These systems should largely be integrated and benefit from each other through cascade utilization and industrial synergies. However, there are many alternative choices to be made for technologies that utilizes the same type of biomass. Here the choice of technologies will depend on what type of biobased products is prioritized to create most value for the society and the best business cases for industries.

The Biomass and Extensification scenarios have large impacts on the land use in Denmark. Especially the Extensification scenario results in large areas with less intensive agriculture, more organic agriculture, more diverse forests, and set-aside areas, which have the potential to increase biodiversity and nature values. Between 5 and 11 % of the farmed area was set aside for natural succession and extensive grazing in 2030 in the different Extensification scenarios.

Rewetting of organic soils caused significant reductions in Greenhouse gas (GHG) emissions, and the conversion of annual crops into perennial grassland increased soil carbon content, while removal of more straw reduced soil carbon. Together with effects on nitrous oxide and methane emissions from all land-use changes GHG emissions were reduced by between 0.9 (BAU) and 5.3 (Extensification -20 %) M tonnes CO_2e yr^{-1}.

The change of annual crops into perennial crops reduced nitrate leaching significantly. Together with effects of more catch crops and improved manure management etc., reductions in leaching of between 2,000 (BAU) and 40,000 tonnes nitrate-N yr^{-1} from the root zone was calculated compared with the reference (todays practices).

Budget economic costs on farm field changes and for transportation of biomass for local biorefineries or biogas plants were calculated at between 870 (Biomass -20 %) and 1,390 (Extensification -20 %) M DKK in total. In the Biomass scenario, the 14.5 M tonnes biomass dry matter had an estimated cost of DKK 930 M, while in the Extensification scenario, the 12.3 M tonnes of dry matter had an estimated cost of DKK 1,000 M, which means DKK 64/tonnes and DKK 81/tonnes, respectively. These costs need to be covered by revenues from the products produced in the bioindustry, and by the values of the GHG and nitrate leaching reductions obtained. Based on statistical data, the more intensive land-use depicted in the scenarios will increase the employment for the Biomass scenario of 1,300 full time positions and 500 full time positions in the Extensification scenario. In addition to this, there is an employment effect from the biorefineries with an estimated 2.5 persons at a small-scale biorefinery. There is raw material to supply approx. 150 biorefineries in the Biomass scenario and approx. 130 biorefineries in the Extensification scenario, which can increase employments by 375 and 325 full time positions, respectively.

Finally, we discuss how a vibrant and sustainable bioeconomic sector may be developed. We do not start from scratch as the bioeconomy has a long tradition in agriculture, forestry, and the related industries (e.g. sugar, potato starch, dairy, fish, abattoirs, saw mills, and pulp and paper industry). However, a much higher throughput of biomass and the use of many new types of biomass as well as new conversion technologies, will require significant research, development, and investments in industries to deliver the biobased raw materials for the material industry. Biomass is also expected to deliver bioenergy components to supplement the future renewable energy system, which in Denmark will be mainly based on wind and solar power but will require balancing input from imports of power and from local bioenergy resources. The biomass used for bioenergy in such a cascading process will deliver biogenic CO_2 for PtX and/or for Carbon Capture and Storage.

The transformation of our energy system to become renewable and zero emission seems to be more or less on track to complete by 2045 and reach milestones by 2030. On the other hand, the just as big transformation and development of the bioeconomic sector has been given less focus and less funding to reach zero emission targets for agriculture, forestry, aquaculture, and the related industries. Thus, there is a strong need for well-prepared strategies with clear milestones, and description of the needed support mechanisms from research & development and from public-private investments.

1 Introduction

The bioeconomy is expected to take over significant parts of the fossil economy during the green transition of our society over the coming decades. However, the biomass resources that can be sustainably sourced are limited and uncertain. They depend on a combination of productivity parameters as well as on the sustainability of the production and its effects on society, climate, environment, and biodiversity. This makes projections of the realistic contribution of biomass for the green transition uncertain, and the development of a suitable supporting political framework challenging.

Gylling et al. (2016) argued that it would be possible to increase sustainable biomass supply by 3-4 times without any significant change in resources for food production. This analysis included agriculture, forestry, and a number of minor land-based biomass sources. Since then, technologies have been developed significantly, both for the production of aquatic resources as well as cascading biomass biorefining, enabling the production of multiple products of higher value from the same biomass (i.e. novel functional food ingredients and alternative proteins). Also, since 2016, the public debate has intensified regarding the future level of animal production in Denmark and on how to implement regenerative aqua- and agricultural practices, putting additional pressure on the development and diversification of biomass production and utilisation.

The current analysis includes these aspects with the aim of providing updated scenarios for the potential use of land and sea for the provision of biomass, and possible effects on climate, environment, and the economy. The latter effects, however, are only analysed for agriculture – the sector providing the largest amount of biomass in Denmark.

2 Scenario technologies

The analysis is based on scenarios for the future land-use development in agriculture and forestry (Mortensen and Jørgensen, 2021; 2022; Nord-Larsen and Johannsen, 2022), as well as for the future use of marine resources (Bruhn et al., 2022). The newest knowledge on production methods that are resource efficient in order to maximize carbon capture by photosynthesis, and to utilize nutrients efficiently to reduce eutrophication of the environment, have been used to frame the scenarios. Also, political decisions and strategies agreed upon before the cutoff of July 2021 have been used to frame the scenarios, e.g. the EU Water Framework Directive, the European Green Deal, and national goals on climate and the setting aside of forest land for nature protection.

Some of the technologies we have implemented in the scenarios are:

- Increased use of perennial grass-legume mixtures that cover the soil year-round. The longer growing season compared to annual crops increases the capture of solar radiation, which in turn increases carbon capture and biomass yield (Manevski *et al.*, 2017). The active crops year-round support nutrient uptake from the soil and significantly reduce the risk of nitrate leaching (Manevski et al., 2018). Today, approx. 80 % of Danish agricultural land is with annual crops, and this share can be reduced, if there is a relevant use of the biomass produced from perennial crops within the bioeconomy.

- Green biorefining of fresh green leaves from grass, clover, lucerne, beetroots etc. (Figure 2.1) has been highly optimized over the last five years, providing a protein concentrate with qualities similar to that of soybean meal (Stødkilde et al., 2021). In this process, a number of side-products are under development, such as cattle feed, biomaterials (packaging, textiles, insulation etc.), colorants, and fermentation into chemicals for production of plastic and other biobased products. These potentials are further unfolded in Ambye-Jensen (2022). The first two commercial green biorefineries have been inaugurated during 2020-21.

- Increase in low-trophic regenerative aquaculture of mussels and seaweeds as Nature-based Solutions for mitigating coastal eutrophication and climate change, while producing biomass for food, feed, or blue biorefineries, with focus on i.e. protein, lipids, and hydrocolloids (Bruhn et al., 2022).

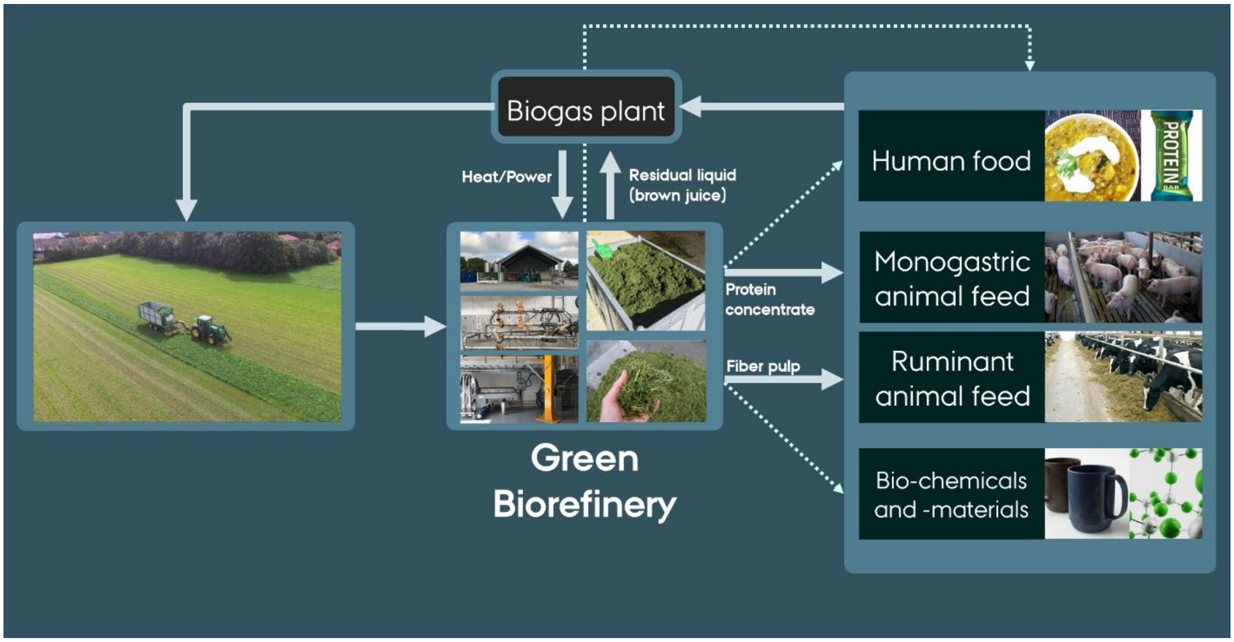


Figure 2.1. *Sketch of the concept of green biorefinery, where grass is separated into a protein concentrate, a fibre pulp and a residual liquid (brown juice). Fully drawn lines denote already developed processes and the dotted lines processes under development (source: Morten Ambye Jensen).*

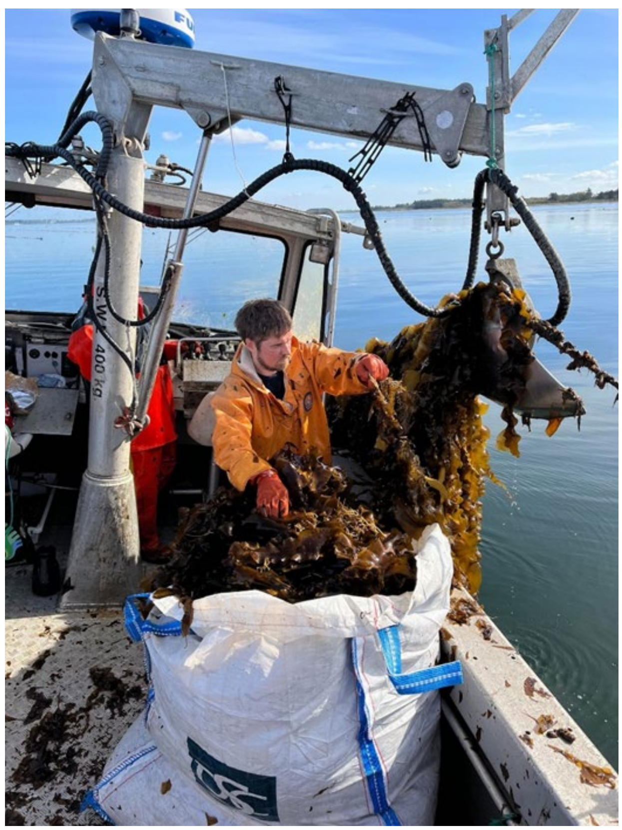


Figure 2.2. *Harvest of sugar kelp in Denmark (photo: Mette Møller Nielsen).*

3 The resource base for Danish biomass production

The total Danish land area of approx. 43,000 km^2 is highly affected by human activities: 61 % of the land is occupied by agriculture, 13 % by forestry*, 14 % by cities, roads etc., while natural areas including lakes and streams cover 12 % (Odgaard et al., 2021). Earlier analyses have shown that approx. 20 M tonnes of dry matter of biomass are produced from the land under cultivation, of which approx. 18 M tonnes were harvested (Gylling *et al.*, 2016). Using a common European standard for calculation, analyses from the EU Joint Research Centre estimated, that an annual mean of almost 25 M tonnes of dry matter biomass were produced in Denmark in the period of 2013-2018 (Gurría et al., 2020 and Figure 3.1). In additions, the changes in production systems into more resource efficient crops, mentioned in Chapter 2, can significantly increase productivity, and at the same time reduce negative impacts on environment, nature, and climate.

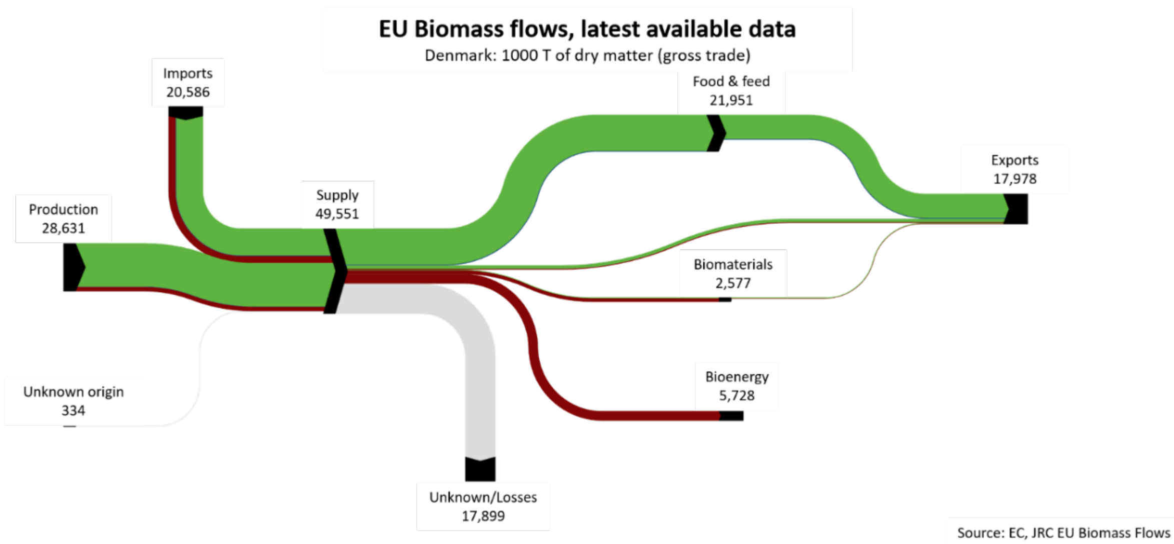


Figure 3.1. *Sankey diagram of biomass flows for Denmark in 2018 as computed by the EU Joint Research Centre based on general EU Statistics. Green flows are crops and animal products, brown are wood, and blue are from fisheries. Accessed from https://datam.jrc.ec.europa.eu/datam/mashup/BIOMASS_FLOWS.*

The Danish Exclusive Economic Zone (EEZ) covers 105,989 km^2 of the sea around Denmark. While this area has been intensively used for fishing activities over centuries, the finfish aquaculture production is limited due to the general eutrophication of the Danish coastal waters. In recent years, low-trophic aquaculture (LTA) of non-fed nutrient extractive species, such as mussels and seaweeds, has been gaining interest as a tool for mitigating the coastal eutrophication, while at the same time providing marine biomass. While the

* The forest area is estimated at 14.7% based on data from the Danish National Forest Inventory (Nord-Larsen *et al.* 2021). Differences are due to differences in the forest definition and assessment approaches.

cultivation technology of mussels is at a technological readiness level enabling upscaling, seaweed cultivation technology is still developing. In the Maritime Plan for the Danish seas, the authorities encourage coexistence between maritime activities, such as marine energy production and LTA.

4 Scenario definitions

In the analysis, we have established three fundamental scenarios, each with different implications for agriculture, forestry, and marine biomass. The three scenarios are:

- Business-as-usual (BAU) in which we mimic a continuation of the current conditions for production of biomass. In the BAU scenario, only initiatives that have been started and legislation that have been approved (e.g. on cover crops and setting aside forest for nature protection) are included while policy targets on climate and environment are not.
- Biomass in which we assume sustainable intensification of the biomass production to provide a high output of biomass to support societal needs of the bioeconomy.
- Extensification in which we take into account significant environmental, climate and nature concerns that increase the area set aside for biodiversity purposes.

Throughout the report, the BAU scenario is compared to the two alternative scenarios, demonstrating the implications of both intensification and extensification in the use of land and marine resources. The specific definitions of the three scenarios differ between agriculture, forestry, and marine biomass production.

4.1 Agriculture: Three main scenarios for 2030

Business-As-Usual

In the BAU scenario, an increased utilization of the available resources of e.g. straw, rapeseed oil, and slurry is assumed, but no changes in cropping systems, harvesting techniques or variety selection are foreseen. Details on assumptions and calculations of biomass production in the three scenarios are described in the background material (Mortensen and Jørgensen, 2021). The assumptions on the BAU scenario includes:

- Historical increase in crop yield and feed efficiency, and reduction in farmed area due to infrastructure and urbanization (Dalgaard and Mortensen, 2022).
- Increased utilization of residual biomass from straw and animal manure (Adamsen *et al.*, 2021; Energistyrelsen, 2021).
- The existing production of rapeseed oil is used 100 % for biorefining.
- On organic soils, approx. 15,000 ha are rewetted with no harvest of biomass (Miljø- og fødevareministeriet, 2020).
- The increase in organic farmed area is based on the historical trend from 2005-2015 (4,900 ha/year) (Blicher-Mathiesen and Sørensen, 2020).

- Afforestation of 1,900 ha per year

Biomass scenario

The Biomass scenario represents an intensification in the use of agricultural land, to provide more biogenic resources as part of a green transition. The Biomass scenario includes:

- Development in crop yield, feed efficiency, farmed area, and organic farming as in BAU.
- Conversion to cereal and rapeseed varieties with a 15 % increase in straw yield.
- Alternative harvesting technology with a 15 % increase in straw recovery.
- On organic soils, approx. 50,000 ha are rewetted and converted into 70 % paludiculture and 30 % natural succession and extensive grazing.
- On soils that are sensitive to leaching of nitrate to surface waters, approx. 319,000 ha of annual crops (cereal, maize, and rapeseed) are converted to sugar beets (44,000 ha) and grass-clover (275,000 ha).
- On loamy soils with a low carbon to clay ratio, approx. 99,000 ha of annual crops (cereal, maize, and rapeseed) are converted into grass-clover, facilitating an increase in soil carbon storage.
- On sandy soils sensitive to leaching of pesticides to groundwater reservoirs, approx. 17,000 ha of annual crops (cereal, maize, and rapeseed) are converted into grass-clover.
- Cover crops are harvested on approx. 198,000 ha. Mixtures including N_2-fixating species are allowed for the system to self-regulate N-availability.
- Leaves from the existing area of sugar beets are harvested (approx. 31,000 ha).
- Biomass cuttings from road verges and watercourse clearings are utilized.
- Optimized manure handling (quick removal and cooling) is assumed to increase the total manure dry matter (DM) by 7.5 %.
- Afforestation of 5,600 ha per year, mainly with fast-growing coniferous species.

Extensification scenario

The Extensification scenario includes measures with reduced intensity of input and measures reducing the land use for cultivation of agricultural crops:

- Development in crop yield and feed efficiency as in BAU.
- Increase in organically farmed area by 100% compared to 2018 (23,250 ha/year). A large part of the new organic farming area is assumed to be on the new grasslands on nitrate sensitive soils.
- Conversion to cereal and rapeseed varieties with a 15 % increase in straw.
- Alternative harvesting technology with a 15 % increase in straw recovery.
- On organic soils, approx. 100,000 ha are rewetted and converted into 30 % paludiculture or harvest of natural vegetation, and 70 % natural succession and extensive grazing.
- On soils that are sensitive to leaching of nitrate to surface waters, approx. 247,000 ha of annual crops (cereal, maize, and rapeseed) are converted to grass-clover with a reduced fertilization.
- On loamy soils with a low carbon to clay ratio, approx. 91,000 ha of annual crops (cereal, maize, and rapeseed) are converted into grass-clover, facilitating an increase in soil carbon storage (80 % of the area with fertilization at current N-norms and 20% with reduced fertilization).
- On sandy soils sensitive to leaching of pesticides to groundwater reservoirs, approx. 17,000 ha of annual crops (cereal, maize, and rapeseed) are converted into 50 % grass-clover for biorefining, and 50% natural succession and extensive grazing.
- Cover crops are harvested on approx. 205,000 ha. Mixtures including N_2-fixating species are allowed for the system to self-regulate N-availability.
- Leaves from the existing area of sugar beets are harvested (approx. 31,000 ha).
- Biomass cuttings from road verges and watercourse clearings are utilized.
- Optimized manure handling (quick removal and cooling) is assumed to increase the total manure DM by 7.5 %.
- Afforestation of 5,600 ha per year. 50 % mixed deciduous species and 50 % natural succession.

4.1.1 Agriculture: Sub-scenarios with changes in the animal production in 2030

While animal production and feed demand are kept stable in the main scenarios, two sub-scenarios with a changed animal production are analysed within the Biomass and Extensification scenarios. This is done, acknowledging the large biomass use for feed purposes, and the impact of the animal production on global climate change (Jørgensen et al., 2021). Thus, sub-scenarios with an overall 20 % decrease in the national animal production in 2030 are analysed for each of the two main scenarios, resulting in a lower fodder demand, manure production, and use of straw for animal bedding. Similarly, sub-scenarios with a 20 % increase in animal production for 2030 are analysed for each of the two main scenarios, resulting in an increase in domestic production of fodder and production of manure available for biogas, while the increased use of straw for animals reduces the amount of available straw for biorefining.

The sub-scenarios with changed animal production are assumed to affect the import/export balance, while the areas converted for new crops for biorefining are generally kept the same as in the main scenarios. The only exception is an area of approx. 160,000 ha with roughage crops (20 % of the total area with roughage crops) that are converted into grass-clover for biorefining in the Biomass scenario with reduced animal production. In the Extensification scenario with reduced animal production, this area is set-aside as natural succession and extensive grazing. In the scenarios with increased animal production, the increased demand for roughage is assumed to be fulfilled by the fibre-fraction of the biorefining processes, while the increased demand for grain and rapeseed is adjusted via import. The new production of grass protein from biorefining of grass and clover is substituting soy import, and in the Extensification scenario with reduced animal production, an excess of grass protein occurs, which is exported as feed. Alternatively, the excess area due to lower animal production in Denmark may be utilized in many other ways. Instead of producing grass protein for export as animal feed, a share of this area could e.g. be used for producing refined green proteins for human consumption, or for a production of protein-rich vegetables for direct human consumption.

4.2 Forestry: Three scenarios for 2030

Future biomass production from the Danish forests is estimated from the current status of the forest as reported by the National Forest Inventory (Nord-Larsen *et al.*, 2021). This includes the current forest area and its distribution to tree species, age-classes, and tree sizes.

Instruments applied in the three scenarios are included in previous studies of potentials to increase forest biomass production (Gylling *et al.*, 2012; Graudal *et al.*, 2013) and include:

- Expectations related to afforestation
- Expected rotation age
- Species distribution in afforestation and reforestation
- Methods applied in afforestation and reforestation
- Area set aside for nature protection
- Thinning intensity

- Assortment distribution
- Genetic improvements

The different instruments are combined to produce the scenarios reflecting different expectations regarding the conditions for future forest management and production (Table 4.1).

Table 4.1. *Scenarios for the development in future conditions for forest management and production.*

	BAU	**Biomass**	**Extensification**
Afforestation	1,900 ha/yr.	5,600 ha/yr.	5,600 ha/yr.
Species choice in afforestation	As present	Fast growing species, mainly conifers	50 % Natural succession. 50 % Broadleaves
Species choice in reforestation.	Broadleaved forest is regenerated with broadleaves, conifers with conifers.	Broadleaved forest is regenerated with 50 % conifers and 50 % broadleaves. Coniferous forest is regenerated with conifers.	Broadleaved forest is regenerated with broadleaves. Coniferous forest is regenerated with 50 % conifers and 50 % broadleaves.
Methods applied in afforestation and reforestation.	As present.	Increased use of nurse crops.	As present.
Rotation age.	As present.	Reduction in rotation age.	Increasing rotation age.
Set aside area for nature protection.	Until 2024 as present. From 2024 including 75,000 ha set aside area for nature protection of which 75 % of the coniferous forest is harvested and left for natural succession.	Until 2024 as present. From 2024 including 75.000 ha set aside for nature protection with total harvest stop.	Until 2024 as present. From 2024 including 75,000 ha set aside area for nature protection of which 75 % of the coniferous forest is harvested and left for natural succession.
Assortment distribution.	Assortment distribution with current distribution to industrial and energy wood. Up to 50 % residual biomass in smaller diameter classes and 10-30 % in larger diameter classes.	Assortment distribution with high output of wood for bioenergy, making up 95 % in small diameter classes and 25-65 % in larger diameter classes. Residual biomass makes up 5% for all diameter classes.	Assortment with focus on timber production. High utilization of harvest residues in conifers. Up to 15 % residual biomass in broadleaved forest.

Projections are based on a set of survival models estimated on repeated measurements of national forest inventory plots, making up a representative sample of contemporary forest management. The models were developed in relation to the Danish National Forest Accounting Plan and updated in relation to the national climate projections (Johannsen *et al.*, 2022) and reflect current management practices (Johannsen *et al.*, 2019). The survival models are combined with the current age and species distribution in a Markov-chain model iterating forest development in 5-year periods corresponding to the rotation length of the data collection in the Danish NFI. Projections of afforestation, entering the lowest level of the Markov-chain model, is based on scenario specific expectations regarding afforestation levels and its species composition. In BAU the afforestation is assumed to follow previous trends at 1,900 ha/yr while in the Biomass and Extensification scenarios, the afforestation is assumed to result in 25 % forest land in 2089 in accordance with long standing national policy, totaling 5,600 ha/yr.

End of rotation felled amounts are estimated from national forest inventory data, while intermediate thinnings and development of tree size is obtained from national forest growth models. The assortment distribution of felled wood is estimated from projected tree sizes using a set of species type specific assortment distribution tables.

All three scenarios are based on a frozen policy regarding the decision to set aside 75,000 ha of forest land before 2024. As the area specific implementation of the decision has yet to be decided, we used the area distribution used in the national climate projections (Johannsen *et al.*, 2022). Two scenarios (BAU and Extensification) include instruments to accommodate biodiversity including removal of exogenous conifers, establishment of forest grazing on 1/3 of the set aside area, and scarification of 25 % of the growing stock in broadleaved trees.

4.2 Marine biomass: Three scenarios for 2030

Marine biomass from Low Trophic Aquaculture (LTA) is highly nutritious and has the potential for positive climate and environmental impact as it allows for capture and reuse of nutrient and carbon emissions, supporting the circular bioeconomy (Duarte *et al.*, 2021; Gephart *et al.*, 2021; Golden *et al.*, 2021). Expansion of LTA needs to take multiple factors into consideration, i.e. maritime spatial planning and the biological/ecological carrying capacity of marine areas. The area specific yield of mussels is higher than that of sugar kelp.

Marine biomass contains high concentrations of omega-3 fatty acids, essential vitamins and minerals, and for the animal part in particular, a high content of crude protein that can replace fishmeal in animal feed. Seaweeds have lower contents of proteins and lipids but are presently exploited by the industry for food, and for their hydrocolloids, bioactive compounds, and pigments. Various seaweeds are presently explored as feed additives for reducing the methane emissions from ruminants {Thorsteinsson, 2023}.

Marine biomass is here limited to include biomass not included by quota fisheries, mussel dredging, or finfish aquaculture, and it only includes production forms that are presently realised or under development: 1) low trophic aquaculture (LTA) of blue mussel (*Mytilus edulis*) on lines or nets for consumption or nutrient mitigation; 2) LTA of sugar kelp (*Saccharina latissima*); 3) fishery of two non-quota marine species: common star fish (*Asterias rubens*) and sea lettuce (*Ulva* sp.), 4) discard, and 5) landings of other species of marine invertebrates and non-quota finfish. The latter two are based on Petersen *et al.* (2021). Full exploitation of existing fisheries quota and production of microalgae are not included.

The three marine scenarios are defined and aligned as close to the terrestrial scenarios as possible, i.e. maximising biomass production without negative impact on the marine environment.

The sub-scenarios of a 20 % reduction and increase in animal production are not taken into consideration in relation to the marine biomass production.

The marine Extensification scenario is defined as an implementation of LTA to serve as a Nature-based Solution (NbS)), defined as "*Actions to protect, sustainably manage and restore natural or modified ecosystems, which address social challenges (e.g. Climate Change), effectively and adaptively, while simultaneously providing human well-being*" (Cohen-Shacham *et al.*, 2016).

The assumptions of the Biomass and Extensification scenarios only affect the LTA production of mussels and sugar kelp for nutrient mitigation, and the harvest of sea lettuce, whereas the production of other types of marine biomass is assumed to undergo the same development regardless of scenario.

In the Biomass Scenario, the LTA of both mussels and sugar kelp is proposed in areas with maximal area efficiency for each species. In the Extensification Scenario, the areas for cultivation are given as the actual wind farm areas, and thus the area efficiency will be sub-optimal. In principle, simultaneous implementation of The Biomass and Extensification Scenarios is possible. The here given production numbers, however, cannot be immediately added up as the BAU is implicit in both.

Business-As-Usual

The marine BAU 2030 scenario is based on the following assumptions:

- Production of relevant marine biomass is market driven and trends observed within the period 2010 to 2020 are projected to 2030.
- Projection of increases in yields, landings and areas for production are based on existing and relevant data from 2010-2020
- No fundamental changes in temperature, salinity, and nutrient availability in Danish waters until 2030
- No changes in existing Danish legislation on licences for LTA of mussels and seaweed
- No changes in existing Danish legislation affecting harvest/fishery of starfish and sea lettuce
- The coming Maritime Spatial Plan (Havplan) allows for the here proposed exploitation of marine areas for LTA of mussels and seaweed

- Fishery of starfish is projected with a maximum annual harvest of 10 ktonnes as 20-40% of the national stock assessment in Limfjorden (Petersen *et al.*, 2016; Petersen *et al.*, 2021).

Biomass Scenario

The marine Biomass 2030 scenario is based on the following assumptions:

- Production of mussels and seaweeds for counteracting eutrophication is implemented as a mitigation tool in the coming third generation of national water area plans (2021-2027) for achieving 5% of the N reduction target, hereof a 90 % by mussels and 10 % by sugar kelp.

- Nitrogen reduction targets in the marine environment are assumed to be 13,100 tonnes N/year, fully implemented by 2030.

- Production of mussels and sugar kelp are placed in marine areas where the nutrient uptake efficiency is maximal (Holbach *et al.*, 2020; Boderskov *et al.*, 2021).

- Production of mussels for mitigating eutrophication is implemented using the system with the at present highest Technological Readiness Level (longlines), assuming that predation from eiders is reduced to a minimum (Bruhn *et al.*, 2020a).

- Production of sugar kelp is implemented using the most cost-efficient system available at present (5 line system (Zhang *et al., 2022*)).

- Harvest of sea lettuce is implemented as a habitat restoration tool in the coming third generation of national water area plans with two active harvesting boats in Denmark (2021-2027).

Extensification scenario

The marine Extensification scenario 2030 is based on the following assumptions:

- The coming Maritime Spatial Plan and national policies supports co-existence between marine wind farms and NbS, such as LTA of mussels and sugar kelp.

- Ten percent of existing and planned wind farm area in Danish waters (excluding the North Sea) is dedicated to LTA of mussels and sugar kelp (5 % for mussels, 5 % for sugar kelp).

- The area for existing or planned wind farms in Danish waters is defined as wind farms that are now active, under construction or has obtained licence for construction before 2030 (future wind farms in the North Sea is not included in the scenarios (Bruhn et al, 2022)

- Harvest of sea lettuce is implemented as a tool for habitat restoration, and scaled up to five active harvesting boats in Denmark in 2030 (Bruhn *et al.*, 2020b).

5 Scenario results

5.1 Agriculture: Production of biomass for biorefining in 2030

Compared to the baseline, calculated as a mean from 2015 to 2019, the BAU-scenario for 2030 results in an increase of approx. 4.5 M tonnes DM biomass production from agriculture (Figure 5.1) by increased utilization of already known sources and technologies. The largest component is heavy expansion in the utilization of animal manure (e.g. for biogas production) as predicted by e.g. the Danish Energy Agency (Energistyrelsen, 2021).

In the Biomass and the Extensification scenarios, the conversion of large areas with cereals, rapeseed, and maize into crops for biorefining, results in a deficiency in grain feed production. Furthermore, in the scenarios with a 20 % increase in animal production, an overall 20 % increase in both roughage and concentrate feed is assumed. Thus, from the products of biorefining, we have subtracted an estimated share of the fibre fraction to substitute the share of roughage crops that are lacking in these scenarios, before calculating how much fibre is available for other purposes. In most of the scenarios, the entire production of high-value grass protein from biorefining is used for substituting soy import. Only in the Biomass scenario with 20 % reduction in animal production, a part of the grass protein is in excess after all soy import is substituted. The entire brown juice fraction from biorefining is available for other purposes such as biogas and fermentation-based production, with the digestate being recycled as fertilizer.

Compared to the baseline, the Biomass scenario for 2030 results in an increase of close to 11 M tonnes of biomass DM, with a potential increase of 13 M tonnes if the animal production is reduced by 20 %, where some of the roughage area is turned into grass-clover for biorefining. The Biomass scenario with 20 % increase in the animal production results in a lower increase of approx. 10 M tonnes compared to the baseline.

Even though the Extensification scenario for 2030 results in up to 11 % of agricultural land being set aside for nature protection (see chapter 5.6), the scenario results in an increase in biomass availability of more than 8 M tonnes DM compared to the baseline. This is because crops with a longer growing season and thus a higher carbon capture is anticipated, and that more of the available straw and manure is utilised. If animal production is reduced by 20 % in the Extensification scenario, biomass availability compared to baseline is slightly lower (8 M tonnes DM higher compared to baseline) due to a lower quantity of manure available, while areas not needed for production of roughage are set aside for natural succession and extensive grazing instead of being used for crops for biorefining as in the Biomass scenario. If animal production is increased by 20 % in the Extensification scenario, the biomass production available for biorefining is slightly less than 7.5 M tonnes DM, the lowest number of the 2030-scenarios except for BAU. This difference compared to the other Extensification scenarios is mainly due to a high use of the fibre fraction as animal feed, that is not entirely compensated for by a higher manure production.

The biomass production for biorefining in the two scenarios with increased animal production is still relatively high, which is sustained by the assumption of an increase in grain import in these scenarios. This will likely have a significant negative impact through indirect land-use effects (iLUC), which is not analysed for in this study.

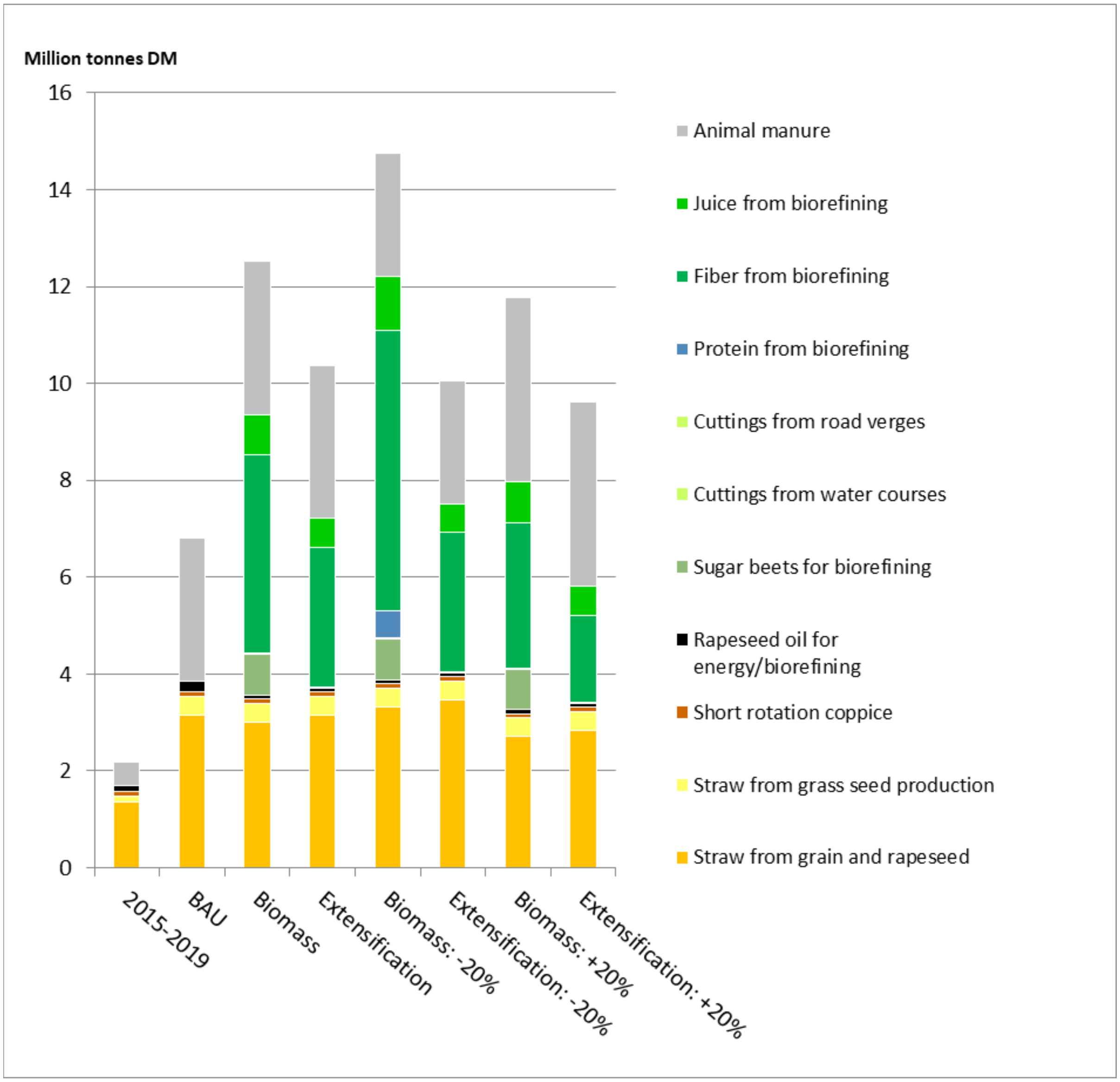


Figure 5.1. *Potential biomass production for biorefining (M Tonnes DM) in 2030-scenarios for Danish agriculture. BAU = Business-As-Usual. " -/+20 %" = scenarios with a 20 % reduction/increase in Danish animal production. The required quantity of fibre from biorefining to substitute roughage crops from areas converted into biomass production have been subtracted from the total production potential. Similarly, protein from biorefining substitute soy protein import, leaving only an excess of green protein in the Biomass scenario with reduced animal production (Mortensen and Jørgensen, 2021).*

5.2 Forestry: Production of biomass for biorefining in 2030

The different forestry scenarios have implications for both the production of biomass as well as the build-up of forest carbon stocks. Also, contrary to the other sectors the application of various instruments related to the different scenarios are slow to manifest in differences in biomass production owing to the slow growth and late maturing of the forest resource. Consequently, we here report the differences in biomass production over a 100-year period.

Forest area and carbon stocks

The projections of forest area development differ significantly between the different scenarios both in terms of area and its distribution to tree species (Figure 5.2). In the Biomass and Extensification scenarios the forest area is expanded to 1.079 M hectares in 2120 while it is expanded to 0.793 M hectares in the BAU scenario within the 100 years of simulation. The three scenarios also differ considerably in terms of the tree species distribution. Where fast growing conifers (including Christmas trees and greenery) make up 85 % of the forest area in the Biomass scenario after 100 years whereas broadleaves make up 87 % in the Extensification scenario.

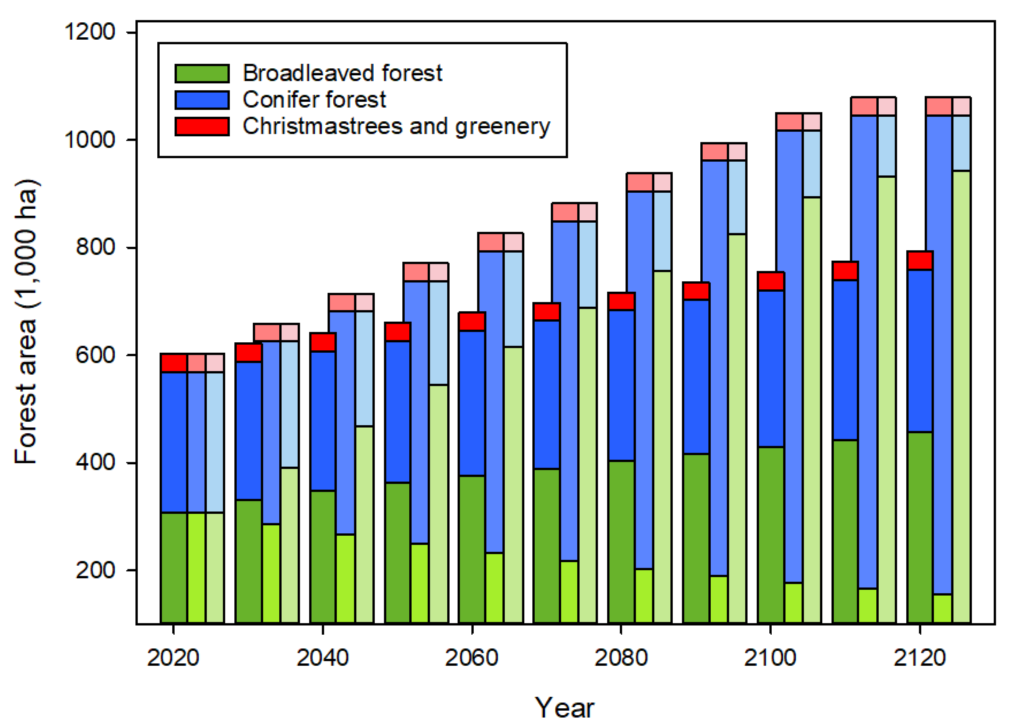


Figure 5.2. *Development of the forest area for the three scenarios: Business-as-usual (full color), Biomass (weaker color), Extensification (weakest color).*

The increased afforestation in the Biomass and Extensification scenarios increases the biomass stocks relative to the BAU scenario (Figure 5.3). However, increased focus on production in the Biomass scenario results in a faster build-up of biomass owing to the larger share of fast-growing tree species. Oppositely, in the Extensification scenario, use of natural succession and a large share of broadleaves in the afforestation results in a slower and lower build-up of biomass resources.

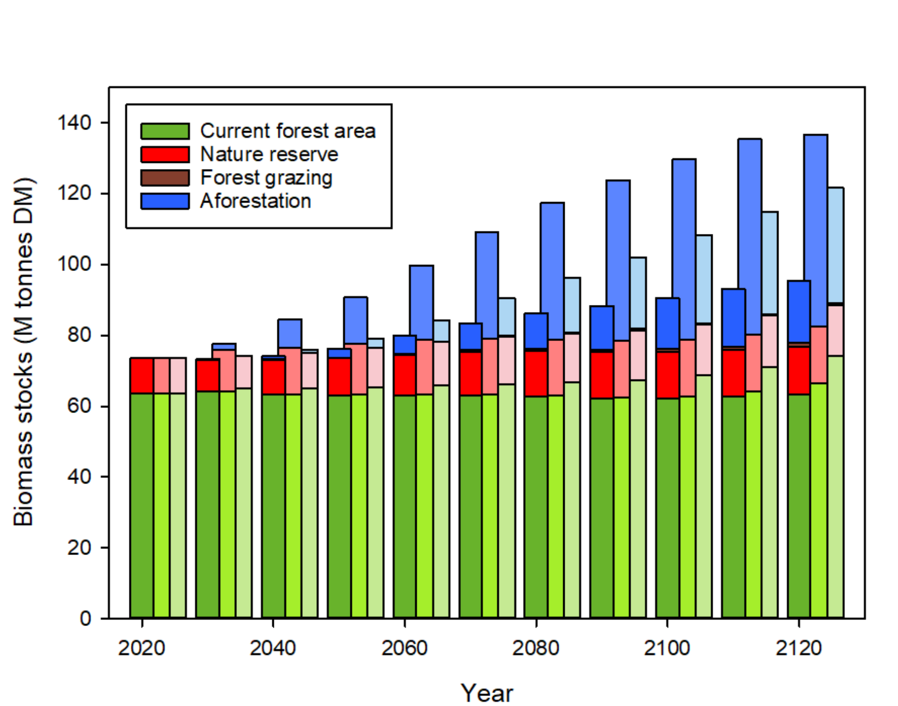


Figure 5.3. *Biomass stocks for the three scenarios: Business-as-usual (left, full color), Biomass (center, weaker color), Extensification (right, weakest color). Biomass stocks are distributed to different forest types, reflecting availability for materials, biorefinery and energy.*

Forest biomass production

All scenarios initially show a relatively high biomass harvest owing to a skewed age-class distribution of the Danish forests with a large proportion of large and mature trees (Figure 5.4). Reflecting the harvest probabilities feeding into the Markov-chain model, much of the mature biomass will be harvested in the first decade showing large production. In the BAU scenario, biomass production is 2.7 M tonnes DM/year during the first decade, decreases when the mature trees are harvested and increases again owing to the continued afforestation and stabilizes around 3.1 M tonnes DM/year. Owing to the setting aside of nature protection areas and a larger share of broadleaves in the afforestation the average biomass production per hectare declines from 4.5 tonnes DM/ha/year at the initiation of simulations to around 4.0 tonnes DM/ha/year. Similarly, the share of broadleaved forest biomass increases from 43 to 53 % during the simulations. The share of timber (excluding “Rest” from the calculation) is relatively stable around 34 % during the 100 years of simulations.

In the Biomass scenario, the biomass production increases fast during the first 30 years of the simulations, illustrating the large afforestation with fast growing species and widespread use of nurse trees. During the 100 years of the simulation, the total production of biomass increases from 2.6 to 5.8 M tonnes DM/year and the average production from 4.0 to 5.4 tonnes DM/ha/year. During the simulations, the share of timber falls from around 45% to 50% in 2050 due to the extensive use of nurse trees, which are primarily harvested for bioenergy or biorefining. Hereafter, the share of timber increases again as the main tree species are maturing. The share of conifer wood increases from currently 55 % to 89 % in the 100-year perspective of the simulations.

Resulting from the extensive afforestation, biomass production in the Extensification scenario increases from 2.7 to 3.3 M tonnes DM/year, hereby resulting in a similar production as the BAU scenario (Figure 5.4). However, owing to the extensive use of natural succession and native, broadleaves in the afforestation, average production falls from around 4.3 tonnes DM/ha/year to around 3.0 tonnes/ha/year. For the same reasons, the share of coniferous wood in the biomass production is decreasing from currently 58 % to 20 % at the end of the simulations.

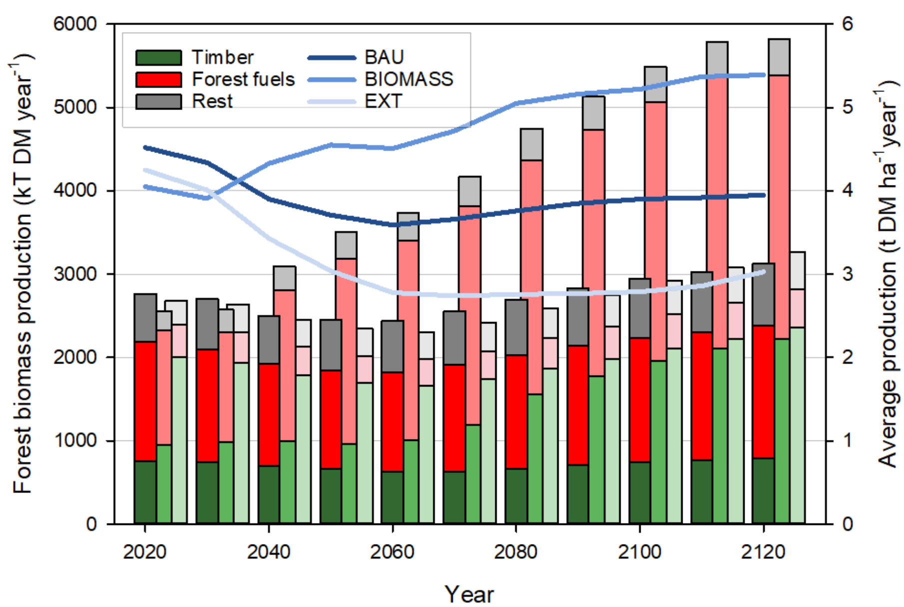


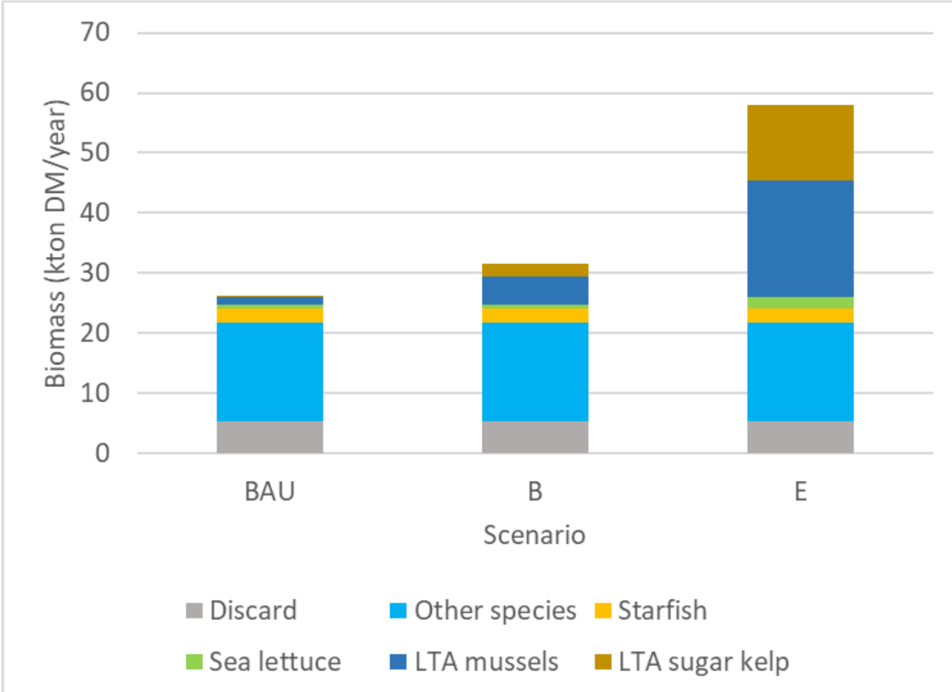
Figure 5.4. *Forest biomass production (bars, left axis) for the three scenarios: Business-as-usual (full color), Biomass (weaker color), and Extensification (weakest color) and distributed to different assortments. Forest fuels and Rest (currently unharvested residues) are readily available for biorefining as part of the bioeconomy. Average production (lines, right axis) shows the harvesting of biomass per unit forest area.*

5.3 Marine biomass: Production of biomass for biorefining in 2030

Assuming BAU scenario, marine biomass in the form of blue mussels, starfish, sugar kelp, sea lettuce, discard as well as landings of other species of invertebrates and non-quota fin fish, is expected to contribute with

98 ktonnes fresh weight (FW) in 2030. This contribution is increased to 151 or 402 ktonnes FW in the Biomass and Extensification scenarios, respectively, assuming implementation in future water area plans of LTA of mussels and seaweed as a tool to mitigate coastal eutrophication. This is equivalent to a total annual biomass supply of 26, 32, and 58 ktonnes DM or 6, 8 or 18 ktonnes of crude marine protein/year for the three scenarios (Figure 5.5). In the Biomass and Extensification scenarios, most of the marine crude protein, 32 % or 62 % respectively, will derive from mussels produced in LTA.

Realization of the Biomass and Extensification scenarios will require use of 2,902 or 13,124 ha, respectively. This is equivalent to only 0.02 or 0.09 % of the Danish Exclusive Economic Zone of 105,000 km^2, compared to the 61% of Danish area on land dedicated to agriculture. Expanding the Extensification scenario to also include the North Sea will double the estimated LTA biomass production in 2030 but requires development of robust cultivation technology to withstand the forces of wind and waves in the more exposed environment (Maar et al, 2023).



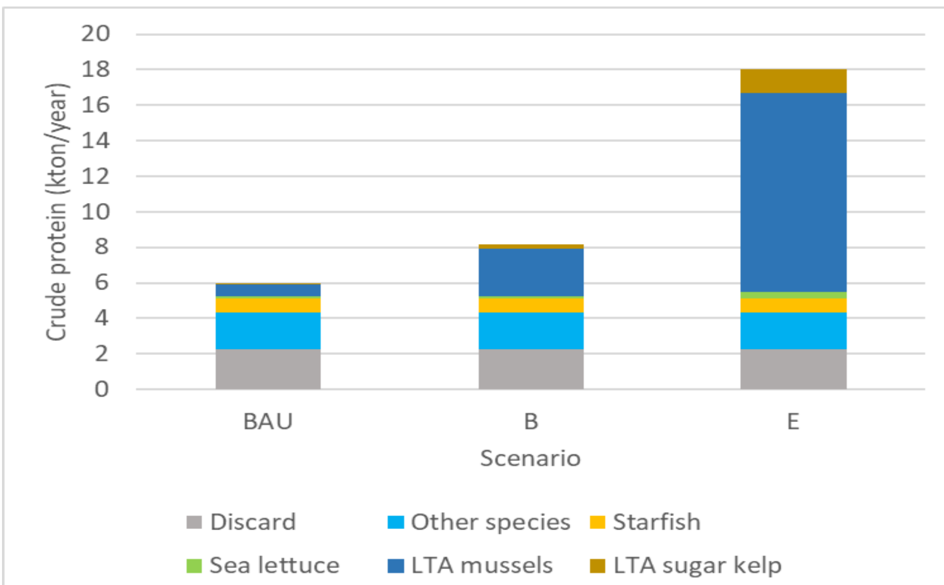


Figure 5.5. *Annual potential production of biomass (ktonnes DM/year) or crude marine protein (ktonnes/year) assuming the Business-As-Usual (BAU), Biomass (B) or Extensification (E) scenarios.*

5.4 Organic waste and by-products from industry

By-products from the primary processing industries

The calculation of waste residues and by-products originating from the primary sector and processing industry is based on average production records for the years 2016-2018 (Statistikbanken, 2021). The estimation method employed for the food industry is based on Jensen et al. (2018).

Table 5.1. *Waste from the primary processing industry, tonnes DM, annual average (2016-2018) (Statistikbanken, 2021).*

	Sales products	Losses in the food chain	Residual products
Cereals, flour, and bread	881,779	158,720	26,251
Fruit and vegetables	234,621	85,637	76,262
Dairy products	867,957	56,417	444,865
Meat	1,053,049	131,631	363,768
Fish and shellfish	555,438	136,082	796,809
Oilseeds and legumes	234,656	39,892	131,556
Roots and root vegetables	337,493	161,997	53,469
Others	2,801,793	496,478	-
Total	6,966,786	1,266,853	1,892,979

Note: Sales products are goods brought up for sale. Losses in the food chain are wastage and losses in connection with production, and residual products are not directly produced for sale, e.g. cuts from slaughterhouses but may have secondary uses for e.g. pet food.

Approximately 7 M tonnes DM products are generated annually through the sales of various products across the eight organic production categories depicted in Table 5.1. There is an annual waste of 1.3 M tonnes DM related to the production of goods in the food supply chain, e.g. grinding flour or baking bread. Furthermore, residual products comprise almost 1.9 M tonnes DM/year, which however for the most part is already utilized for livestock feed among other things. As a rough estimate, the mean value of the two categories, 1.6 M tonnes is expected available for further processing in the bioindustry.

The amount of organic waste from the primary sector and the processing industry is not projected to 2030. However, the total amounts are only expected to change marginally due to the developments in land use change for agriculture, aquaculture, and forest as a result of the three scenarios. However, the distribution between sectors may change, e.g., in the +/- 20 percent livestock sub-scenarios.

Household waste

The development in total household waste and thus implicitly the quantity of organic waste generated by society is considered to be independent of the development in land use change for agriculture, aquaculture, and forest. Instead, the development in household waste will ultimately be governed by the developments in the private consumption and general economic growth. Moreover, this development will also be affected by policy initiatives, incentives, and regulations, both at the national and EU level, aimed at reducing household waste and/or mitigating the increasing waste trends in society. In a Danish context, the focal point is to increase recycling as an alternative to incineration and in the same process phase out the import of household waste from other countries. These policy initiatives are described in the "Climate Plan for a Green Waste Sector and Circular Economy" (Regeringen, 2020).

The Danish Waste Association has made a projection of the development in Danish waste volumes from 2018 towards 2030. The projections are calculated using the FRIDA economic model (Miljøstyrelsen, 2019).

In the baseline scenario, the projection is exclusively based on the development in private consumption, number of households and economic growth. As such, the baseline projection does not include the potential of reducing household waste through various political instruments. For the baseline scenario, the total waste volumes will increase from approximately 13.0 M tonnes in 2018 to approximately 14.8 M tonnes in 2030. The share and composition of the organic waste is assumed to be the same in 2030 as in 2018 and is estimated by dry matter content at 0.32 M tonnes in 2018 and 0.44 M tonnes in 2030.

5.5 Biomass utilization through biorefining

Biorefining deals with the conversion of biomass into different products and includes a complex system of processing technologies. Biorefining is a renewable analogue to oil refining and is defined as "the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials) and bioenergy (biofuels, power, and/or heat)" (IEA, Task 42, Cherubini, F., 2009). The diverse list of possible products, vast variety of biomass resources and multiple process technologies emphasizes the complexity of biorefining. Biorefining will always be a system with many options and alternatives all with pros and cons, and we have to prioritize.

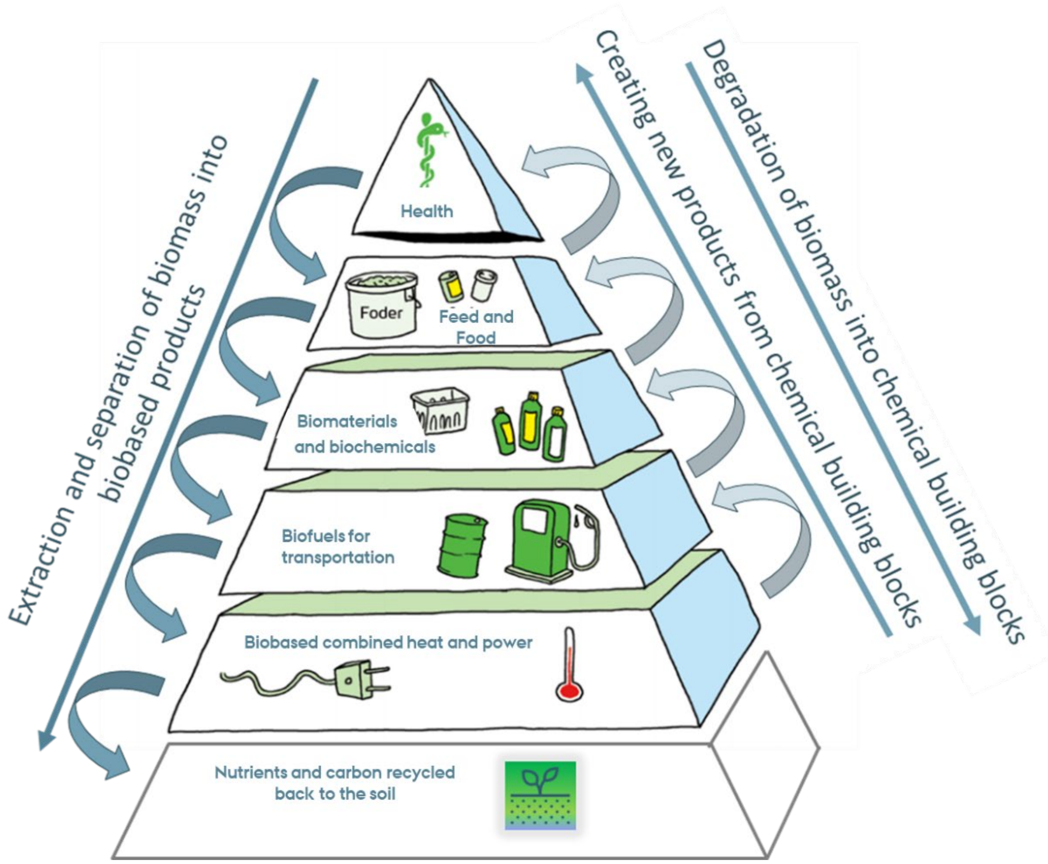


Figure 5.6. *Product pyramid for biorefining with cascade utilization. The relationship between typical market value and quantitative market size for different product categories. The blue arrows illustrate the cascade utilization of biomass which can either go up or down between the product categories, depending on whether it is separation and extraction of existing biomass components, or decomposition of biomass followed by build-up from chemical building blocks (From Lange and Lindedam (2016), adapted by M. Ambye-Jensen 2021).*

A basic principle of biorefining is cascade utilization of biomass resources. It strives to use all the components of the biomass to their full potential in a cascade of various products. The product types vary enormously in quantity and value and can be divided as seen in Figure 5.6. Medicinal- and health-promoting products typically have the highest market value, followed by food, feed, biochemicals, biomaterials, biofuels, bioenergy in the form of electricity and heat, and finally the value in recycled nutrients and carbon back to the soil. However, the quantitative market size for these product categories is typically inversely proportional to the value per kg of product.

There are two fundamentally different ways of producing biobased products. (i) For one, the existing structure and chemical components of biomass are utilized, which via extraction and separation are utilized in their existing or easily converted form to desired products. A good example of this is using wood directly for construction and the extraction and separation of proteins from green biomass, where it is important to preserve the protein structure from the biomass as much as possible to maximize the quality and value of the protein products. (ii) Second, biomass can be decomposed, to varying degrees, into smaller chemical building blocks, from where new desired products can be build. A good example of this is hydrothermal liquefaction (HTL), where biomass is decomposed and converted into a crude oil (among other process streams), which can subsequently be refined into biofuels according to the similar principles used for fossil oil refining. These two approaches are also illustrated in Figure 5.6. It is an important point that the two approaches mean that cascade utilization can go both ways, up and down the product pyramid, and that the cascade can be interrupted and "change direction" by combining the two approaches.

The analysis in this report illustrates how the biomass potentials from the above scenarios can be used via different processing technologies for different products and to what amounts. The processing technologies and product categories used in the analysis are kept as general as possible and uses simple estimates for conversion efficiencies from biomass to product, which can be adjusted over time if developments show that there is a need for this.

The amount of products is calculated for some technologies as alternatives, where one product cannot be produced in parallel with the other, as they use the same biomass source. For other technologies, the products will be produced in parallel, as it is part of the technology to split the biomass into different product streams. Table 5.3 shows a list of biomass conversion technologies, biomass input, and product examples used in the analysis, and further details of this analysis can be found in (Ambye-Jensen, 2022).

5.5.1 Biomass resources and components for biorefinery purposes

The biomass from the scenarios coming from agriculture, forestry, marine sources, and industrial side streams are here combined for use through biorefining. Different biomass resources have different structure and content and are therefore better suited for some applications than for others. In this analysis, the biomass resources are divided into their primary structural and biochemical components and quantified in relation to an estimated content of each component in each type of biomass. These components are proteins/amino acids, lipids, carbohydrates (cellulose, hemicellulose, and simple carbohydrates), lignin, and inorganic matter.

For each type of biomass, the contents of these components are estimated from the biomass on-line data collection Phyllis2 (www.phyllis.nl), as well as the authors' assessment (Table 5.2). Estimates of the composition of all types of biomass can be found in Ambye-Jensen (2022).

Table 5.2. *Total amount of biomass from both agriculture, forestry, marine and waste resource scenarios, divided into the biomass components of protein/amino acids, lipids, cellulose, hemicellulose, simple carbohydrates, lignin and ash.*

Biomass component [M tonnes/yr]	Protein/ Amino acids	Lipids	Cellulose	Hemicellulose	Simple carbohydrates	Lignin	Ash
BAU	0.77	0.25	3.74	2.78	0.13	1.89	1.65
Biomass	2.40	0.39	6.73	4.81	1.58	3.02	2.44
Extensification	1.92	0.35	5.70	4.08	0.69	2.56	2.21

Both the Biomass and Extensification scenarios result in significantly more available biomass components compared to the Business as Usual. The Biomass scenario generally gives rise to larger amounts of biomass in 2030 (Table 5.2). The most significant differences between the biomass potential in the Biomass and Extensification scenarios is the amount of green biomass and the amount of wood available for biorefining (excl. timber and industry wood). The increase in green biomasses results in an additional production of especially protein that goes from 1.62 M tonnes in the Extensification scenario to 2.08 M tonnes in the Biomass scenario, as well as a significant increase in carbohydrates, which is 1.03 M tonnes/year higher for cellulose, 0.74 M tonnes for hemicellulose, and 0.89 M tonnes for simple carbohydrates. The large difference in simple carbohydrates is because the Biomass scenario includes a yield of 0.84 M tonnes/year of sugar beet for biorefining, where the Extensification scenario does not include beets for biorefining, and that the green biomasses have a relatively high content of free sugars estimated at 12 % of dry matter on average.

The origin of the total biomass components in the Biomass scenario (Table 5.2) can be seen in Figure 5.7. The large contributions of biomass are coming from agriculture and forestry. The biomass contribution from side streams and especially the sea is in comparison very limited, however many high value and readily available sources of protein, carbohydrates, and lipids are coming from sea and side-stream biomasses. Consequently, these biomasses could therefore contribute to the high value products illustrated in the top of Figure 5.6.

The following examples of biorefining and product estimation is only based on the biomass amounts from the Biomass scenario.

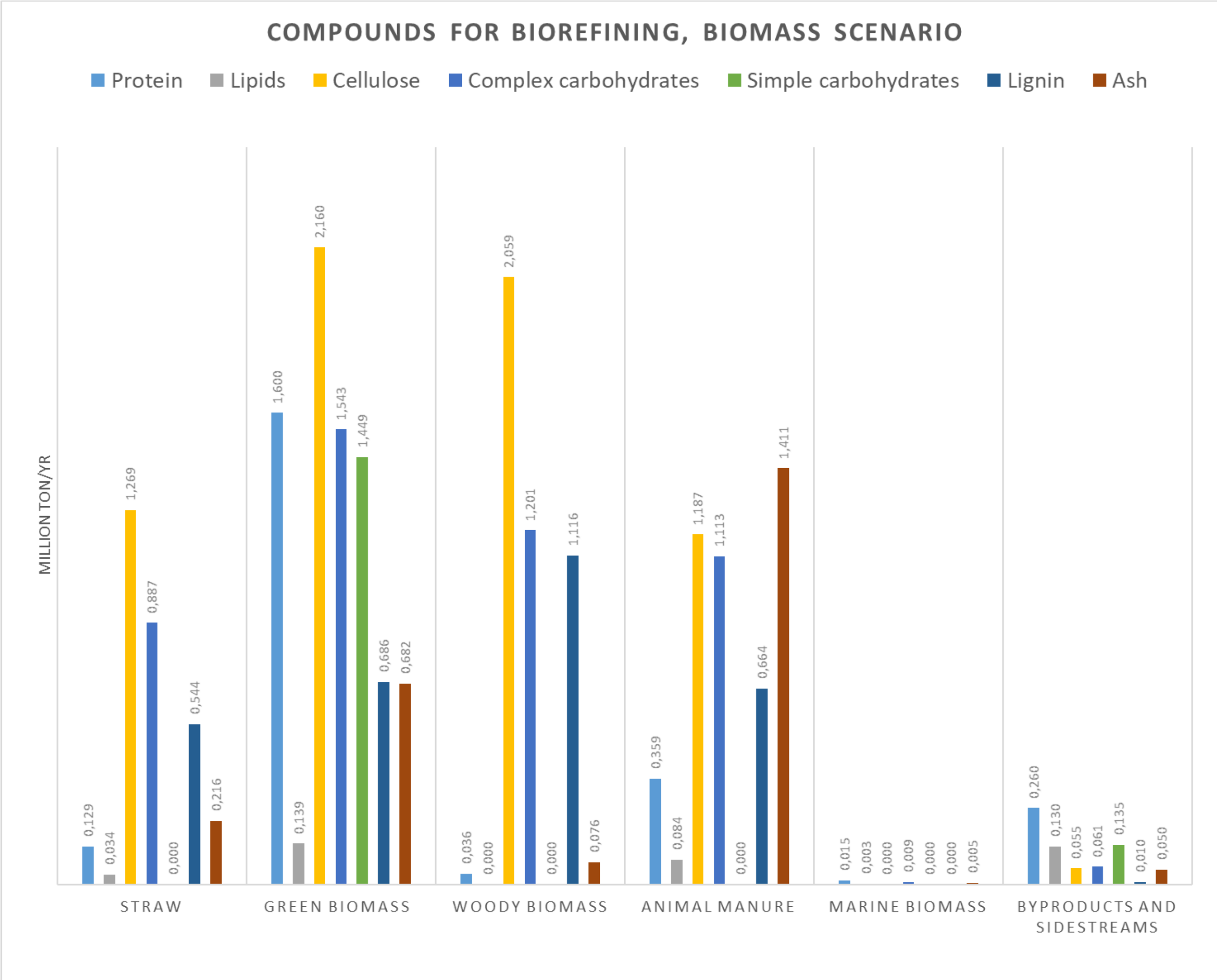
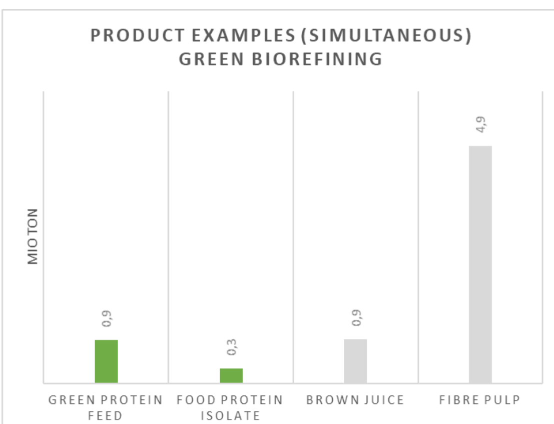


Figure 5.7. *Biomass resources available for biorefining in 2030 for the Biomass scenario, broken down into the components protein/amino acid, lipids (fat), carbohydrates (including cellulose, complex carbohydrates (other than cellulose) and simple carbohydrates), lignin and inorganic substances (ash).*

5.5.2 Green biorefining as an enabler for increased grass production and utilization of green leaf residues for feed and food

The large conversion of area in the Biomass and Extensification scenarios to the production of green biomasses results in a large potential for green biorefining in 2030. The green biorefining separates soluble protein and other soluble plant components from fresh green plants via wet fractionation (juicing), from which protein can be separated into feed or food products. Food protein products generally require higher purity and a more selective separation, typically based on membrane filtration, compared to feed protein products, where the protein is precipitated by heat or pH adjustment and subsequently centrifuged. In this analysis, it is assumed that 17 % of total solids (TS) in the input biomasses can be separated into protein products, of which the distribution between feed and food product is 3:1. In addition to the protein products, 13% of TS comes out in the form of readily soluble carbohydrates and nutrients in the brown juice and 70 % of TS ends up in the fibre pulp (pressing residue after juicing). These residual streams can be used as input to other biorefining technologies. Figure 5.8A shows the product potential for green biorefining. It is estimated that 887,000 tonnes of protein concentrate can be produced for feed, which can replace equal amounts of imported soybean meal, while at the same time producing 296,000 tonnes of protein isolate for use in food. Such production would result in 904,000 tonnes/year of DM brown juice containing soluble carbohydrates and nutrients and 4.87 M tonnes/year of fibre pulp for use in cattle feed, or, as in this analysis, as input to other biorefining technologies. Figure 5.8B shows the distribution of bioresources that contribute to the product example. It can be seen here that by far the greatest potential for green biorefining comes from areas that have been converted to dedicated production of grass and legumes for green biorefining (86 %). The other biomass inputs are catch crops that contribute 7 %, sugar beet tops with 4 %, and green biomass from wetlands with 3 %.

If this potential is to be realized, it will require 230-350 green biorefinery facilities across Denmark with an input capacity of around 20-30,000 tonnes DM/year, which is similar to the scale that is being implemented at the two first commercial plants in Denmark. Development within optimal logistics and scaling of green biorefineries, which will typically be adapted to local conditions, and the possibilities for integration with existing industries in the area, will most likely result in great variation in possible plant sizes and therefore number of plants.



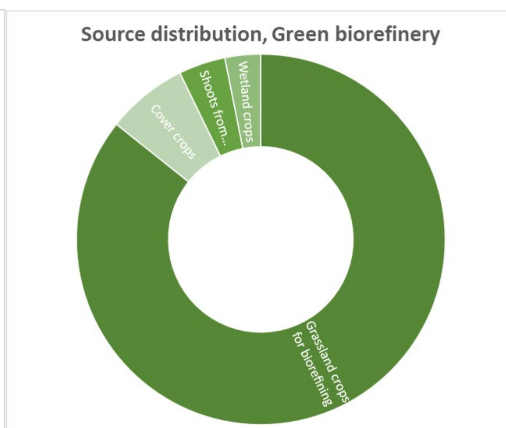


Figure 5.8. A (left): *Product potential for green biorefining, Biomass scenario. Green protein feed is feed quality protein concentrate with estimated protein content of 50 %. Food protein isolate is food grade protein isolate with estimated protein content of 80 %. Brown juice is juice with a high content of soluble carbohydrates, and fibre pulp is the pressing residue after juicing with a high fibre content (lignocellulose). Products and side streams are produced simultaneously and are not alternatives.* ***B*** *(right): The distribution of bio-resources used for the product potential in A.*

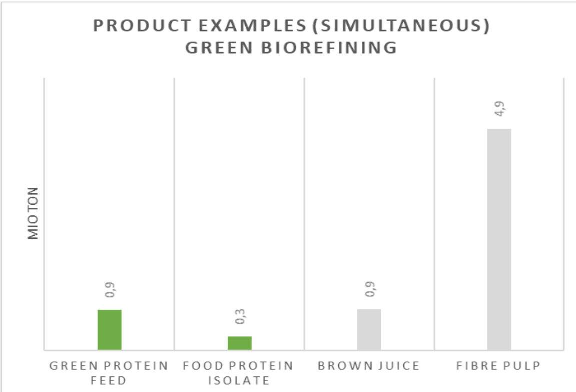
5.5.3 Biorefinery technologies and product potentials

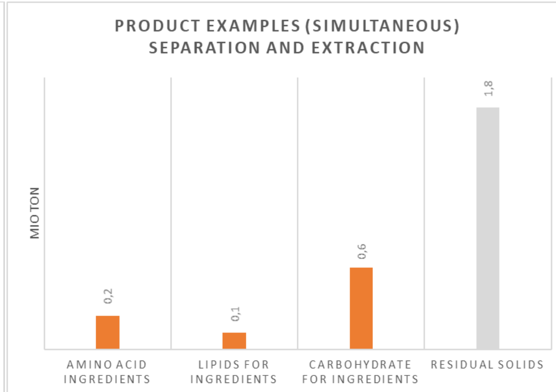
Similar to the product example on green biorefining, the analysis calculates product examples from seven other potential biomass conversion technologies based on the Biomass scenario. For each technology, it is assessed which biomasses are suitable for the processing technology and the product examples. This illustrates the possibilities and quantitative potentials that an emerging bioeconomy could establish from the Biomass scenario resources. The eight technologies, the biomass input, and the product examples can be seen in Table 5.3. The purpose of the potentials is to see how much each technology would result in if all appropriate biomass is converted through this technology. The same biomass resources are therefore being used for several of the technologies. As the biomass can only be used once, these are alternative product potentials that cannot be produced in the calculated quantities at the same time. In the case of green biorefining, however, an exception has been made; from here both fibre pulp and brown juice are used in several of the other biorefineries. The calculated product examples are presented for all eight technologies in Figure 5.9.

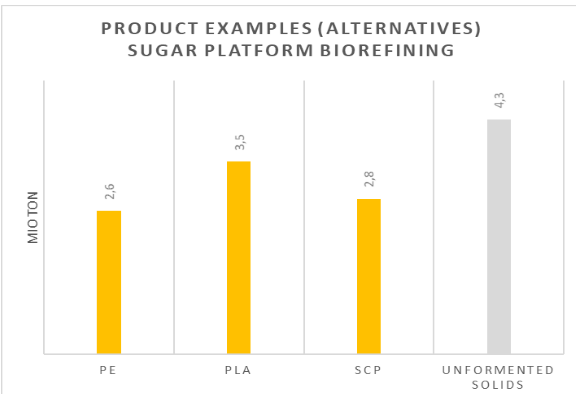
Table 5.3. *List of biomass conversion technologies, biomass input, product examples and residues produced for each of the eight biorefining technology examples in the analysis.*

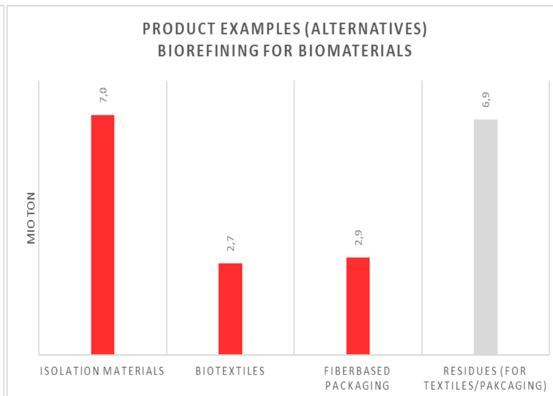
Biomass conversion technology	Biomasses used	Product examples and residues
Green biorefining	Grassland crops for biorefining Sugar beets Shoots from sugar beets Paludiculture crops Harvested cover crops	• Protein concentrate for feed • Protein isolate for food Residue: Fibre pulp Brown juice
Extraction and separation	Starfish Blue mussels Sea lettuce Sugar kelp Brown juice Fish side-streams Slaughter side-streams Vegetable side-streams Dairy side-streams Cereal & oilseed side-streams	• Amino acids for ingredients (feed/food) • Lipids for ingredients (feed/food) • Carbohydrates for ingredients (feed/food) Residue: Extracted solids and soluble nutrients
Sugar platform biorefining	Straw from grain and rapeseed Straw from grass seed production Fibre pulp Brown juice Sugar beets Wetland crops Cover crops Hedges and gardens Forest wood for biorefining Sea lettuce Sugar kelp	• Polyethylene (PE) for bioplastic • Poly lactic acid (PLA) for bioplastic • Single cell protein (SCP) for feed and food Residue: Non-fermented solids
Biomaterial production	Straw from grain and rapeseed Straw from grass seed production Fibre pulp Hedges and gardens Forest wood for biorefining Sea lettuce Sugar kelp Mussel shells	• Insulation material • Textile based on cellulose/alginate • Packaging based on cellulose/alginate Residue: Depends on the product. For cellulose based materials it would be side streams containing hemicellulose and lignin fractions (the form and content depends on exact cellulose extraction method). Mussel shells for land-filling or concrete production

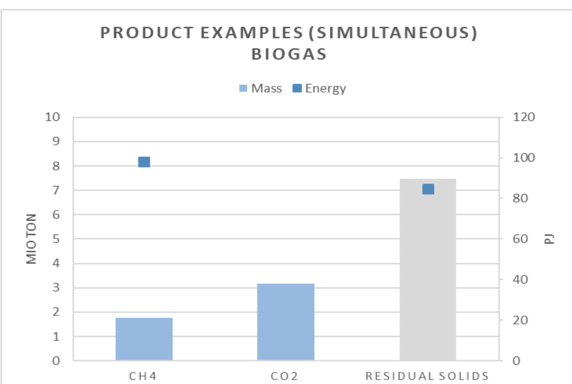
Biogas production from residue-biomass	Straw from grain and rapeseed Straw from grass seed production Fibre pulp Brown juice Waste water sludge Cow manure Pig manure Deep litter	• CH2 • CO2 Residue: Digested solids (digestate) with nutrients
Hydrothermal Liquefaction (HTL)	Straw from grain and rapeseed Straw from grass seed production Hedges and gardens Forest wood for biorefining Fibre pulp Wetland crops Wastewater sludge Cow manure Deep litter	• Jet fuel (require addition of H_2) • Diesel • Heavy fuel Residue: Soluble compounds in aqueous solution
Pyrolysis of dry solid biomass	Straw from grain and rapeseed Straw from grass seed production Hedges and gardens Forest wood for biorefining Fibre pulp Wetland crops	• Jet fuel (require addition of H_2) • Biochar • District heating Residue: None – residue solids ends up as biochar
Pyrolysis of wet biomass	Fibre pulp Wastewater sludge Cow manure Pig manure Deep litter	• Biochar • Activated carbon • District heating Residue: None – residue solids ends up as biochar

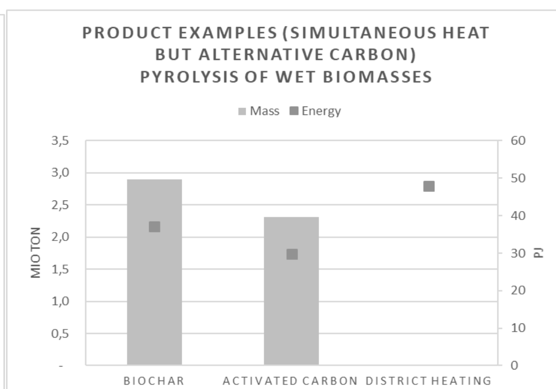

PRODUCT EXAMPLES (SIMULTANEOUS)
GREEN BIOREFINING
MIO TON
0,9
0,3
0,9
4,9
GREEN PROTEIN FEED
FOOD PROTEIN ISOLATE
BROWN JUICE
FIBRE PULP


PRODUCT EXAMPLES (SIMULTANEOUS)
SEPARATION AND EXTRACTION
MIO TON
0,2
0,1
0,6
1,8
AMINO ACID INGREDIENTS
LIPIDS FOR INGREDIENTS
CARBOHYDRATE FOR INGREDIENTS
RESIDUAL SOLIDS


PRODUCT EXAMPLES (ALTERNATIVES)
SUGAR PLATFORM BIOREFINING
MIO TON
2,6
3,5
2,8
4,3
PE
PLA
SCP
UNFORMENTED SOLIDS


PRODUCT EXAMPLES (ALTERNATIVES)
BIOREFINING FOR BIOMATERIALS
MIO TON
7,0
2,7
2,9
6,9
ISOLATION MATERIALS
BIOTEXTILES
FIBERBASED PACKAGING
RESIDUES (FOR TEXTILES/PAKCAGING)


PRODUCT EXAMPLES (SIMULTANEOUS)
BIOGAS
Mass
Energy
MIO TON
PJ
0
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
120
CH4
CO2
RESIDUAL SOLIDS


PRODUCT EXAMPLES (SIMULTANEOUS HEAT
BUT ALTERNATIVE CARBON)
PYROLYSIS OF WET BIOMASSES
Mass
Energy
MIO TON
PJ
-
0,5
1,0
1,5
2,0
2,5
3,0
3,5
0
10
20
30
40
50
60
BIOCHAR
ACTIVATED CARBON
DISTRICT HEATING

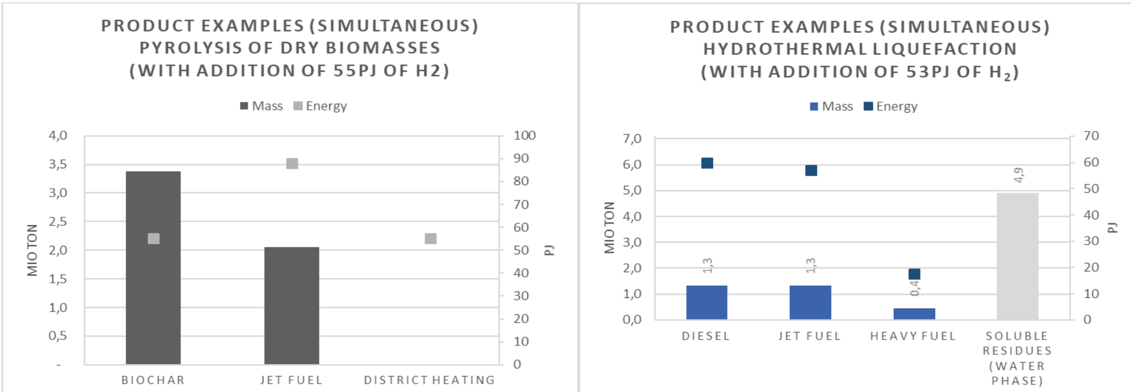


Figure 5.9. *Potential product examples from eight different biomass conversion technologies using the biomass from the 2030 scenarios. (A detailed description for each technology and its product examples can be found in Ambye-Jensen, 2022).*

5.5.4 Cascade utilization of biomass by integrated biorefinery systems

Biorefining is not just one technology. In the ideal version, biorefining is one large system of integrated technologies that transform the total bio-resources through cascade utilization and enables truly sustainable production of all the products we want most and which create the greatest value possible for our society. This vision for the future of sustainable biorefining requires a strong focus on synergy, both in the form of practical, technical, industrial, and industry-related synergies, as well as significant interdisciplinary interaction between all steps in the circular value chain. Figure 5.10 illustrates how biorefining via cascade utilization of biomass resources can contribute to several product categories simultaneously, how they can be linked in a circular value chain, and how this requires industrial synergies across the value chain.

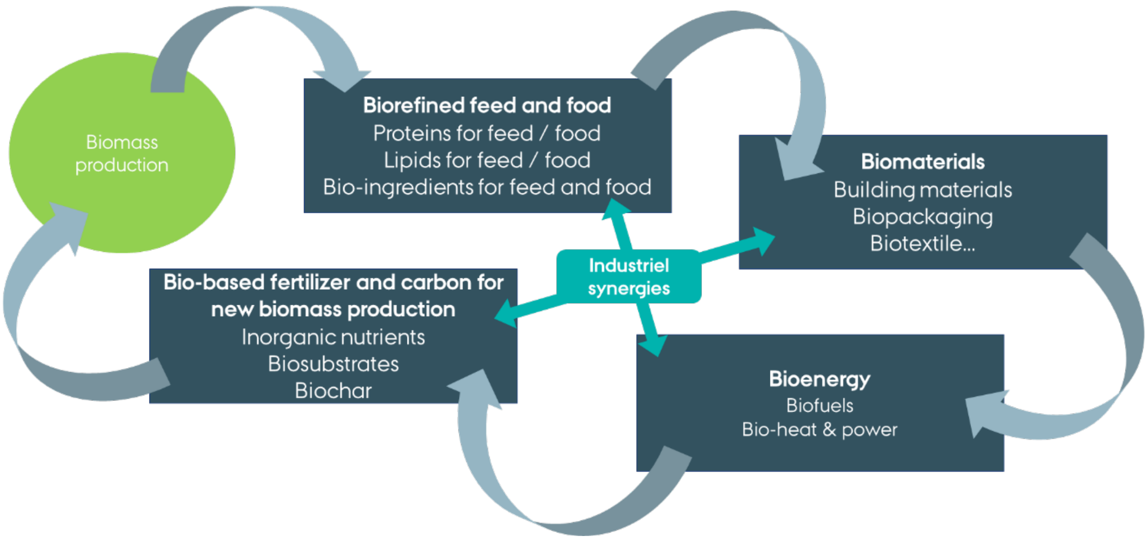


Figure 5.10. *Overview of product categories, and of how biorefining technologies through cascade utilization can produce them all in a circular value chain, as well as how industrial synergies can be established across product categories.*

The eight technologies presented in section 3, each with their own examples of a product potential, all have their advantages and disadvantages. Some work best for converting some kinds of biomass and others are better suited for other kinds - even though it is technically possible to convert all kinds of biomass into a desired product. Some will work best on a large scale in large central plants (e.g., the sugar platform biorefining or pyrolysis of dry biomasses), while others will work best, more locally, in smaller decentralized plants (e.g., the green biorefining or the pyrolysis/HTL of wet biomasses where transport costs will be relatively higher). Some have direct synergy effects from being established sequentially one after the other, thus cascade utilizing the biomasses for even more value, while others are alternative technologies that use the same kind of biomass but produce widely different and perhaps even mutually exclusive products.

There are therefore an incredible number of choices that must be made to bring about the above vision of the future bioeconomy. These choices are, for example, which technologies are used for which biomasses and which products gives the best economic value or value to society.

The biomass potentials from the two scenarios for 2030, however, clearly show that a great deal of biomass can be available for biorefining purposes. Much more biomass and many more types than what one technology will be able to handle. In relation to the capacity of the eight technologies included in section 3, it will require a significant number of plants, both large and small, if all this biomass is to be processed through biorefining. This alone is an argument highlighting that there is room for many different kinds of biorefining and the development of many different kinds of biorefining synergies.

In the analysis, we calculate two examples of cascade utilization and technology integration. If one takes as a starting point a cascade utilization that prioritizes utilization of the functional and structural components in the biomass before starting to decompose the bioresources and build new products, the biorefining system could look like in Figure 5.11.

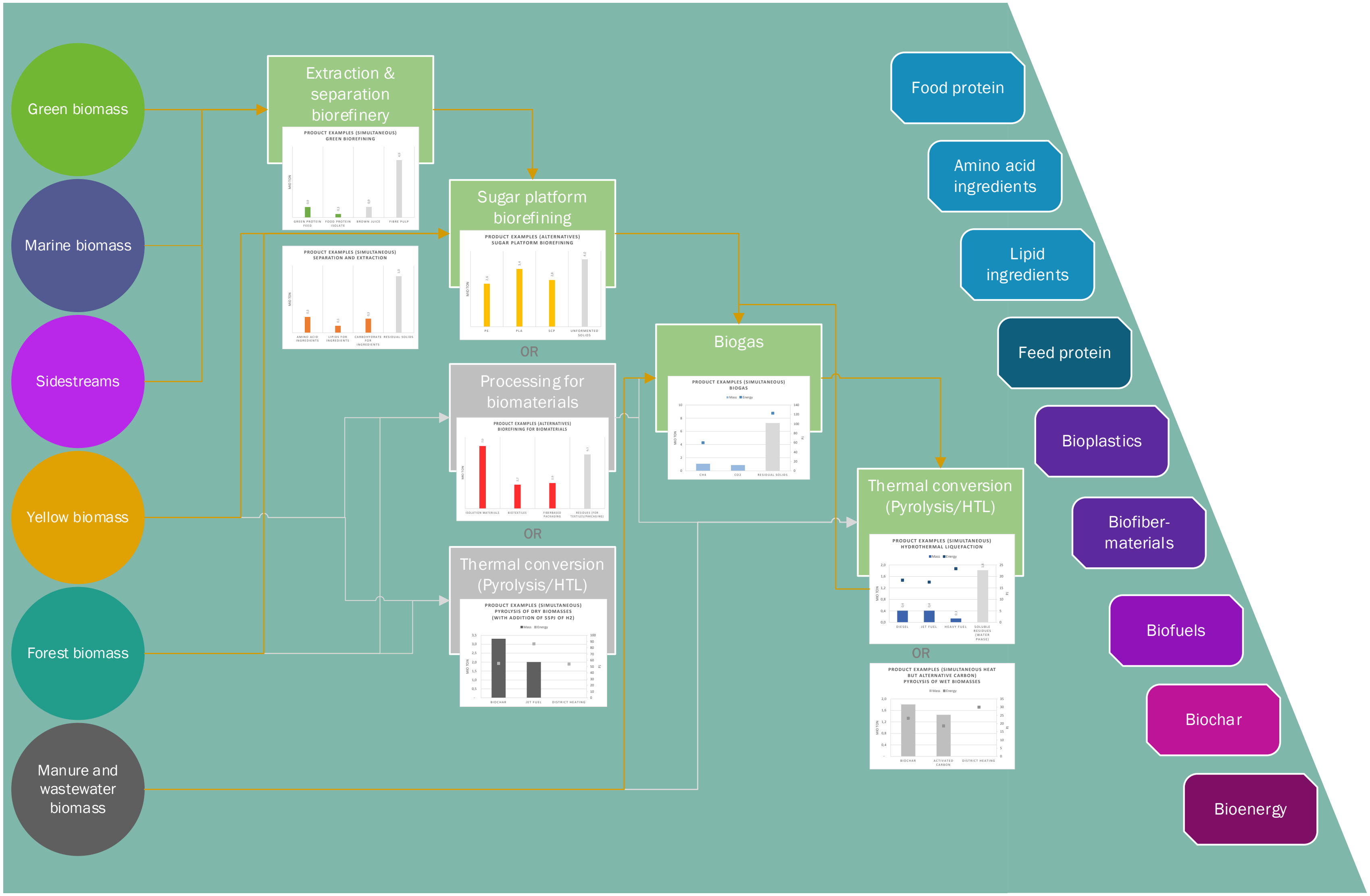


Figure 5.11. *Biorefining system that cascades the bioresources. Yellow arrows draw a system for simultaneous process flows for inputs and outputs from different biorefining technologies. The grey arrows draw alternative process streams to alternative technologies for each bioresource and residual stream. On the left are the product categories that are possible to produce from such a biorefining system.*

If the bioresources follow the yellow process streams in Figure 5.11, it will result in the product composition presented in Table 5.4. This is just one example where several technologies are linked together and utilize each other's process streams. In this scenario, sugar platform biorefining is at the centre and the scenario producing huge amounts of bioplastics in the form of PLA. However, the sugar platform biorefining could likewise produce several other fermentation derived biochemical products. Alternatively, it could be replaced by another technology, as illustrated by the grey arrows in Figure 5.11.

Table 5.4. *Product composition in the cascade scenario from Figure 5.11 (yellow arrows), where sugar platform biorefining plays a central role in the conversion of lignocellulosic carbohydrates, the residual stream is used for biogas and the residual stream from biogas is used through HTL.*

Product category	Product	Technology	Amount	unit
Food protein	White protein	Green bioref	0.3	M tonnes
Ingredients	Amino acids	Ext. & Sep.	0.3	M tonnes
Ingredients	Lipids	Ext. & Sep.	0.1	M tonnes
Feed protein	Green protein	Green bioref	0.9	M tonnes
Bioplastics	PLA	Sugar platform bioref.	3.4	M tonnes
Biofuels	Jet fuel	HTL+refining	0.4	M tonnes
Biofuels	Diesel	HTL+refining	0.4	M tonnes
Biofuels	Heavy	HTL+refining	0.1	M tonnes
Biofuels	CH4	Biogas	96	PJ

In the other cascade example, the sugar biorefining platform has been replaced by pyrolysis and further refining resulting in production of jet fuel, biochar, and energy for district heating. The product example from such a scenario is seen in Table 5.5.

Table 5.5. *Product composition in the cascade scenario from figure 5.11 (grey arrows) where pyrolysis plays a central role in the conversion of lignocellulosic biomass.*

Product category	Product	Technology	Amount	Unit
Food protein	White protein	Green bioref	0.3	M tonnes
Ingredients	Amino acids	Ext. & Sep.	0.3	M tonnes
Ingredients	Lipids	Ext. & Sep.	0.1	M tonnes
Feed protein	Green protein	Green bioref	0.9	M tonnes
Biofuels	Jet fuel	Pyrolysis+refining	2.4	M tonnes
Circularity product	Biochar	Pyrolysis	3.3	M tonnes
Bioenergy	District heating	Pyrolysis	54	PJ

In conclusion, biorefining of the biomass potentials from both the Biomass and Extensification scenarios of land use in 2030 gives rise to significant amounts of new bio-based products. The amounts of biomass resources are so large and so diverse that several biorefining systems can be established producing both food, feed, chemicals, materials, liquid fuels, power, and heat. These systems should largely be integrated and benefit from each other through cascade utilization and industrial synergies. However, there are many alternative choices to be made for technologies that utilizes the same type of biomass. Here the choice of technologies depends on what type of biobased products is prioritized to create most value for the society and the best business cases for industries.

5.5 Land use changes on the agricultural area in 2030

The changes in agricultural production due to new areas of crops for biorefining affect the national area available for different uses. In 2017, approx. 0.05 M ha were used for bioenergy production, while this number increases to approx. 0.1 M ha in 2030 in the BAU-scenario, due to afforestation and an increase in share of rapeseed oil used for energy. In the optimized scenarios for 2030, the area producing biomass for biorefining ranges from approx. 0.5 to 0.7 M ha (Figure 5.12). However, the biorefining is anticipated to provide significant amounts of fibre used as feed to substitute areas with roughage crops, and high-value protein concentrate substituting soy imports. If these fodder components are subtracted as a share of the total area with crops for biorefining, the total farmed area for biorefining for non-feed purposes is approx. 0.4 to 0.6 M ha in 2030 (Mortensen and Jørgensen, 2021). In the Biomass and Extensification scenarios, feed supply is maintained partly through the share of products from biorefining, and partly through an increase in import of grain and rapeseed (Figure 5.13). However, future biorefineries may provide food and feed components from many of the raw materials handled (even wood can be digested by microbes into valuable protein feed), and there is not a clear distinction between the uses for food vs non-food. In reality, market demands will determine what will pay off best to produce in the biorefinery.

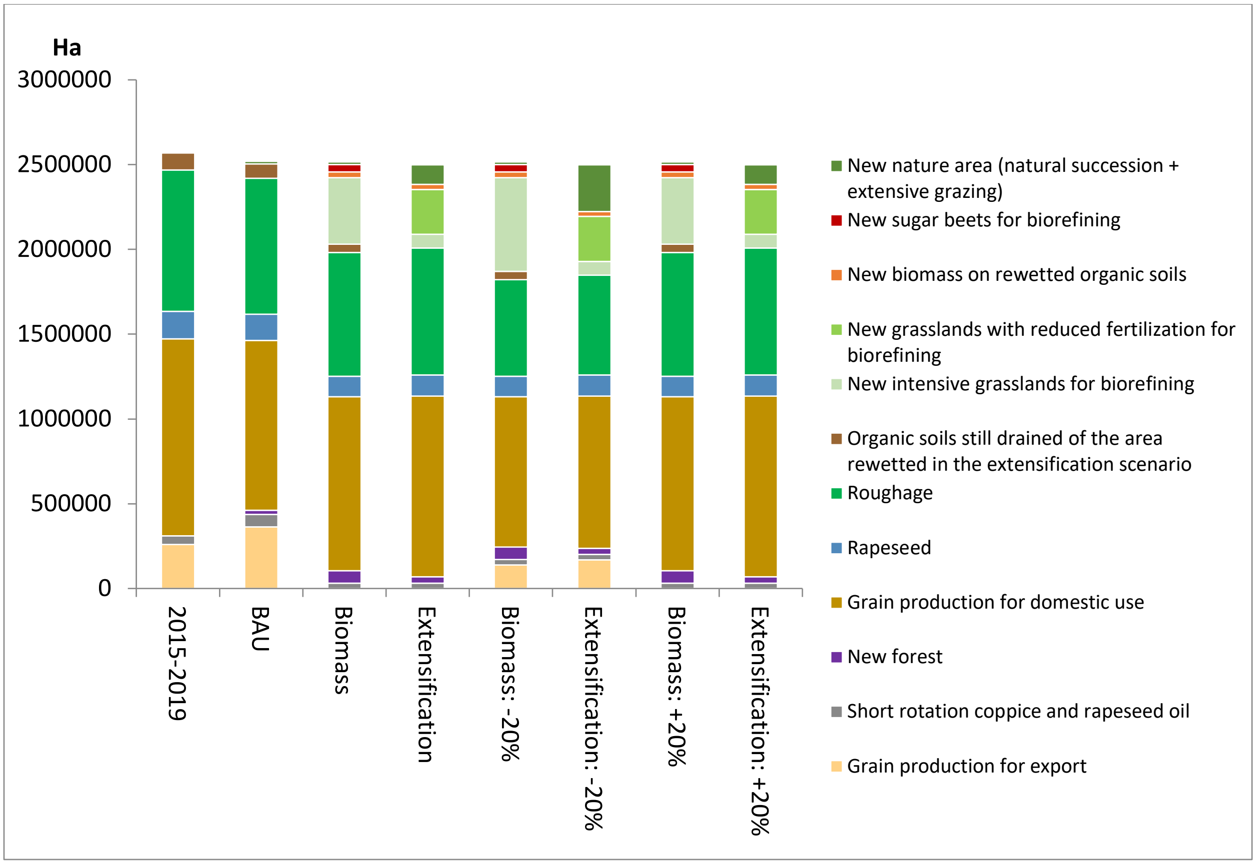


Figure 5.12. *Estimated land use changes on agricultural area in Denmark for the 2030-scenarios. The numbers only include the main agricultural crops, as production of minor productions and vegetables are kept stable in the scenarios. The total agricultural area is expected to be approx. 2.5 M ha in 2030 compared to 2.6 M ha in 2017 (Dalgaard and Mortensen, 2022).*

The large area of farmland converted into crops for biorefining affects not only the land use on the agricultural area in Denmark but also the area needed abroad to supply the Danish animal production. As roughage feed is not practically feasible for import, it is prioritized to produce all roughage feed needed in the specific scenarios, while reducing the area used for cereals and rapeseed. This results in a substantially lower grain export and in some scenarios even a shift to a net import of grain.

In the scenarios with a reduced animal production in 2030, a net export of grain is possible, and soy imports can be substituted by grass-protein from biorefining. The latter depends on whether land use change is targeted toward biomass production for biorefining or if extensification of the farmed area is preferred. In the scenarios with increased animal production, a substantial net import of grain is needed (in contrast to the significant grain export in the BAU-scenario), and soy import is substantial in both the Biomass and the Extensification scenario when animal production is increased. Other new land uses may compete with the components mentioned in this analysis, such as an expected increase in photovoltaics on agricultural land (Jakobsen, 2022).

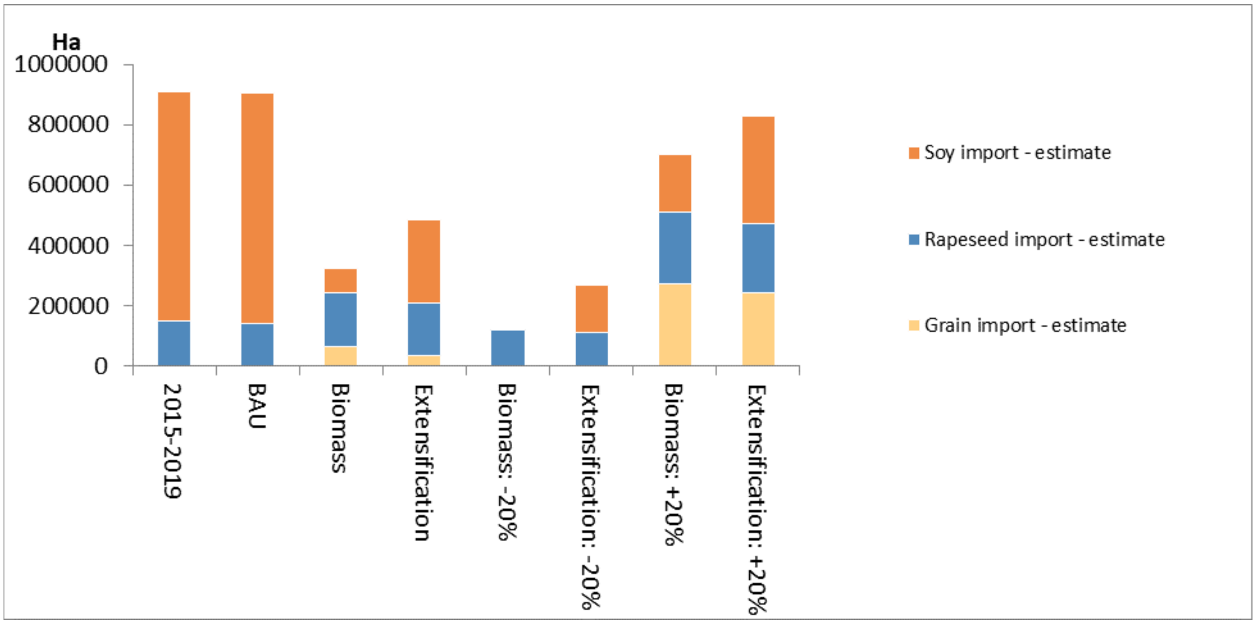


Figure 5.13. *The area needed in other countries to produce the feed imported to Denmark (soy, rapeseed and grain) in the scenarios for 2030. The area used for imported rapeseed and grain is estimated by Danish mean yield across grain species and varieties (Statistikbanken, 2021), while the area used to grow imported soy is based on estimates by Callesen et al. (2020).*

In the scenarios with reduced animal production in 2030, the area used for net export of grain could potentially be converted into more areas for biomass production or nature. In the Extensification scenario with a 20 % reduction in animal production, an area for extensive grazing and natural succession of approx. 0.27 M ha is established on areas now used for farming (Figure 5.12). This area constitutes just above 10 % of the farmed area in Denmark, and thereby this scenario will probably be the only one out of the seven 2030-scenarios to fulfil the EU target that at least 10% of agricultural area is under high-diversity landscape features in 2030 (Altinget, 2020). In the Biomass scenario with a 20 % reduction in animal production, the increase in area for nature is only 0.6 % of the agricultural area but may be increased if the area for grain production for export is reduced.

In the BAU scenario (and the Biomass scenario), we assume the increase in organic farming to be divided equally on all crops, whereas in the Extensification scenarios, we assume the further increase in organic farming compared to BAU, to be allocated to the new areas with grass-clover for biorefining. More details on the allocation of the new areas with organic farming in the different scenarios are found in Mortensen and Jørgensen (2022). Furthermore, it is important to consider whether the production of organic versus conventional grass-clover for biorefining matches the demand.

5.6 Effects on nature, climate and environment from changes in agricultural landuse

Effects on nature

The two optimized agricultural scenarios have large effects on the land use in Denmark. Especially the Extensification scenario results in large areas with less intensive agriculture, more organic agriculture, more diverse forests, and set-aside areas, which have the potential to increase biodiversity and nature values in Denmark (Dalgaard *et al.*, 2020). Approximately 5 % of the farmed area is set aside for natural succession and extensive grazing in 2030 in the main Extensification scenario. In the Extensification scenario with 20 % reduction in animal production, 11 % of the farmed area is changed into natural succession and extensive grazing, while the share is 5 % in the scenario with 20 % increase in animal production. For the Biomass scenarios, 0.6 % of the farmed area is changed into natural succession and extensive grazing. However, the conversion of 0.4 to 0.6 M ha of annual crops (depending on the scenario) into perennial grassland with mixtures of grass-clover represents a potential value for biodiversity depending on management (Dalgaard *et al.*, 2020).

Effects on greenhouse gas emissions

Rewetting of carbon-rich organic soils results in substantial reductions of greenhouse gas (GHG) emissions and is one of the most feasible ways to reduce greenhouse gas emissions from agriculture (Klimarådet, 2020). In the Biomass scenario, 50,000 ha of the organic soils with the highest carbon content are rewetted in 2030 (soils with more than 12 % carbon), which is estimated to reduce the GHG emissions from agriculture by approximately 1.6 M tonnes of CO_2 equivalents (CO_2e) per year (Table 5.6). In the Extensification scenario, 100,000 ha of organic soils are rewetted in 2030 (including both soils with more than 12 % C content and soils with 6-12 % carbon), with the estimated reduction in GHG emissions of approximately 3.0 M tonnes of CO_2e per year. These reductions can be compared to a reduction of 0.6 M tonnes of CO_2e per year in the BAU-scenario where 15,000 ha of organic soils are rewetted. The calculation of reductions in GHG emissions via rewetting of organic soils is done by emissions factors in Greve et al. (2021) and includes changed emissions of both CO_2, N_2O and CH_4.

Perennial grasslands have substantial positive effects on soil carbon storage compared to annual crops (Ledo *et al.*, 2020), and thus the new areas with grass-clover for biorefining reduce the total GHG emissions related to agriculture (Olesen *et al.*, 2016). An increased area with optimized cover crops also contributes to increased soil carbon storage (Mortensen *et al.*, 2021), while an increased area with sugar beets for biorefining in the Biomass scenario may reduce soil carbon stocks (Hamelin *et al.*, 2012). Conversely, increased fertilization of the grass-clover in the Biomass scenario induces an increase in nitrous oxide emissions (Olesen et al., 2016). It is estimated that the combined effects on soil carbon stocks and nitrous oxide emissions due to the combination of these measures on mineral soils will reduce GHG emissions from agriculture by between 1.7 and 2.2 M tonnes of CO_2e per year in the different scenarios. Straw removal for combustion has a significant negative effect on soil carbon content compared to direct mulching on the field. However, it may be possible to increase soil carbon more than by mulching the straw if it is rather used for pyrolysis and a biochar fraction is then returned to the soil (Olesen *et al.*, 2018). It is also an option to use the undigested fibre fraction after biogas production of manure for pyrolysis with a possible increase in long-term soil carbon storage (Schouten *et al.*, 2012). Due to those strong dependencies on technology choices, such technology effects of increased utilization of straw and manure in the scenarios have not been included in the estimated GHG effects.

Table 5.6. *Estimated reductions of GHG emissions from agricultural land use changes in 2030-scenarios (M tonnes CO2e yr⁻¹) based on a 20-year perspective for soil C, and a 100-year perspective for nitrous oxide and methane (Hamelin et al., 2012; Jørgensen et al., 2013; Olesen et al., 2016; Olesen et al., 2018; Greve et al., 2021; Mortensen et al., 2021; Andersen et al., 2023). The sub-scenarios of both Biomass and Extensification scenarios are calculated with -/+ 20 % changes in animal production only for the effects on land-use i.e., not including effects on enteric fermentation in ruminants (Jørgensen & Mortensen, 2023).*

	BAU	**Biomass**	**Extensification**	*Biomass -20%*	*Extensification -20%*	*Biomass: +20%*	*Extensification +20%*
Soil C effect of rewetting organic soils (M tonnes CO_2e yr^{-1})	0.6	1.9	3.2	1.9	3.2	1.9	3.2
Effects on N_2O and CH_4 emission of rewetting organic soils (M tonnes CO_2e yr^{-1})	0.0	-0.3	-0.2	-0.3	-0.2	-0.3	-0.2
Soil C changes on mineral soils (M tonnes CO_2e yr^{-1})	0.3	1.8	1.7	2.2	1.8	1.8	1.7
Effects on N_2O and CH_4 emission on mineral soils (M tonnes CO_2e yr^{-1})	0.0	-0.1	0.3	-0.1	0.4	-0.1	0.3
Total (M tonnes CO_2e yr^{-1})	**0.9**	**3.3**	**5.0**	**3.7**	**5.3**	**3.3**	**5.0**

An increased animal production in Denmark will increase the Danish GHG emissions from animal production but could potentially lower the relative global GHG emissions of animal production under the precondition that a less climate-efficient production is offset elsewhere (Kraka-Deloitte, 2022).

In forests, all three scenarios result in increased carbon stocks owing to the continued afforestation. The build-up of carbon stocks is faster and larger in the Biomass scenario as a result of a larger afforestation rate compared to the BAU and faster growth of the trees. In contrast, widespread use of domestic broadleaves and natural succession in the Extensification scenario results in slower build-up of carbon stocks. This study did not include direct or indirect effects on substitution of materials resulting from changed biomass production. These effects may however significantly contribute to the net carbon emissions resulting from different strategies (Nielsen *et al.*, 2020; Nielsen *et al.*, 2021).

Effects on nitrate leaching from agricultural land

In all optimized scenarios for 2030, large areas that are sensitive to nitrate leaching are converted from grain, maize, and rapeseed to crops for biorefining with lower levels of nitrate leaching (Figure 5.12). This area is calculated to meet 60 % of the reduction target in nitrate leaching that has been postponed from the 2nd Water Plan Period (2015-2021) until after 2021 (Styrelsen for Vand- og Naturforvaltning, 2016). The remaining 40% is assumed to be reached by collective measures and other targeted measures. In both the Biomass and Extensification scenarios, the effect of the conversion of annual crops to perennial grass-clover on the nitrate-sensitive soils are estimated by the empirical model NLES5 (Børgesen *et al.*, 2020) to approximately reduce the N load to the sea by 3,700 tonnes of N per year. This represents a substantial share of the targets set for meeting the Water Framework Directive in 2027.

Further reductions in nitrate leaching can be expected from the conversion from annual crops to perennial grass-clover on loamy soils with a low carbon to clay ratio, and on sandy soils sensitive to leaching of pesticides to groundwater reservoirs, from the rewetting of carbon-rich organic soils, from the increased use of manure for biogas, and from the increased afforestation rate. The total effects on nitrate leaching from the root zone is estimated for each scenario in Table 5.7 without including effects of alternative management and use of manure, and with changes to the amount of manure in the scenarios with changes in animal production. The reductions have been calculated using the mean reduction in nitrate leaching from conversion into grassland (4 years of grass renewed with ley in a grain crop) calculated by the NLES5 model in the nitrate sensitive areas (33.5 kg N ha^{-1} in the Biomass scenario, 41.4 kg N ha^{-1} in the Extensification scenario) and reduction values for other changes based on (Olesen *et al.*, 2016; Olesen *et al.*, 2018, and Eriksen *et al.,* 2020). However, these results may be further refined by detailed NLES5 calculations, and inclusion of retention values to the sea if the final effects here are to be evaluated.

Table 5.7. *Estimated reduction in nitrate leaching (tonnes nitrate-N/year) from the root zone due to agricultural land use changes in 2030-scenarios (Olesen et al., 2016; Olesen et al., 2018, and Eriksen et al., 2020). The sub-scenarios of both Biomass and Extensification scenarios are calculated with effects on crop production from -/+ 20 % changes in animal production.*

	BAU	**Biomass**	**Extensification**	***Biomass: -20%***	***Extensification: -20%***	***Biomass: +20%***	***Extensification: +20%***
Reduced nitrate leaching (tonnes nitrate-N yr^{-1})	2,000	22,000	25,000	29,000	40,000	21,000	23,000

The areas of nitrate sensitive soils are clustered in certain parts of Denmark (Mortensen and Jørgensen, 2021) due to certain catchments having substantially higher nitrate reduction targets compared to others (Figure 5.14, Figure 5.15, and Figure 5.16). In ID15 catchments with a relatively low share of maize compared to other annuals, a larger area has to be converted to meet the reduction targets, as the effect on nitrate leaching by converting grain or rapeseed to grassland is lower than the conversion of maize. In the Biomass scenario, an area of approx. 319,000 ha is converted from grain, maize, and rapeseed into grass-clover (approx. 275,000 ha) and sugar beets (approx. 44,000 ha) for biorefining. In the Extensification scenario, approx. 247,000 ha of grain, maize and rapeseed is converted into grass-clover for biorefining (with reduced fertilization). More details on the calculations of these nitrate sensitive soils and the GIS maps is given in background material (Mortensen and Jørgensen, 2021). There is a potential overlap between some areas of nitrate-sensitive soils and the share of organic soils where land use is changed in the 2030 scenarios. Therefore, these areas need to be analysed in detail to describe specific changes and overlaps for the different scenarios in case of implementation.

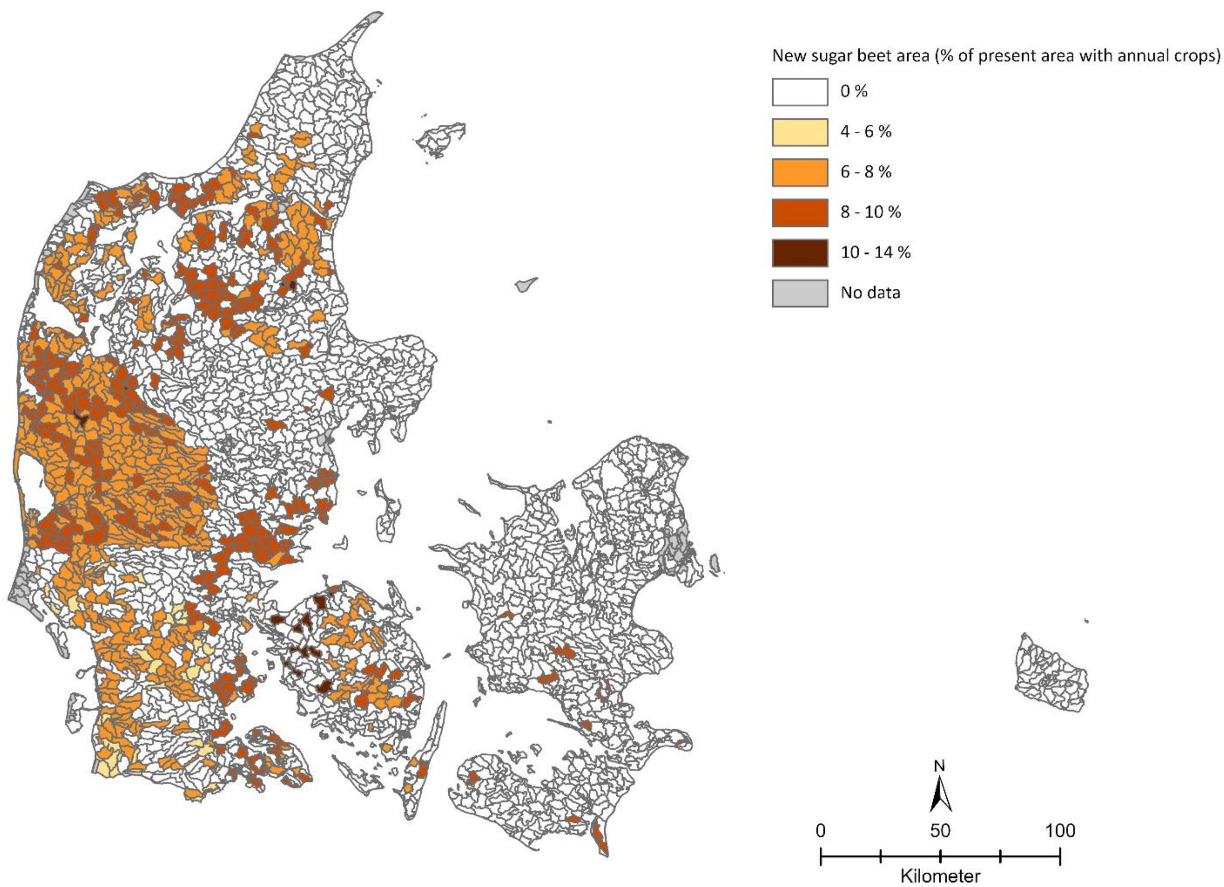


Figure 5.14. *Distribution of new areas with sugar beets for biorefining in the Biomass scenario.*

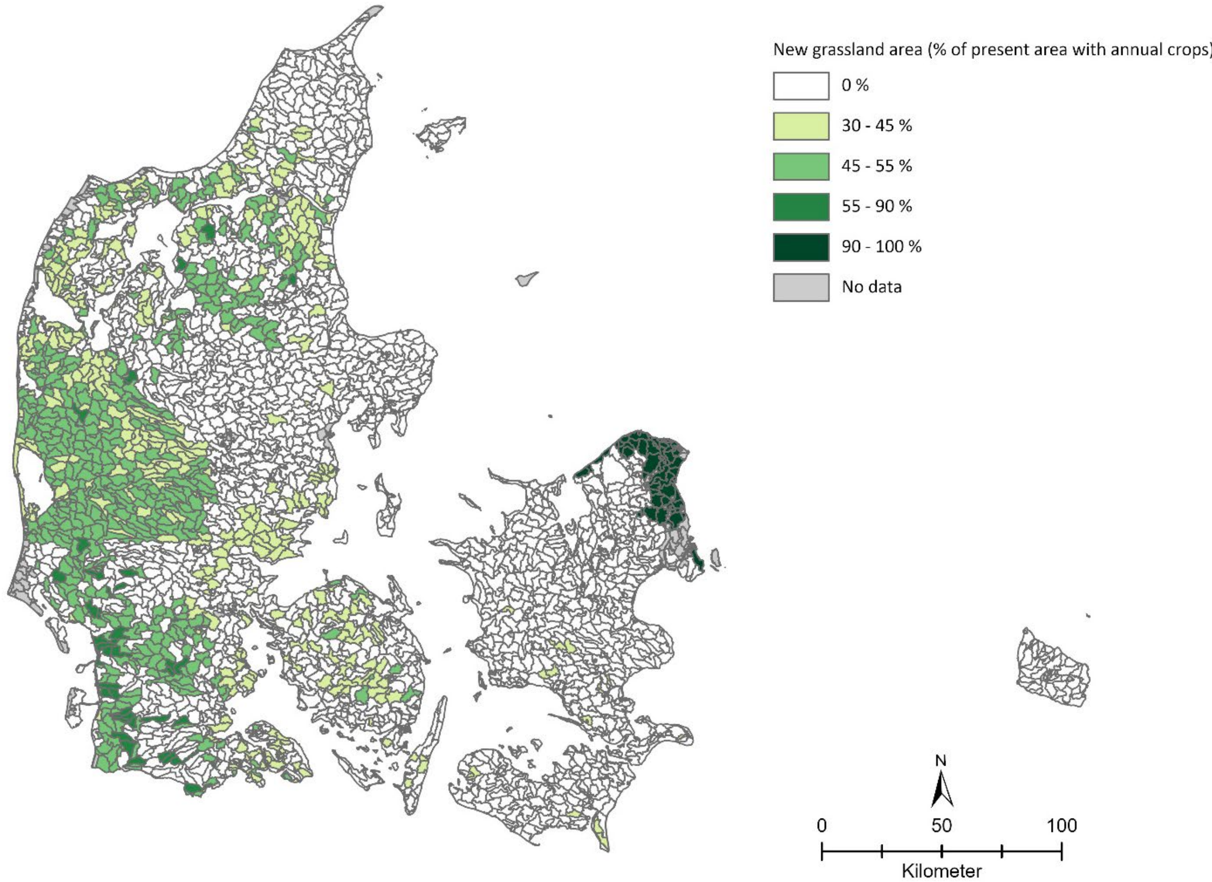


Figure 5.15. *Distribution of new grass-clover crops for biorefining in the Biomass scenario.*

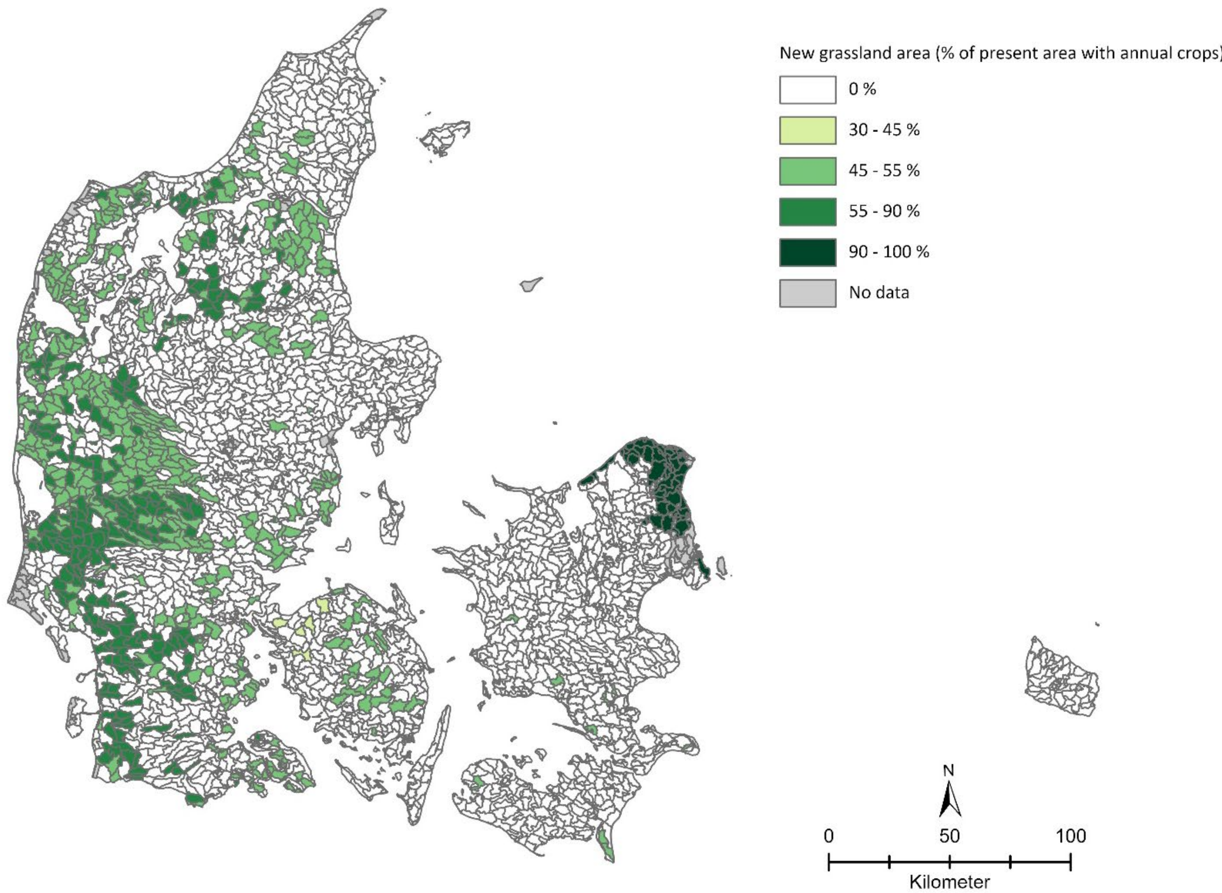


Figure 5.16. *Distribution of new grass-clover crops for biorefining in the Extensification scenario.*

5.7 Effects on import and export of agricultural cash crops

Import and export of grain, rapeseed, and soy are significantly affected by the new area with crops for biorefining (Figure 5.17). A shift from grain export to grain import will occur unless the Danish animal production is decreased. However, while grain import increases, the new production of grass protein substitutes a large proportion of the soy import. Thus, an overall shift from soy import (expensive in both economic and environmental terms) to import of relatively cheap feed grain is the main consequence on the import/export balance. The potential export of grass protein, if all soy imports can be substituted, seems only realistic in a scenario with a reduced animal production and optimization of the agricultural area for biomass production. Whether an excess of high-value grass protein should be exported for fodder or if it can be further refined into products for human consumption should be evaluated, as well as whether an area for producing protein-rich plants (e.g., peas and beans) for direct human consumption could substitute a share of the area with crops for biorefining. However, annual legumes for human consumption will have a higher N-leaching compared to grasslands.

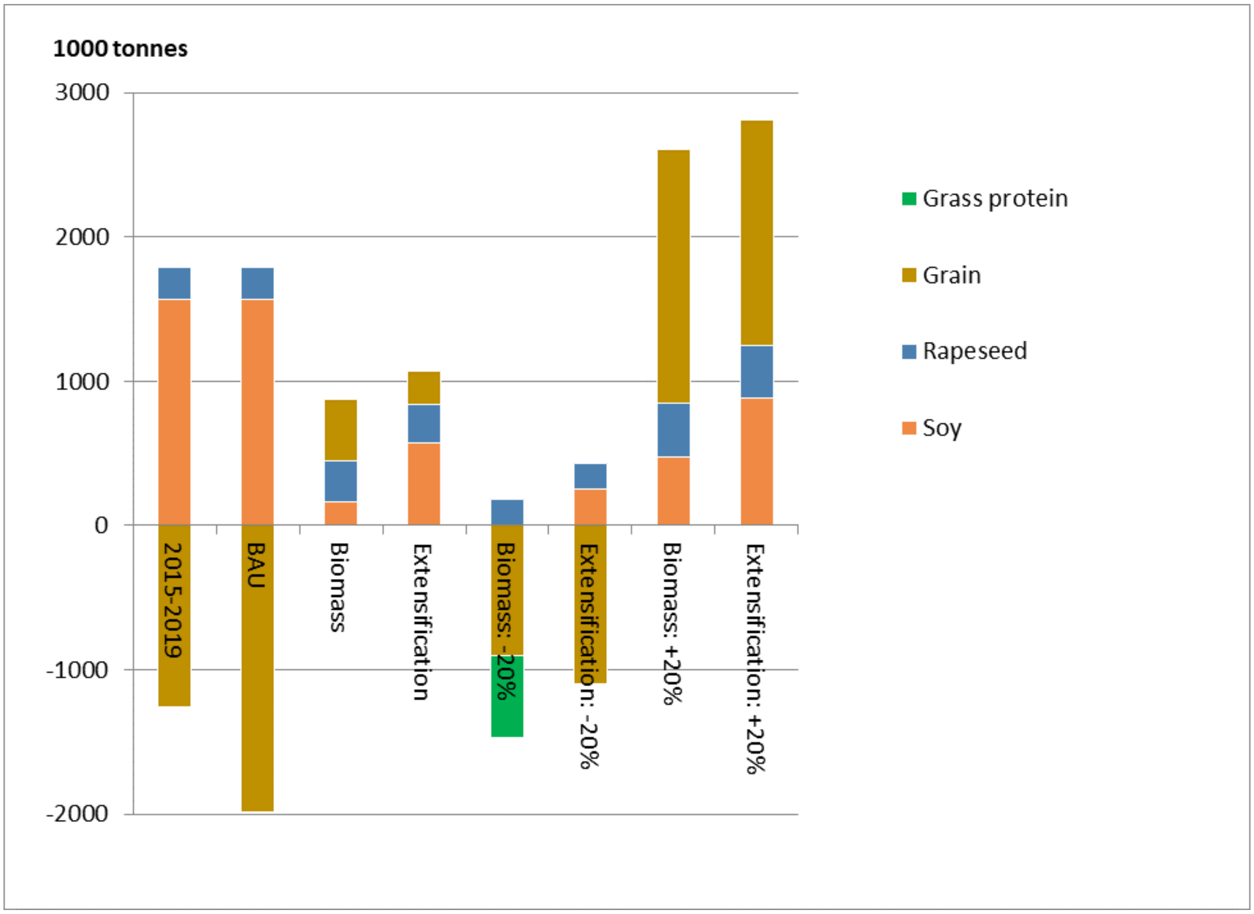


Figure 5.17. *Estimation of the import/export balance of the most important cash crops for different 2030-scenarios. The increase in grain export in the BAU scenario for 2030 compared to baseline is based on using the entire excess area that theoretically comes due to crop yield increase and stable animal and food production in 2030. Positive values represent import, while negative values represent export.*

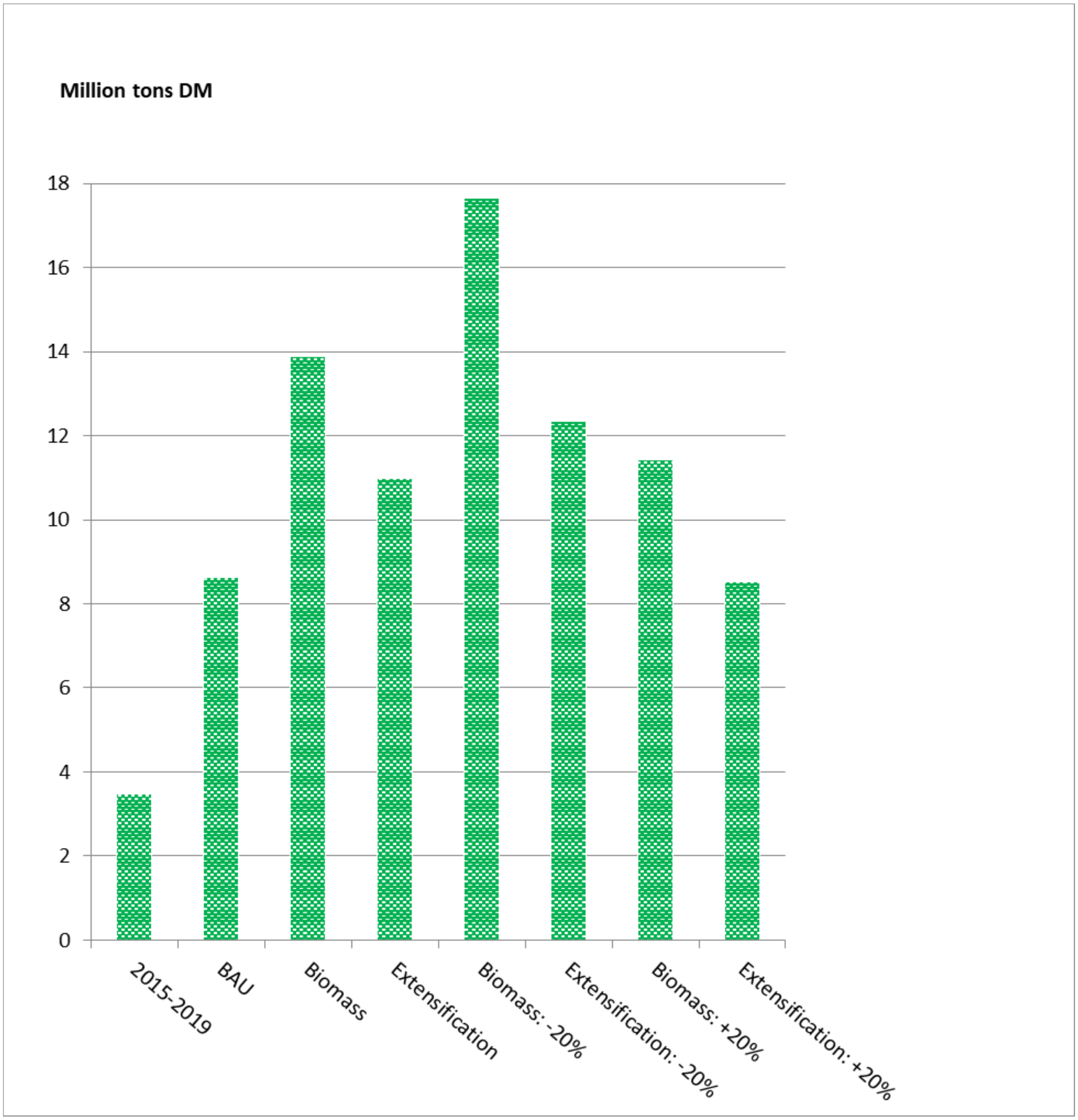


Figure 5.18. *Net biomass production for biorefining. The net import (or net export) of cash crops (Figure 5.17) in M tonnes of DM is subtracted from (or added to) the total sum of biomass production available for biorefining (Figure 5.1). The changes in production of animal products that occur in the scenarios with 20% changes in total animal production in Denmark are not included.*

Considering the large differences on the import/export balance of cash crops between the scenarios (Figure 5.17), DM values for the net import/export balance for these crops have been aggregated with the biomasses available for biorefining (Figure 5.18), to give an overview of total change in national dry matter production for biorefining and export/import of cash crops. This shows that increasing the animal production does not only reduce the potential for production of biomass for biorefining in Denmark as shown in

Figure 5.18, but taking into account the higher need of biomass production for fodder outside Denmark further reduces the surplus. However, a 20 % increase in animal "biomass" (DM), or a 20 % decrease, could be a supplementary information to give the full overview of changes between scenarios.

5.8 Economic assessment of agricultural scenarios

The present analysis is based on the above-described scenarios for Danish agriculture projected to 2030. The analysis has focus on the economic implications of an increased production of biomass and the utilisation for biorefining. In the scenarios, the potential to produce and deliver an additional amount of biomass for biorefining is estimated without effect on the animal production. The diversion to biomass crops and harvest and transport of other biomasses will have potential cost or income depending on the individual biomass in question. Gross margin estimates will be used as estimates for the consequences.

About 95% of the converted agricultural area changes from annual grain crops to perennial grass-clover for green biorefining, therefore the budget economy of green biorefining will be an important basis for the further economic assessment. There are several other types of biomass that can be used for bioenergy and biorefining, however these utilisations are not specified or described to an extent, where it is meaningful to conduct specific economic calculations. Focus for the economic assessment will therefore mainly be based on agricultural changes.

Biorefining of grass-clover

Depending on the scenarios, approx. 425,000 hectares of the farmed area is converted to grass-clover for biorefining in the Biomass scenario and approx. 375,000 hectares in the Extensification scenario (Mortensen and Jørgensen, 2022). Together with the additional collected green biomass from other sources the green biomass from grass-clover can potentially be biorefined to 1.1 M tonnes soy equivalent in the Biomass scenario and close to 0.7 M tonnes soy equivalent in the Extensification scenario.

As basis for the following budget economic assessments, it has been decided to build on technical data from a basic decentralized stand-alone biorefinery plant producing soy quality green protein, fibre pulp and brown juice.

As mentioned above, in the Biomass scenario approx. 425,000 hectares of the farmed area are converted to production of grass-clover for biorefining and approx. 375,000 hectares are converted in the Extensification scenario. At the same time, there is focus on a better utilization of the biological resources generated.

Short description of the decentralized biorefining

The production of green protein from grass-clover is not yet fully commercialized in DK, therefore we have a lack of full-scale experience for the biorefinery concept. Currently, there is a demonstration platform and a smaller scale pilot plant both operated by research institutions. Two semi-commercial farm-scale plants have been built for the season 2021 based on the experiences from the above-mentioned pilot scale plants and various demo scale projects. The capacity of these semi-commercial plants is about 20.000 tonnes of DM grass-clover input, annually (Morten Ambye-Jensen, personal communication, 2021).

A similar size decentralized biorefinery plant with a capacity of 20,000 tonnes of DM grass-clover input and an output of 3,600 tonnes DM protein, 14,000 tonnes of fibre pulp DM and 2,500 tonnes DM brown juice was described and used for economic assessment in Jensen and Gylling (2018) and Børgesen *et al.* (2018). The size and capacity are chosen based on the experiences from pilot scale and field scale demo activities. The necessary farming area to supply the grass-clover biomass is estimated to 2.600 hectares. The assessment is made based on three price-levels for the protein: low (conventional), medium (non-GMO) and high (organic) protein products.

Organization

Based on the experience from the green drying industry, it is assumed that harvest, logistics/transport to the biorefinery is managed centrally by the biorefinery or hired contractors. The farmer grows the grass-clover and sells it to the biorefinery as a standing crop on the field, while the biorefinery manages the harvest and logistics in terms of scheduling and operations planning.

Pilot scale experiences have shown that an efficient logistics setup is extremely important for the quality of the harvested grass-clover and thus for the processing at the biorefinery plant and the quality of products from the biorefinery.

The harvest/logistics setup chosen is a self-propelled forage harvester and lorry transport from field to biorefinery, which has shown to be the most cost-efficient system. It should be noted that even with an efficient harvest and logistics setup, the cost of harvest and transport of the grass-clover biomass is around 40 % of the total cost.

Table 5.8 shows the budget economic result of a medium scale biorefinery where the result is a surplus to payment for the biomass.

Table 5.8. *Budget economic assessment of a medium scale green biorefinery producing either conventional, non-GMO or organic protein concentrates.*

	Conventional	Non-GMO	Organic
	1,000 DKK/Year	1,000 DKK/Year	1,000 DKK/Year
Revenue			
Dried protein	9,445	13,979	18,890
Fibre fraction	15,074	15,074	17,084
Brown juice	688	688	688
Total revenue	25,207	29,740	36,661
Costs			
Harvest & transport, biomass	5,642	5,642	6,722
Transport, fibre fraction	843	843	914
Transport, brown juice	1,083	1,083	1,083
Auxiliary cost	727	727	727
Energy	1,525	1,525	1,525
Personal cost	1,474	1,474	1,474
Capital cost	2,834	2,834	2,834
Total costs	14,127	14,127	15,278
Surplus for feedstock payment			
- DKK/year	11,079	15,613	21,383
- DKK/FEN	0.69	0.97	1.33
- DKK/Kg DM	0.86	1.21	1.66

Source: Børgesen *et al.* (2018), Pavlou *et al.* (2016), Sopegno *et al.* (2016), and Claus Grøn Sørensen, (personal communication).

Based on the results the biorefinery can pay the farmer 0.86 DKK/kg DM, 1.21 DKK/kg DM and 1.66 DKK/kg DM for conventional, non-GMO or organic grass as standing crop on the field, respectively.

For further assessment of the economic implications of conversion of agricultural land, the "surplus for feedstock payment" for the standing biomass on the field will be used as the price that the biorefinery can pay for a standing crop of conventional, non GMO and organic grass-clover biomass on the field. These prices will be used in the further calculations for the conversion costs of the various crops in question.

Biomass not dependent of scenarios

The scenario estimated agricultural biomass and other biomass independent of the scenarios (Table 5.9) is estimated to a total of 14.5 M tonnes dry matter in the Biomass scenario and 12.3 M tonnes dry matter in the Extensification scenario. The biomass available independent of scenarios constitute a potential of approx. 2 M tonnes of DM, of which by-products from the agricultural primary industries accounts for close to 75% of the total (Table 5.9, Figure 5.19). It should be noted that by-products from the primary industries and household waste are indirectly dependent on the agricultural production, but it has been chosen to include them here.

Table 5.9. *Types of biomass independent of scenarios*

	Total biomass (Tonnes DM)
Wastewater sludge	120,000
Cuttings from water course clearings	7,076
Cuttings from road verges	14,201
By-products from the primary industries	1,579,918
Household waste	315,201
Total	2,036,396

Note: Wastewater sludge is assumed to have a DM content of 15 percent (Birkmose *et al.,* 2015).

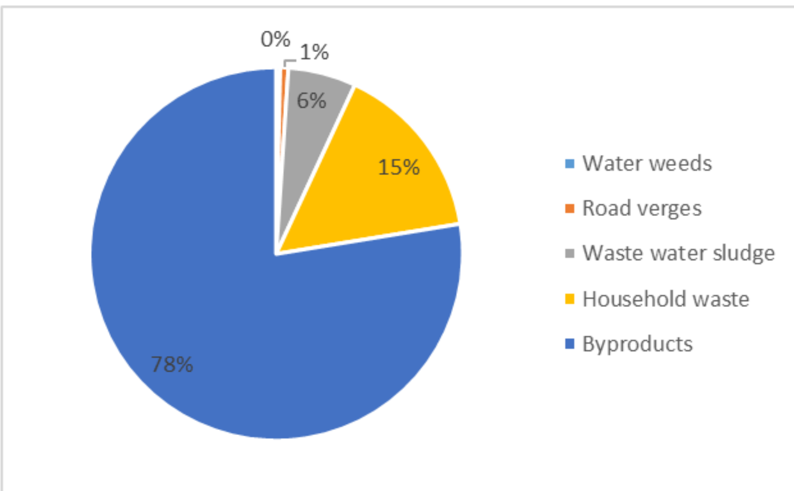


Figure 5.19. *Types of biomass independent of scenarios.*

The scenario-independent agricultural biomass is however only a small part of the total estimated biomass for biorefining in 2030, as can be seen from Table 5.10. The total estimated biomass for biorefining adds up to 14.5 M tonnes in the Biomass scenario and 12.3 M tonnes in the Extensification scenario. The projection for organic waste is based on the FRIDA model (Miljøstyrelsen, 2019).

Table 5.10. *Current (2015-2019) and expected biomass production in agriculture towards 2030.*

Biomass type (M tonnes DM)	2015-2019	BAU	Biomass	Extensification
Straw	1.49	3.55	3.40	3.54
Green biomass (grass and herbs)	0.00	0.00	5.79	3.50
Animal manure	0.47	2.95	3.17	3.17
Rapeseed oil	0.13	0.22	0.08	0.08
by-products	1.58	1.58	1.58	1.58
Organic waste (Household waste and residual water sludge)	0.32	0.44	0.44	0.44
Total	5.82	11.49	14.46	12.3

Economics concerning cultivation of biomass crops for biorefining

Estimates for the economy of cultivation are based on budgetary calculations from Farmtal Online[2]. The selected crops include conventional or organic grown; spring barley, winter barley, winter wheat, winter rapeseed, maize, sugar beet and clover grass in rotation. The analysis differentiates between sandy and loamy soils, as well as whether fertilizer is used with or without livestock manure the exception being sugar beets (for biogas) which is only grown without livestock manure.

Table 5.11 shows the estimated gross profit effects when converting the abovementioned crops to grass-clover or sugar beets for biorefining. The changes are shown for a low, moderate, and high price for grass-clover for biorefining of 0.69, 0.97 and 1.3 DKK FEN, respectively. These can be viewed as the market price for conventional, non-GMO and organic grass-clover for biorefining. As such, the organic price will represent a shift from a conventional grown crop to organic grass-clover for biorefining.

Table 5.11. *Gross profit effect on crop level, conversion to grass-clover for biorefining.*

	Sandy soils (JB 1-3)			Loamy soils (JB 5-6)		
Price of grass, DKK/FEN	0.69	0.97	1.33	0.69	0.97	1.33
Spring barley to grass-clover, DKK/ha	-1,940	583	2,973	-3,575	-869	1,694
Winter barley to grass-clover, DKK/ha	-2,271	252	2,642	-4,055	-1,350	1,214
Winter wheat to grass-clover, DKK/ha	-3,410	-887	1,503	-7,060	-4,355	-1,792
Winter rapeseed to grass-clover, DKK/ha	-2,894	-370	2,020	-5,480	-2,775	-212
Maize to grass-clover, DKK/ha	-5,033	-2,510	-119	-5,292	-2,586	-23
Sugar beets to biogas/biorefining, DKK/ha	-958	-958	-958	909	909	909

Note: Single crops, incl. manure.
Source: Farmtal Online

2 https://farmtalonline.dlbr.dk/Navigation/NavigationTree.aspx

The gross profit effect varies with regards to the crops grown, soil type and the price of grass-clover for biorefining. Among other, a large spread can be seen for the three cereals included in the analysis. For example, when converting spring barley and winter barley to grass-clover for biorefining with a moderate grass price (0.97 DKK/FEN), there is a potential gross profit of 583 and 252 DKK per hectare on sandy soils, respectively. For winter wheat, however, the estimated gross profit effect of conversion will result in a loss of 887 DKK per hectare. Similarly, the conversion of winter rapeseed and maize will also be associated with a potential gross profit loss. On loamy soils, the gross profit using the moderate price will in all instances be negative. Whilst the estimated gross profit is almost identical across soil types for conversion of maize, namely -2,510 DKK and -2,586 DKK per hectare respectively, soil type has a significant effect on the gross profit for the four other crops. Conversion to grass-clover for biorefining on loamy soils are estimated to have an annual loss in gross profit of between 869 DKK and 4,355 DKK per hectare when using the moderate price. Conversion to sugar beets for biorefining is estimated to a potential loss of 958 DKK/ha on sandy soils and a potential gross profit of 909 DKK/ha Loamy soils.

An estimated total of 483,000 hectares are converted to crops for biorefining in the Biomass scenario and 449,000 hectares in the Extensification scenario, the majority of the converted land is nitrate sensitive soils and loamy soils with high Dexter ratio (Table 5.12). The two scenarios with a reduction of livestock production have an additional 160,000 hectares converted to biomass crops in the Biomass scenario and to natural succession and extensive grazing in the Extensification scenario. The conversion of these 160,000 hectares of roughage area is due to a lower demand of fodder from the livestock sector (Mortensen and Jørgensen, 2022). In the scenarios with 20% expansion of the livestock production there is no change in the estimated converted area compared to the base scenarios.

Table 5.12. *Land-use changes in the two main scenarios and four sub-scenarios (from Mortensen and Jørgensen (2022)).*

Changed to (1000 ha)	*2030*	**Biomass**	**Extensification**	*Biomass: -20%*	*Extensification: -20%*	*Bio-mass: +20%*	*Extensification: +20%*
Nitrate sensitive soils	High intensive grass for biorefining	275	0	275	0	275	0
	Medium intensive grass for biorefining	0	247	0	247	0	247
	Sugar beets for biorefining	44	0	44	0	44	0
	Sub Total	*319*	*247*	*319*	*247*	*319*	*247*
Loamy soils with high Dexter-index	High intensive grass for biorefining	99	73	99	73	99	73
	Medium intensive grass for biorefining	0	18	0	18	0	18
	Nature (succession and extensive grazing)	0	0	0	0	0	0
	Sub Total	*99*	*91*	*99*	*91*	*99*	*91*
Areas with risk of pesticide-leaching to drinking water	High intensive grass for biorefining	0	0	0	0	0	0
	Medium intensive grass for biorefining	17	9	17	9	17	9
	Nature (succession and extensive grazing)	0	9	0	9	0	9
	Sub Total	*17*	*17*	*17*	*17*	*17*	*17*
Rewetted organic soils	Intensive paludiculture for biorefining	34	0	34	0	34	0
	Extensive paludiculture for biorefining	0	29	0	29	0	29
	Nature (succession and extensive grazing)	13	66	13	66	13	66
	Sub Total	*48*	*94*	*48*	*94*	*48*	*94*
	Non-farmland	2	6	2	6	2	6
Changed roughage area	High intensive grass for biorefining	0	0	160	0	0	0
	Nature (succession and extensive grazing)	0	0	0	160	0	0
	Sub Total	*0*	*0*	*160*	*160*	*0*	*0*
	Grand Total	**483**	**449**	**643**	**610**	**483**	**449**

Key economic results from agriculture

The top five categories in Table 5.13 represent either costs or revenues associated with the conversion of existing crop production. These includes nitrate-sensitive soils, loamy soils with high Dexter index, areas with risk of pesticide-leaching to drinking water, rewetted organic soils, and changed roughage area, all of which are either converted to grass-clover and sugar beets for biorefining or for nature (Table 5.12). The costs of this conversion are estimated to be approximately 365 M DKK in the Biomass scenario and 440 M DKK in the Extensification scenario (Table 5.13).

The remaining seven categories in Table 5.13 represent supply chain costs, i.e., the cost of bringing the biomass in question to a biorefinery. These biomass fractions are largely independent of the scenario calculations, and consequently the total supply chain costs of the additional biomass do not differ substantially between the scenarios, i.e., DKK 563 M and DKK 578 M in the Biomass and Extensification scenario, respectively. The cost of additional biomass is about 60% of the total cost for the biomass intended for biorefining. Note, however, that the potential revenue from the turnover of this biomass is not included.

Table 5.13. *Key economic results from agriculture (M DKK).*

	Biomass -scenario	Extens. -scenario	Biomass -20 %	Extens. -20 %	Biomass +20 %	Extens. +20 %
Nitrate sensitive soils	-326.2	-237.0	-326.2	-237.0	-326.2	-237.0
Loamy soils with high Dexter index	-199.2	-190.7	-	-	-199.2	-190.7
Areas with risk of pesticide-leaching to drinking water	-5.6	-15.1	-	-	-5.6	-15.1
Rewetted organic soils	166.4	3.6	166.4	3.6	166.4	3.6
Changed roughage area	-	-	-149.4	-572.5	-	-
Sub-total (Converted land)	*-364.6*	*-439.2*	*-309.2*	*-805.9*	*-364.6*	*-439.2*
Organic Waste	-28.3	-28.3	-28.3	-28.3	-28.3	-28.3
Waste water sludge	-8.5	-8.5	-8.5	-8.5	-8.5	-8.5
Leaves from sugar beets	-27.0	-27.0	-27.0	-27.0	-27.0	-27.0
Cuttings from water course clearings	-9.5	-9.5	-9.5	-9.5	-9.5	-9.5
Straw	-1.6	-1.7	-1.4	-1.5	1.8	1.8
Cover crops	-479.2	-497.1	-479.2	-497.1	-479.2	-497.1
Cuttings from road verges	-8.8	-8.8	-8.8	-8.8	-8.8	-8.8
Sub-total (Additional biomass)	*-562.9*	*-577.6*	*-562.7*	*-580.7*	*-563.1*	*.581.0*
Total	-927.4	-1,016.8	-871.9	-1,386.6	-927.4	-1,016.8

Note: Sums in M DKK

As can be seen from Table 5.13, only the conversion of rewetted organic soils has a positive effect on the gross margin. In the Biomass scenario, the estimated gross margin will result in an annual revenue of 166.4 M DKK, while it is estimated at 3.6 M DKK in the Extensification scenario. The difference is due to differences in size of the converted area and the intensity of production between the scenarios. In the Extensification scenario, a large proportion of the area is set-aside for nature, which has no economic production value in this analysis.

The single largest costs are estimated for the conversion of annual crops on nitrate sensitive areas by approximately DKK 326 M and DKK 237 M in the Biomass and the Extensification scenario, respectively. This is mainly a result of the scenario definitions, i.e., that more hectares of this area type are being converted relative to the others. It should be emphasised that the cost effectiveness of the conversion of nitrate sensitive areas is approximately double that of loamy soils with high Dexter index. The primary difference in the effect on the gross margin between the scenarios is a result of both the intensity in cultivation (more spring barley on sandy soils) but also of the conversion to sugar beet cultivation for biogas production on loamy soils.

The conversion of areas with risk of pesticide-leaching to drinking water is estimated to result in an annual loss of DKK 5.6 M and DKK 15.1 M for the Biomass and the Extensification scenarios, respectively. Here, the difference is mainly a result of the degree of utilization of the converted land. In the Extensification scenario, an area is set aside for nature, whereas the entire area in the Biomass scenario is converted to grass-clover production.

For loamy soils with high Dexter index, the costs of conversion are estimated to roughly DKK 199 M and DKK 191 M for the Biomass and Extensification scenario, respectively. Here, the difference – however small - is also a result of the degree of utilization of the converted land. In the Extensification scenario cultivation is not as intensive as in the Biomass scenario.

Of the two scenarios where livestock production is regulated by +/- 20 %, the largest conversion cost is realized for changed roughage areas in the Extensification scenario -20 % with DKK 572.5 M This is due to that the full area is set-aside for natural succession and extensive grazing, which has no additional value in this analysis. In the Biomass scenario with -20 % livestock production, there will also be a high though considerably smaller cost of DKK 149.4 M since the entire area is converted to grass-clover production.

The key economic results from agriculture are depicted in Figure 5.20. As illustrated, the major costs in the different scenarios are associated with the conversion of nitrate sensitive areas and changes in roughage areas, respectively, as well as the supply chain costs associated to cover crops.

As stated above around 60 % of the estimated total cost for the biomass intended for biorefining is supply chain costs for the described additional biomass. Especially harvest and utilization of cover crops represents a large resource but also a relatively high cost.

In the Biomass scenario, the 14.5 M tonnes biomass dry matter has an estimated cost of DKK 930 M and in the Extensification scenario, the 12.3 M tonnes of dry matter has an estimated cost of DKK 1,000 M, which means DKK 64/tonnes and DKK 81/tonnes, respectively.

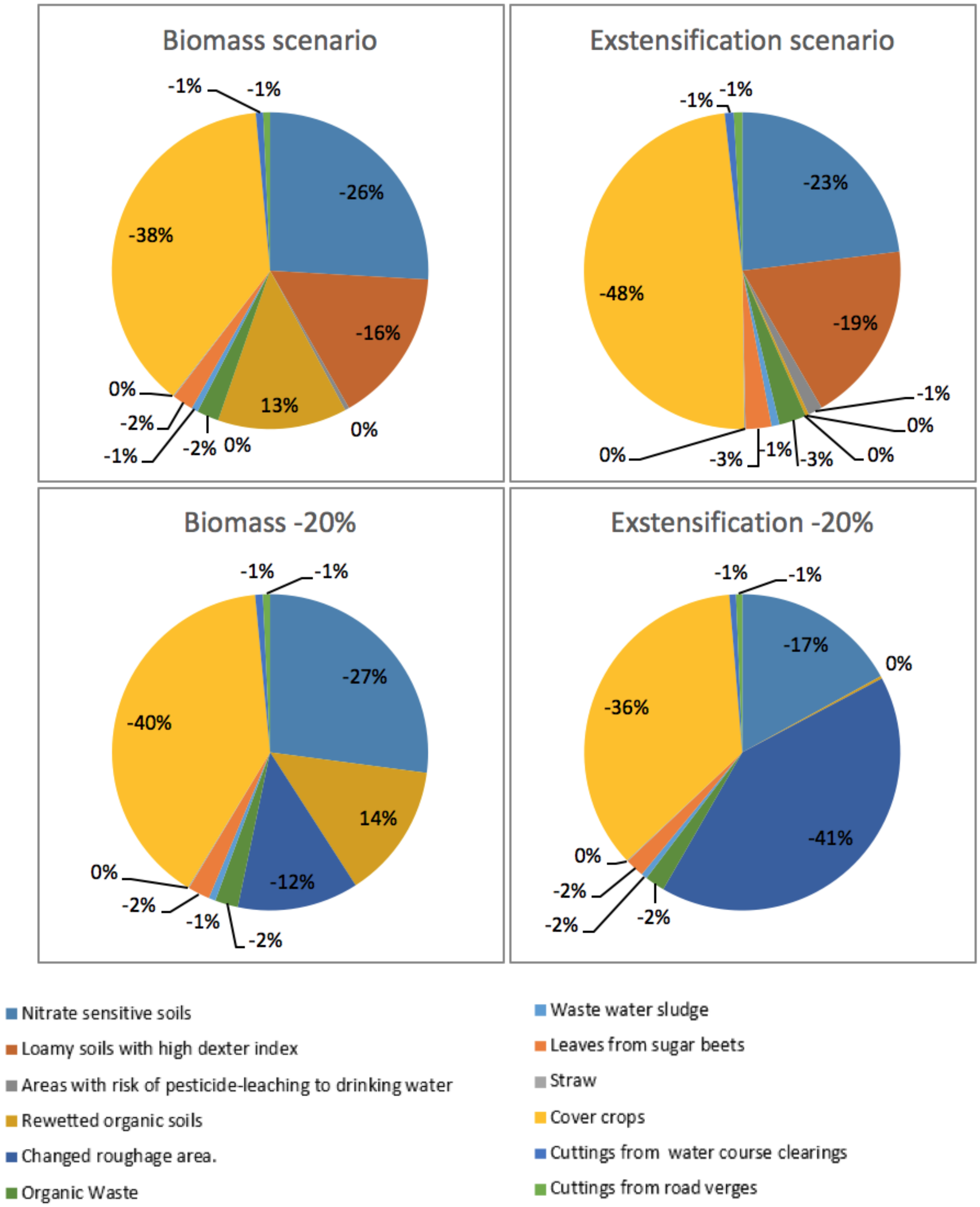


Figure 5.20. *Key economic results from agriculture.*

Effects on employment

The employment effects of the changes in cropping are estimated based on statistical data. Most of the changes are from grain crops to grass-clover for biorefining. These changes result in increased time consumption. As an example, the conversion of spring barley to grass-clover for biorefining where the additional estimated time consumption is 4.4 hours per hectare (Danmarks statistik, 2021).

Consequently, in total, there will be a significant estimated positive employment effect from converting substantial agricultural areas from grain production to grass-clover for biorefining. In addition to this, there is an employment effect from the biorefineries with an estimated 2.5 persons at a small scale biorefinery (Jensen and Gylling, 2018). Potentially there is raw material to supply approx. 150 biorefineries in the Biomass scenario and approx. 130 biorefineries in the Extensification scenario.

The conversion from annual grain crops to grass-clover for biorefining will result in an estimated 830 full time employees in the Biomass scenario and an estimated 675 full time employees in the Extensification scenario.

In addition to this, there is an expected positive employment effect of 540 -550 full time positions in collecting/harvesting and transport the additional biomass types in the Biomass scenario and 310 full time positions in the Extensification scenario (Table 5.14 and Table 5.15).

In total there will be an estimated positive employment for the Biomass scenario of 1,300 full time positions and 500 full time positions in the Extensification scenario.

Table 5.14. *Biomass-scenario: Changes in full time positions (2,000 hours).*

Biomass scenario	
Rewetting of organic lowland	*-127*
15.000 ha to roughage	-101
17.500 ha to low yielding grass	-88
17.500 ha to paludiculture and thatching material	61
Conversion of annual grain crops	*1,022*
391.000 ha annual grain crops converted to perennial grass-clover	899
44.000 ha additional sugar beets	123
Harvest of other biomass	*407*
192.000 ha cover crops are harvested	283
119,000 ha leaves from existing and new sugar beet cultivation are harvested	196
Biomass cuttings from road verges and watercourse clearings are utilized.	*2*
Total estimated change in employment	**1,376**

Table 5.15. *Extensification scenario: Changes in full time positions (2,000 hours).*

Extensification scenario	
Rewetting of organic lowland	*-604*
70.000 ha to roughage	-469
20.000 ha to low yielding grass	-100
10.000 ha to paludiculture and thatching material	-35
Conversion of annual grain crops	*760*
346.500 ha annual grain crops converted to grass-clover	797
8.500 ha set aside	-37
Harvest of other biomass	*342*
199.000 ha cover crops are harvested	292
31.000 ha leaves from existing sugar beet cultivation are harvested	51
Biomass cuttings from road verges and watercourse clearings are utilized.	*2*
Total estimated change in employment	**500**

Export and import

A substantial amount of agricultural land, consisting of primarily cereals but also rapeseed and maize, is converted to grass-clover in the two main scenarios. In turn, this has a significant impact on the imports and exports of cereals and rapeseed in the scenario calculations when domestic livestock production is assumed to be unchanged. While the exports of cereals will be increasing in BAU (Table 5.16), imports of rapeseed cake and soy are estimated to remain unchanged.

Table 5.16. *Import/export balance from the sales of main crops (1,000 tonnes) (from Mortensen and Jørgensen, 2022).*

Crop	**2015-2019**	**BAU**	**Biomass -scenario**	**Extens. -scenario**	**Biomass -20 %**	**Extens. -20 %**	**Biomass +20 %**	**Extens. +20 %**
Soy	1,564	1,564	166	569	0	256	479	881
Rapeseed	224	224	279	270	186	177	372	364
Cereal	-1,258	-1,988	427	235	-902	-1,094	1,756	1,564
Grass	0	0	0	0	-564	0	0	0

Note: Positive numbers represent imports and negative numbers represent exports

The conversion of grain crops to grass-clover for biorefining will result in an import of cereal by 2030 of 427,000 tonnes and 235,000 tonnes respectively in the Biomass and Extensification scenarios, provided an unchanged livestock production as well as a development in yields and feed-efficiency as described in (Dalgaard and Mortensen, 2022). However, the estimated decline in the domestic cereal production should be considered as marginal and without significant impact on the cereal supply balance. As such, the decline remains largely within the observed fluctuation in yields over a 10-year period (Statistikbanken, 2021).

Moreover, since cereal is an internationally traded good, it is not considered to be problematic for the supply balance and thus livestock production, neither in terms of quantity nor price.

In the sub-scenarios, where livestock production is assumed to either increase or decrease by 20%, the related effect on the feed balance as well as on the exports of pork and dairy products have been estimated in following two paragraphs.

Feed balance

To maintain feed balances, it is especially imports or exports of grass protein and cereal that will be affected in the -20 percent and +20 percent scenarios, respectively. In the scenarios with a 20% decrease in livestock production, there will subsequently be a "cereal surplus" of around 1 M tonnes in 2030 in both sub-scenarios (see Table 5.16), which can be exported. Concurrently, the import of rapeseed cake is around 180,000 tonnes for both these sub-scenarios, which roughly corresponds to a 100,000 tonnes decrease cf. to the original scenarios. Whilst a smaller livestock production in the -20 percent Biomass scenario will induce a complete phase-out of soy imports, the adjoining increase in grass-clover production will result in the export of just over half a million tonnes of grass protein. Meanwhile, soy imports are reduced to just over 250,000 tonnes in the -20 percent Extensification scenario with no export of grass protein.

With a 20 percent increase in livestock production, a soy import of almost 500,000 tonnes is expected in the Biomass scenario and almost 900,000 tonnes in the Extensification scenario. Moreover, by 2030, the import of rapeseed cakes is estimated at around 370,000 tonnes in both sub-scenarios, while cereal import drastically increases to around 1.7 and 1.5 M tonnes in the Biomass and Extensification sub-scenario, respectively (Table 5.16).

Changes in export value from pork and dairy products

The current total export value of pork (2016-2019) is averaged at DKK 31.2 billion annually and DKK 20.2 billion annually for dairy products. Given that the home market demand is supplied first, a 20 percent decrease in livestock production results in a smaller export income of DKK 10.2 billion. Correspondingly, a 20 percent increase in livestock production will result in a larger export income of DKK 10.2 billion.

6 Discussion

6.1 Biomass types from agriculture, forestry and aquaculture and implications of their use

6.1.1 Agricultural biomass

The potential production of agricultural biomass can be divided into five main categories characterized by origin and usability for energy purposes and biorefining (Figure 6.1). Green biomass is the main driver of the differences between the scenarios. This is due to significant differences in the size of the area that is converted into grass-clover for biorefining and differences in yield between the Biomass and Extensification scenarios (see Mortensen and Jørgensen (2021) for details). Furthermore, the share of the fibre fraction that is needed to substitute roughage varies significantly in the scenarios due to changes in animal production.

Yellow biomass is straw from cereal and rapeseed production as well as from grass seed production and is relatively stable between the 2030-scenarios. A 15 % increase in removal of straw may have a negative impact on the soil carbon stocks. However, there is a potential for returning biochar from pyrolysis of e.g. straw to agricultural soils. This may be especially relevant on the loamy soils where there is a low content of soil C and on sandy soils where biochar may also have a positive effect on soil fertility and water holding capacity (Borchard et al., 2019; El-Naggar et al., 2019).

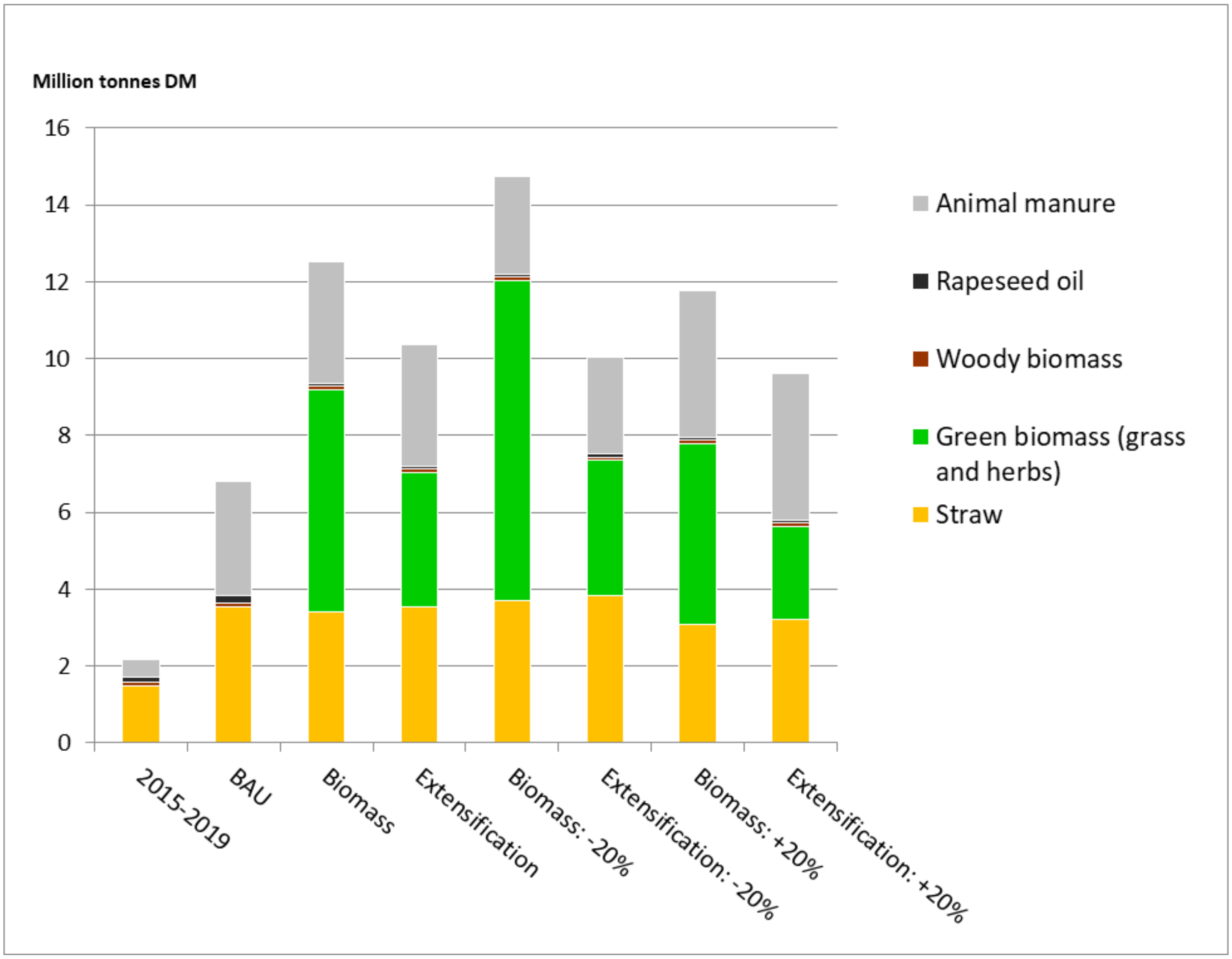


Figure 6.1. *Biomass production on the agricultural area (M tonnes DM) for 2030-scenarios based on biomass type and usability. BAU = Business-As-Usual. "-/+20%" = scenarios with a 20% reduction/increase in Danish animal production. The required quantity of fibre and protein from biorefining to substitute roughage crops from areas converted into biomass production and soy import have been subtracted from the total production potential (Mortensen and Jørgensen, 2022).*

Animal manure available e.g., for biogas production, is relatively similar throughout the 2030-scenarios, where the main differences are due to decreased or increased animal production. In the BAU-scenario, the quantity of animal manure available for e.g., biogas is comparable to the quantity in the optimized scenarios, due to biogas being a well-known technology. The share of animal manure utilized for biogas production has increased heavily from 2017 to 2020 (Fødevareministeriet, 2020), and further increase is expected with existing policies (Energistyrelsen, 2021). In relation to animal manure, the difference between BAU and the optimized scenarios is a more effective manure handling (Adamsen *et al.*, 2021) that is not included in BAU scenario.

Rapeseed oil plays a role for biorefining and energy purposes in the BAU scenario, but it is considered a high value raw material not adequate for direct energy use in the optimized scenarios. The majority of woody biomass is currently derived from forests, with short rotation coppice on agricultural soil as a minor component. Biomass from the forest is not included in Figure 6.1. Depending on demand and economic incentives, woody biomass could be increased e.g. by substituting a share of the perennial grasslands for biorefining with short rotation coppice. However, this will reduce DM yield as the expected DM yield per year is lower for short rotation coppice (approx. 12 tonnes DM/ha) (Gylling *et al.*, 2016) compared to intensive production of grass-clover (approx. 15 tonnes DM/ha) (Cougnon *et al.*, 2017; Manevski *et al.*, 2017). The afforestation on agricultural soils is not expected to provide biomass on this short timespan to 2030, while it increases C storage and potential for later use.

The area with sugar beets for biorefining in 2030 (approx. 44,000 ha in the Biomass scenario while no additional sugar beet production in the Extensification scenario) could be increased with a higher DM production at the expense of some of the large areas with grass-clover for biorefining. This would, however, reduce soil organic carbon, and slightly increase nitrate leaching (Hamelin *et al.*, 2012). However, on the nitrate sensitive areas of this analysis, the areas with sugar beets have already been maximized to a limit where they can still be in a 5-year cropping rotation with other annual crops. Therefore, a further increase in the area with sugar beets would have to be placed outside the nitrate sensitive areas.

Lucerne for biorefining is another alternative to grass-clover mixtures. Lucerne may have lower N_2O emissions from the soil relative to intensively fertilized grass-clover (at least during the growing period), but the mechanisms behind N_2O emissions from soil are complicated, and there is a lack of knowledge concerning these effects, which need to be further assessed. Likewise, estimates on the effects on nitrate leaching from pure legume stands needs more solid investigation.

6.1.2 Forest biomass

Biomass for biorefining or energy may come from all parts of the forest rotation but depends on the site conditions, tree species, forest management, tree size, tree quality, and price structure. Owing to large differences in these preconditions across regions, this produces highly different profiles in terms of biomass production. However, importantly, higher qualities of wood can always be used for less valuable purposes, while the opposite is not possible. For example, large logs suited for sawn timber can be used for pulp and bioenergy, but small trees of poor quality cannot be used for construction. Hence, for industry to attract better qualities of wood, a premium is paid making the higher qualities of wood more expensive. Commonly, quality logs and timber attain prices more than five-fold that of bioenergy. In general, wood for energy is poorly paid and rarely the real objective of forest production.

In managed forest stands established by natural seeding or planting, the plant number is typically much higher than the number of trees in the final crop. This allows selection of the best shaped individuals during thinnings and the mutual shading of the plants improves quality of the final crop. In early thinnings, excess competition is removed and is important for the future development of the stand. At this stage, the thinning trees are typically small and of species undesired for timber production and cannot in the present-day market be utilized as a timber (Figure 6.2). Thus, either the wood is left in the stand or used for biorefining or bioenergy. The choice between utilizing the forest biomass from early thinnings or not depends on the local market for bioenergy (or for biorefining into e.g. biochemicals or cellulose materials), the size of the trees, since small trees may be too expensive to extract, and the accessibility of the site.

In the later thinnings, the wood achieves a size where it can be marketed and used for fibre products such as pulp for paper, in the chemical industry, and for packaging (pallets). As the trees grow larger, an increasing proportion of the coniferous wood is used for construction and for deciduous species for smaller elements in the furniture and flooring industry (Figure 6.2). The minimum diameter of the wood here is typically 15-20 cm. However, the smaller parts of the tree in the top and branches continues to be used as fibre and chemical products, and for bioenergy.

In the late thinnings and in the final harvest, where the trees become large, the proportion of timber assortments is large - for the coniferous species up to 90 % per cent and for hardwood species 50-70 % (Figure 6.2). In the coniferous tree, up to 70 % become construction timber, while for the hardwood it is 45-50 % of the large trees that become furniture or flooring wood. The remainder is used for fibre products and bioenergy. The proportion of wood for energy is usually higher for hardwoods than for conifers because branches and trunks are often less regular and therefore poorly fit industry requirements. In addition, in late thinnings and the final harvest an increasing part of the wood may be become damaged from insect attacks, root rot and wind-throw, making the wood unsuitable for construction timber. In addition, the need to clear the ground prior to re-planting or seeding often creates an incentive to grind or extract tops and branches for bioenergy/biorefining, increasing the share of bioenergy/biorefining in the assortment distribution.

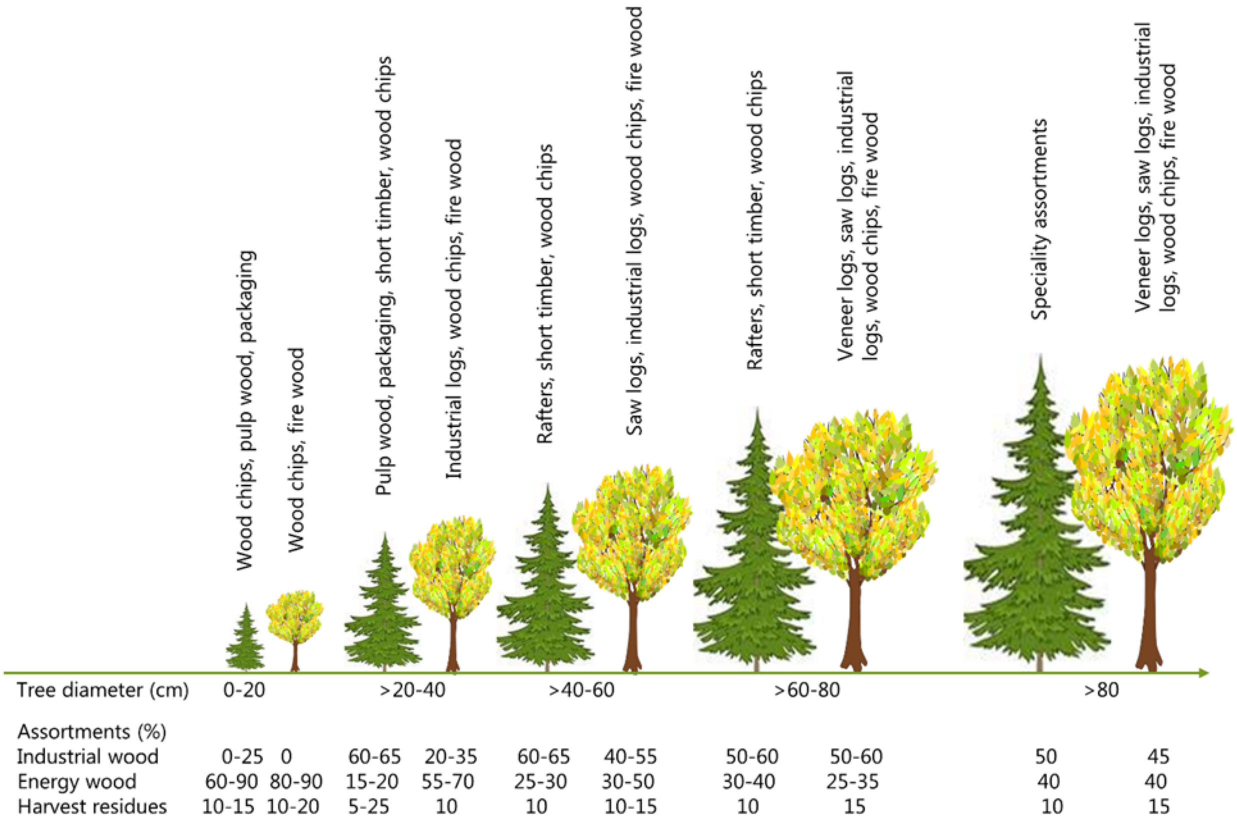


Figure 6.2. *Distribution of assortments at different tree diameters. The distribution is adopted from Graudal et al. (2014) based on experience from major Danish forest management companies.*

6.1.2.1 Industrial residues

When the timber enters the sawmill, the round wood is first debarked. The bark is commonly used for bioenergy and has currently limited alternative use although methods are developed to extract tannins from softwood bark for use as a raw material in resins used in wood products and other material applications. The residual fibre fraction can be used to produce sugar for fermentation products. The bark fraction of the stem is typically 5-7 %.

After debarking, the stems are cut into square or rectangular boards causing a production of residues in the form or slabs, sawdust, and shavings. Typically, the board yield is 45-50 % of the total volume for both conifers and broadleaves. The residues are well suited for products such as particleboards and pulp and part of this is recirculated into other uses while some of it is used for bioenergy. The amount of residues being recycled is unknown. However, under Danish conditions the consumption of particle boards is much smaller than of sawn boards making a large part of this resource available for biorefining or bioenergy with the current market situation.

The wood products are further processed in the building sector, furniture industry and elsewhere, leading to an additional production of residues. The fraction of the wood ending up in the final product is unknown and highly dependent on the processing industry. It is estimated that 10 % of the volume is lost in the final processing. Hence as an example, if 70 % of a final felling in Norway spruce is classified as timber and 50 % of this volume is cut into boards and assuming a final 10 % loss, 32 % of the original volume ends up in the final product. This demonstrates a vast potential for increasing the use of smaller fractions of the wood resource as well as the processing residues for the provision of materials in the green transition of the society.

6.1.3 Marine biomass

In all three future scenarios, marine biomass provides only a minor fraction of future biomass supplies. This can be explained by 1) the TRL of LTA is not comparable to the TRL of agriculture, 2) the area available for LTA is not, and will not be of a size and spatial dominance comparable to the 61 % of land area used for agriculture. However, expecting future development in TRL for cultivation technology to meet the challenges of offshore environments will allow LTA in wind farms and in the North Sea. Further, expanding the assumptions of 10 % of Wind Farm areas used for LTA to larger areas, could increase the contribution of marine biomass in future. Present national and EU strategies working towards a strong and sustainable EU algae sector, the EU Blue Growth strategy (European Commission, 2021) the EU Water Framework Directive (European Parliament and The Council of The European Union, 2000), as well as the Danish ambitions for the expansion of offshore wind production all favour a future scenario with potential of marine biomass production beyond the Extensifiation scenario (Maar et al, 2023).

6.2 How to support an increased supply of sustainable national biomass resources

The transformation from the fossil economy into a bioeconomy integrated with other means of renewable technologies is a major shift in technology focus. We do not start from scratch as bioeconomy and biorefining has a long tradition in agriculture, forestry, and the related industries (e.g. sugar, potato starch, dairy, fish, abattoirs, saw mills, and pulp and paper industry). However, a much higher throughput of biomass and the use of many new types of biomass as well as conversion technologies, will require significant research, development and investments in new industries to deliver the biobased raw materials for the material industry. Biomass is also expected to deliver bioenergy components to supplement the future renewable energy system, which in Denmark will be mainly based on wind and solar power but will require balancing input from imports of power and from local bioenergy resources. The biomass used for bioenergy in such a cascading process will deliver biogenic CO_2 for PtX and/or for Carbon Capture and Storage.

The Danish energy system has been transformed during a 40-50 year period with a long-term strategy supported by several action plans (e.g., Dansk Energipolitik 1976, Energi 2000, Energi 21, Energiaftale 2018, and Denmark's Integrated National Energy and Climate Plan 2019). By 2020, 40 % of total energy use in Denmark was based on renewable resources, and the use of biomass covered 56 % of the renewable share (Energistyrelsen, 2021). Over the last years, development of new energy islands to produce more renewable power has been agreed on, and investments of approx. 210 billion DKK are expected for the first of them (Regeringen et al., 2021a; https://kefm.dk/aktuelt/nyheder/2021/sep/politisk-aftale-bringer-energioeen-i-nordsoeen-taettere-paa-realisering). The large unbalanced power production from wind and solar from e.g. these energy islands are expected to be used to produce liquid fuels (PtX), and recent political agreements will support PtX development by at least 1.25 billion DKK (Regeringen et al., 2022). The co-existence of Low Trophic Aquaculture of mussels and seaweed and fossil free energy production within future off-shore windfarms will allow for increased marine biomass production while at the same time mitigation eutrophication, and leaving other marine areas for Marine Protected Areas (Maar et al, 2023).

Denmark has, as one of few EU nations, not yet produced a national bioeconomy strategy to support the EU strategies (European Commission, 2018). Instead, a National Bioeconomy Panel has been established that recently produced recommendations on the selected value streams "Future Protein Sources" (The Danish Bioeconomy Panel, 2018), "Biopolymers" (The Danish Bioeconomy Panel, 2019), and latest on the available biomass resources (The Danish Bioeconomy Panel, 2022).

The recent Parliament agreement on Green Transition of agriculture has reserved 396 M DKK for the development and implementation of pyrolysis technologies and 260 M DKK for green biorefining technologies (Regeringen et al., 2021b). These are very positive first steps in the transformation of the bioeconomic sector. However, it is conspicuous that this recent investment in the development of the bioeconomy is considerably smaller than the above-mentioned investment agreed on for the further development of the renewable energy sector.

The long journey on transforming our energy system to become renewable and zero emission seems to be more or less on track to succeed by 2050 and reach milestones by 2030. On the other hand, the just as big transformation and development of the bioeconomic sector has been given less focus and less funding to reach zero emission targets for agriculture, forestry, aquaculture, and the related industries (including those today relying on fossil input for material production). Thus, there is a strong need for well-prepared strategies with clear milestones, and description of the needed support mechanisms from research & development and from public-private investments.

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About DCA

DCA - Danish Centre for Food and Agriculture is the entrance to research in food and agriculture at Aarhus University (AU).

The Centre comprises AU departments with food and agricultural science activities. These are primarily Department of Agroecology, Department of Animal Science, Department of Food Science, Centre for Quantitative Genetics and Genomics, and parts of Department of Engineering.

DCA has a Centre Unit, which supports and coordinates DCA activities in relation to research based policy support, industrial and sector collaboration, international collaboration, and communication.

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SUMMARY

This report presents scenarios for future (2030) land-use in agriculture & forestry, and for exploitation of marine resources. The newest knowledge on resource efficient production methods (e.g., maximal carbon capture by photosynthesis & efficient nutrient use) have been used to frame the three scenarios: **Business-as-usual** mimicking a continuation of the current conditions for production of biomass. **Biomass** assuming sustainable intensification of the production. **Extensification** taking into account significant environment, climate and nature concerns. For agriculture, also the effects of +/- 20 % animal production are analysed. The scenarios resulted in increased biomass delivery of up to 13 M tonnes of dry matter for agriculture. No significant increase was found in forestry delivery by 2030 due to the sectors' long production cycles. Marine biomass contributed up to 58 ktonnes of dry matter. Integrated biorefinery systems were set up for analysing cascade utilization of the biomass and budget economics are discussed. The scenarios have large impacts on the land-use with up to 11 % of the farmed area set aside for nature purposes in **Extensification**, and with significant reductions in greenhouse gas emissions and nitrate leaching in all scenarios.