MSc Thesis

The economics of broad bean and dairy production with carbon emissions: A case study for high-latitude agriculture.

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Abstract

Cattle farming is widely considered to be the most profitable use for Finnish agricultural lands with poor growing conditions. But dairy farming inflicts heavy pressure on the environment by leading to eutrophication, land degradation, water deficiencies, and global warming. Literature provides various potential environmental, ecological, and economic incentives to cultivate broad beans. Broad beans can be used as the main protein source for feed, are resilient to a wide variety of environmental circumstances, and the broad bean is relatively easy to process into a meat substitute. The Kontu breed is specifically suitable for the high-latitude agriculture of Finland. Land-use optimization models were used to derive results on the optimal choice between broad bean and dairy production. The private profit of broad beans exceeded the private profit of dairy in a scenario with an average number cows of 0.5 per hectare. By including environmental externalities in terms of global warming potential (GWP), the break-even prices of carbon for both land-use practices were calculated. The break-even price of carbon on a broad bean pasture *(€1070.92)* is well above the carbon prices discussed in the literature, while dairy farming yields a break-even carbon price of *€89.46*. Thus, broad beans are, based on the data used in this research, a viable way of land-use compared to dairy farming in Finland. Including environmental externalities increased the favorability of broad beans even more.

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1. Introduction

The Finnish, high-latitude, agriculture is known for the fact that crop cultivation is rather challenging and subsequently leaves lower yields than comparable pastures in lower latitudes (Peltonen-Sainio, Jauhiainen & Sorvali, 2017; Peltonen-Sainio *et al.,* 2019). Cattle farming is therefore considered to be the most profitable use for Finnish agricultural lands with poor growing conditions (Lehikoinen *et al.,* 2019). But, as widely assessed, cattle breeding and dairy farming are processes that inflict heavy pressure on the environment (Maranon *et al.,* 2011; Reynold, Crompton & Mills, 2011). Besides, in line with the European 'Green Deal', Finland has to find a way to decrease the negative impact of her agriculture.

Literature provides various potential environmental, ecological, and economic incentives to cultivate broad bean (or among others, fava bean, faba bean, horse bean, and English bean) in Finland and other Northern-European countries (Köpke & Nemecek, 2010; Aho *et al.,* 2015). It is thus logical to explore the possibilities of large-scale production of broad beans in Finland, in order to meet 'Green Deal' goals.

In 2019, 16,000 hectares (ha) of arable land was used to produce 24.1 million kilograms of yield (Nieme & Väre, 2019). Finland has 2,246,000 ha of arable land (Macrotrends, 2020) and therefore only 0.7 percent of the arable land is used for broad bean *(Vicia faba L.)* production. About 7 percent of the total land area of Finland is allocated to agriculture (Keskusta, 2019; Byrne, 2019; Yle, 2019). The broad bean is a cultivar that has been around since 500 BC and has always been produced on a minor scale in Finland after it originated in the Middle-East (Stoddard *et al.,* 2009; GRDC, 2018). The production fluctuated heavily over the last decades but is considered an emerging crop again (Peltonen-Sainio & Jauhiainen, 2020). The production of broad beans has already increased substantially between 1996 and 2018 (from 58 ha to 16,000 ha) and is expected to increase further (Peltonen-Sainio & Jauhiainen, 2020). The main reasons for the production increase and potentials are set out in the following sub-chapter.

1.1. Broad bean production

First of all, broad beans can be used as the main protein source for feed. Currently, Finland still imports most of its protein sources for feed. The Finnish Ministry of Agriculture and Forestry states that an increase of broad bean production to 80,000 ha would make Finland independent from imported soy from Brazil (Keskusta, 2019; Byrne, 2019; Yle, 2019). The minister of Agriculture and Forestry, Jari Leppä, hopes to stop all imports of soybean before 2025 to set an important step towards achieving the goal of carbon neutrality in 2035 (Keskusta, 2019; Byrne, 2019; Yle, 2019).

The changing customer perspective towards meat and meat substitutes could be explained as second a possible driver for increasing the broad bean production in Finland (Tophealthingredients, 2020; Jallinoja, Niva & Latvala, 2016). The broad bean is relatively easy to process into a meat substitute because it has a high protein content (about 30 percent) and is rather easy to structure (Beanit, 2020; Askew, 2019). Structuring is the process in which the broad bean protein is processed in such a way that it feels similar to the meat type it is aimed to substitute. Broad bean is, therefore, already widely used as input in meat substitute production. An example is Verso Food. Verso Food is a Finnish company that produces various types of meat substitutes under the brand 'Härkis'. They, for example, produce a minced meat substitute (Versofood, 2018). New investors are constantly attracted by companies like Verso Food, showing the potential of the meat substitute sector and more specifically the use of the broad bean in the industry (Tziva *et al.,* 2020; Versofood, 2018).

Thirdly, broad beans are resilient to a wide variety of environmental circumstances, as the bean does relatively resilient to weather circumstances within a wide range. But, if the weather circumstances are too unfavorable (i.e. extreme frost), the bean could either die or reach maturity early, which both lower the yield substantially (Peltonen-Sainio & Niemi, 2012).

Lastly, increasing the broad bean production, especially when substituting meat production or imports of similar goods, could well contribute to the set environmental goals by the Finnish government and the European Union (Köpke & Nemecek, 2010; Keskusta, 2019; Byrne, 2019; Yle, 2019). Broad bean production contributes to a lower carbon footprint compared to agricultural products. Heusala *et al.* (2020) even show, by a life cycle assessment (LCA), that broad bean cultivation has roughly half the carbon footprint compared to cattle grazing, with a set amount of protein as the functional unit. The on-site positive environmental impacts of broad bean production have been known for a long time and Köpke & Nemecek (2010) described them in a structured and complete manner. Biological nitrogen fixation (BNF) is the main process that the broad bean provides. Nitrogen is one of the nutrients that is much needed for crops to grow and is therefore applied to the pasture before sowing as a fertilizer. The BNF property decreases, or totally eradicates, the need for N-fertilizer application to broad bean pastures (Köpke & Nemecek, 2010). In recent years, excessive nitrogen runoff, nitrogen seeping into the groundwater or other bodies, became a recognized and eminent problem in agriculture. Farmers were either incentivized or forced to tune down their appliance of fertilizer to their pastures. This decreases their yield, assumed that they did not find a way to be more efficient with the fertilizer (van Grinsven *et al.,* 2012). The BNF property of the broad bean can add about 76 to 125 kilograms of biologically fixed nitrogen per hectare to the soil (Merga, Egigu & Wakgari, 2019). In optimal conditions, a broad bean pasture can fix about 21.9 grams of nitrogen per square meter (Merga, Egigu & Wakgari, 2019; López-Bellido *et al.,* 2011). This added nitrogen both has a value by itself and even more in an intercropping system (Aho *et al.,* 2015; Köpke & Nemecek, 2010).

1.1.1. Broad bean production in Finland

The most used broad bean cultivar in Finland is the Kontu breed. The Kontu breed is specifically suitable for the high-latitude agriculture of Finland, as it only needs 102 to 107 days to mature (Stoddard & Hämäläinen, 2011; Skovbjerg *et al.,* 2020). Approximately 12 days shorter than the days to maturation of other cultivars, which is helpful in the Finnish short growing season. Considering that 80% of all the sown seeds in Finland are from the Kontu cultivar, the Kontu breed is assumed to be representative for Finnish broad bean production (Skovbjerg *et al.,* 2020). In the remainder of this thesis, the Kontu cultivar is conveyed when addressing broad beans.

To summarize, the demand for broad beans is expected to increase in the near future, due to more demand for meat substitutes and the need for a substitution for soy as the protein source in the feed (Jallinoja, Niva & Latvala, 2016). Besides, the positive impacts on the environment are known and add to the feasibility of cultivating broad beans on a larger scale in Finland (Köpke & Nemecek, 2010; Aho *et al.,* 2015; Keskusta, 2019).

1.2. Dairy farming in Finland

The other side of the assessment regards dairy farming in Finland. The current beef production is, in 85 percent of cases, a byproduct of dairy production. Thus, only 15 percent of the Finnish beef comes from a cow that is specifically bred to exclusively provide meat (Rinne & Vilkki, 2021).

Originally, cattle grazed while wandering in the woods, eating bark, moss, leaves, and other sources of nutrients and protein that humans were not able to digest properly (Cramp *et al.,* 2014). Over the years, the majority of the cattle translocated to pastures, and the animals are currently fed with grass and feed. Soy and wheat are the main components of the cattle feed. These crops must be cultivated on Finnish soils or imported from elsewhere (Nieme & Väre, 2019). Pasture grazing and the successive feed production to feed cattle is a quite inefficient use of the available Finnish land when compared to the ancient case. In other words, assuming that food production is the main goal of the agricultural sector, using the current grazing land as cultivation area would most probably be more efficient.

Besides, it is widely known that the meat and dairy industries are big pressures on the environment. Every thousand kilograms of Finnish beef produced requires 1700 kilograms of nitrogen, 189 kilograms of phosphorus, and 68300 liters of water, leading to eutrophication, land degradation, and water deficiencies (Joensuu *et al.,* 2019; Ridoutt *et al.,* 2012). Over the last 20 years, the number of dairy cows has heavily decreased and thereby also the beef production, due to more efficient practices and product imports (Mu *et al.,* 2018). More specifically, in the year 2000, there were 364,000 dairy cows and 20 years later it decreased to 262,000 cows in total (Pesonen, 2020).

1.3. Transition boundaries

As in other countries throughout the world, the Finnish government is looking for efficient measures to mitigate carbon emissions and other environmental impacts (Keskusta, 2019; Byrne, 2019; Yle, 2019). The simultaneous developments of increasing broad bean production in Finland and the decrease of conventional dairy and meat products could be a leap towards a higher share of environmentally friendly products in Finland.

Agricultural production generates multiple types of values for a private actor and society. One could think of monetary profits and losses, ecosystem services (Daily, 2003), and negative environmental externalities incurred by agricultural production. The core challenge of comparative assessments is to be complete but concise in terms of the inclusion of relevant parameters. The second challenge is to include parameters that allow a fair comparison between both production processes (Laser *et al.,* 2009). Through optimization models, which will be explained in sub-chapter 2.2., the land-use tradeoffs can be identified and compared. After, the hypothetical implementation of payments for emissions could be assessed with the optimization model as well.

1.4. Research questions

The research question that can be distilled from the sections above is:

"Is broad bean production a viable way of using land compared to dairy farming in Finland, considering private and societal costs and benefits?"

To answer this research question, the proper parameters constructing the private and societal costs and benefits need to be identified. Thereafter, they need to be modeled properly.

1. Which parameters construct the private profit acquirable by a Finnish broad bean farmer?
    a. Which parameters construct the private benefits of a Finnish broad bean farmer and how do they relate to each other?
    b. Which parameters construct the private costs of a Finnish broad bean farmer and how do they relate to each other?
    c. What are the quantifications of these parameters?
2. Which parameters construct the private profit acquirable by a Finnish dairy farmer?
    a. Which parameters construct the private benefits of a Finnish dairy farmer and how do they relate to each other?
    b. Which parameters construct the private costs of a Finnish dairy farmer and how do they relate to each other?
    c. What are the quantifications of these parameters?
3. Which parameters construct the benefit and damage functions incurred by broad bean production and dairy farming?
    a. How can societal benefit and damage functions of broad bean production and dairy production be compared fairly?
    b. Which parameters construct the benefit and damage functions and how do they relate to each other?
    c. What are the quantifications of these parameters?
4. How can these functions be modeled properly?

5. What would be the impact of a hypothetical implementation of emission pricing on both broad bean farming and dairy farming?
    a. What is the reasonable way to compare emissions between broad bean farming and dairy farming?
    b. Which impact category should be used?
    c. Which hypothetical emissions prices are reasonable?

The remainder of this research is build up as follows. First, the case study area will be identified and the use of optimization models will be elaborated upon. Secondly, the iterative process of building optimization models will be explained and set out. Thirdly, the relevant parameters, their relations, and substantiated quantification are touched upon. After that, the models will be run and outcomes interpreted, logically flowing into the results and discussion sections.

2. Materials & Methods

2.1. The case study area

Although the study area is not strictly bounded to any region within Finland. The province of North Karelia is the best fit. With Joensuu as its biggest city (around 76,000 inhabitants), North Karelia is rather remote. Agriculture accounts for 22% of the region's CO_2 emissions, which is above the Finnish average (Interreg Europe, 2020). North Karelia has the highest proportion of agricultural land attributed to organic farming of all provinces (Nieme & Väre, 2019). The region is still identified as traditional in terms of its food culture. More than 67 percent of the revenues in North Karelia come from dairy farming (in 2014). Besides, the summers are relatively short, leaving a short grazing period for cattle and growing season for broad beans (Rizzo, 2017). The combination of the dependency on cattle farming and the tendency towards organic farming is interesting for exploring the possibility to increase broad bean production in this region. As stated in the introduction, 85 percent of beef production is a byproduct of dairy farming (Nieme & Väre, 2019; Rinne & Vilkki, 2021). It is assumed that this is the same for North Karelia because there is no specific data available on this ratio available in the literature. North Karelia has a population of roughly 161,000 inhabitants and roughly 70 percent of the province is covered by forests (Interreg Europe, 2020). Figure 1 shows the location of North Karelia within Finland.

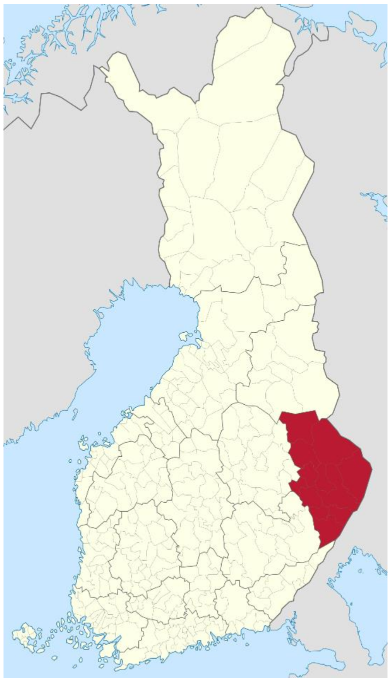

Figure 1. North Karelia's location within Finland (in red). Source: Finland administrative divisions.

2.2. The use of optimization models

In decision making, more specifically regarding agricultural land use, the use of optimization models supports substantiated decision making (Al-Maktoum, 2019; Shaimardanovich & Rustamovich, 2018; Kaim, Cord & Volk, 2018). Mathematical programming provides general solutions to rather complex optimization problems. Optimal profits are found by this model, considering benefits, costs, inputs, and outputs of different products and one or more constraints. In generic terms, mathematical optimization models have a goal, say maximizing function F, by producing a certain amount of x, subject to a constraint. Minimizing a value could also be an objective, for example, cost minimization. The general form is written underneath, assuming that all functions are linear. Note that the functions do not specifically have to be linear.

Maximize (or minimize)	$F(x) = p * x$	(1)
Subject to	$A * x \leq q$	(2)
Subject to	$x \geq 0$	(3)

Where *q* is the available amount of resources needed for the production of *x* and *p* is the market price of one unit of *x*. *A* is a constant and shows how much needs to be extracted from source *q* for the production of one unit of *x*. Equation (3) shows that the production of *x* cannot be negative.

The conditions for mathematical optimization problems can be shaped in various ways. The equations can consist of many more parameters and functions and thus represent more complex optimization questions. The eventual goal for the decision-making unit (DMU) and policymakers is to maximize the private and/or social profit function. Thus maximizing the total value acquirable from an initial set of resources.

2.3. The methodological path

The approach used in this research incorporates different, but connected steps. The steps can roughly be divided into the following:

- The identification of parameters relevant to the profit function of the farmer for both broad bean production and dairy farming. When considering the profit function of a farmer, there are various aspects to consider. It is important to set boundaries for both the production of broad beans and dairy farming to guarantee a fair comparison between both. Researches with similar methods and themes will be used to identify fitting parameters (Kulshretshtha *et al.,* 2016; Juutinen *et al.,* 2020; Peltonen-Sainio *et al.,* 2019). The private optimization method relies on the assumption that the decision-making unit's utility, in this case, the farmer, only consists of monetary parameters. The assumption is thus, that the farmer solely decides based on acquirable profit.

- <u>The identification of parameters relevant to the benefit and damage function of society.</u> As stated in the introduction, the value for society depicts the private value and the value of externalities of private production. It is important to understand which externalities should be included in the benefit and damage function of society. Again, it is key to accommodate a fair comparison between broad bean production and dairy production. Typically, various types of emissions to air, soil, and water are included as a damage function and ecosystem services as a benefit function in agricultural optimization models (Arjomandi *et al.,* 2021; Kulshretshtha *et al.,* 2016; Juutinen *et al.,* 2020; Kaim, Cord & Volk, 2018; Heusala *et al.,* 2020).

- <u>Quantification of the identified parameters.</u> The various parameters need to be quantified. Parameter values could for example rely on a lot of uncertainty or are simply unknown. When the values are unknown, an estimation could be modeled or the overall use of the parameter should be reconsidered. The development and data of Finnish agriculture are documented yearly and in some cases even monthly, which could be used as a viable source for parameter values regarding crop production and milk production (Nieme & Väre, 2019). Besides, researches that either assessed broad bean production and/or dairy farming could be used as a source (Singh *et al.,* 2013; Ward & McKague, 2019; Šarauski *et al.,* 2020; Kulshretshtha *et al.,* 2016). Heusala *et al.* (2020) recently published an LCA on broad bean production in Finland. This assessment can be of great value to this assessment as it shows the carbon footprint of broad bean production.

- <u>Choosing the appropriate optimization model for the optimization problem.</u> After the various parameters are identified, and they can be quantified with a sufficient level of confidence, the search for a fitting optimization model can be initiated. Again, the techniques used in papers with similar objectives can be used as an example. The choice regarding the optimization model depends on the (non-)linearity of the parameter. In addition, the relationship between parameters is also important to consider. A relatively simple model is anticipated, as the parameters in an agricultural production function are not hypothesized to be complex.

- Modeling the optimization problem in MATLAB. MATLAB houses very dedicated modeling software that happens to contain solvers for optimization problems. MATLAB is more than powerful enough to run linear and non-linear optimization models with multiple inputs, constraints, and objectives. Many test runs should be done while improving the model simultaneously. It is important to start with a simple, deterministic model and increase the complexity over time.

- Run the optimization model in MATLAB.

- Assessment of the outcomes of the model. MATLAB has versatile and dedicated plotting software that could well be used to create figures that are the source for interpretation of the outcomes of the assessment. These outcomes are then deducted into valuable conclusions for private actors and policymakers.

3. Data inputs and results

As discussed, constructing and running an optimization model consists of various interdependent steps. Namely, the parameter identification, quantification, and modeling of them. Besides splitting the research steps, the optimization steps should also be divided. In other words, it is convenient to first identify a private optimum without any constraints or externalities involved in the model and add benefit and damage functions subsequently to form a societal optimization problem. There are two main reasons to work in this particular way. Namely, to keep a clear overview of what the intermediate models resolve and the comprehensibility of the reporting. First, a deterministic model will be built to depict both the private and social optimum. After, uncertainty can be partly accounted for by picking parameter values from substantiated distributions, leading to a more stochastic optimization model. By executing a Monte Carlo analysis, the outcomes show the distribution of the optimum constructed from a set number of runs.

The functional unit used in this comparative study between broad bean production and dairy farming is one hectare of Finnish agricultural land. This functional unit is chosen because literature, commonly, provides agronomical data on grams per square meter for production and inputs, and kilogram or profit per hectare for outputs. There are no obstacles foreseen in normalizing the broad bean, nor dairy data to the functional unit. The data could be specified to a particular farm by multiplying the outcomes of the analysis by the number of hectares owned by the farmer. Note that economies of scale are outside of the scope of this assessment and are not accounted for. The parameters included in the models are elucidated in the following chapters.

When assessing agricultural production, one could argue that the benefits and costs are non-evenly accrued over the year and there are months with higher profits than others. Due to the trade-off between a small increase of credibility and substantial time investments, this thesis will not account for the spreading of profits over the year but will assume pay-offs at the end of every accounting year.

An assumption that needs clarification, is the choice to set the land division as the decision variable. Meaning that the functional unit can be seen as a divisible pasture, wherein every fragment can be allocated to either broad bean production or dairy farming. This does not essentially mean that a pasture should be allocated marginally, but the model allows a non-binary choice variable. This model property could be of use when, for example, a constraint enters the model. The allocation variable will be depicted throughout this assessment as x, where the allocation to broad bean production is characterized by x_1 and to dairy farming by x_2. Logically, the total allocation should be equal to one, as no land should lie fallow when optimizing a yearly profit. As can be seen in equation (4). All the code used to run the assessments will be available in the Appendices.

Land allocation: $$x_1 + x_2 = 1 \quad (4)$$

3.1. Private optimization model

For this comparative study, the private profit of broad bean production and dairy farming is the first equation that needs to be filled with parameters. A private optimum consists of the monetary benefits and costs that the decision-maker faces (Perman *et al.,* 2003. P.5). For inputs, one could think of seed, feed, water, fertilizer, herbicide, electricity, fuel, and other operating costs. The yield, the market price for the product, and subsidies construct the total benefits. The total profit, rationally, is the total costs subtracted from the total benefits. Considering that the allocation of land is the choice variable, the total profit of a farmer for one hectare of pasture looks as follows:

Total profit per ha: $$\Pi = x_1 * (b_1 - c_1) + x_2 * (b_2 - c_2) \quad (5)$$

Where Π depicts the total profit for the farmer per hectare, b_1 and b_2 the profit from bean production and dairy farming per hectare respectively, and c_1 and c_2 the costs.

3.1.1. Broad bean production parameters

This sub-chapter will address the substantiation of the parameters constructing the benefits (b_1) and costs (c_1) of broad bean production for a Finnish farmer. An assumption made here, as explained earlier, is that the Kontu cultivar is assumed to be the cultivar used because it requires the shortest growing season and is therefore sown the most in Finland's high latitude agriculture (Stoddard & Hämäläinen, 2011; Skovbjerg *et al.,* 2020).

A combination of academic resources is utilized to find relevant parameters and their values. Predominantly '*An evaluation of yield (stability) and protein content in several commercial cultivars*' by Skovbjerg *et al.,* (2020) and '*a protein crop production in high-latitude agriculture* *overview'* by Peltonen-Sainio & Niemi (2012) are used. The common method applied in the search for mean values and probable distributions is displayed by the decision tree in Figure 2. There is no extensive historical data available on the development of broad bean (producer) prices, thus no econometric methods could be handled to forecast future prices.

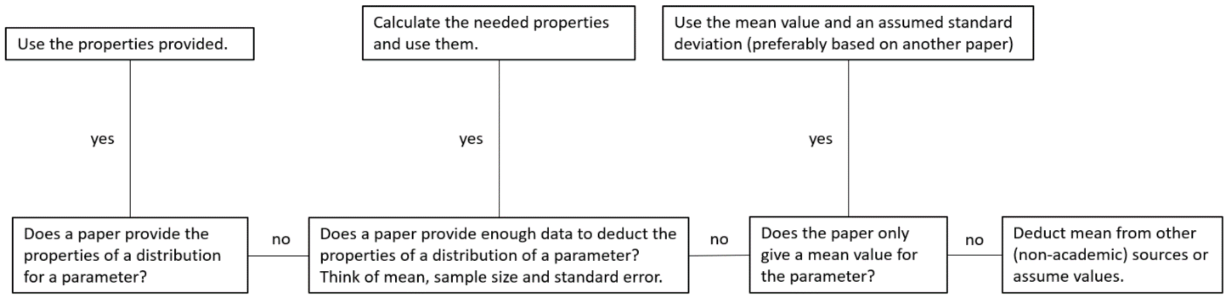

Figure 2. Search guide for distribution parameters.

Thorough literature research led to an extensive construct of the benefits and costs of broad bean production. Table 1 shows the relevant parameters, their values, and distribution properties. The mathematical notations can be found directly after the parameter name in the first column. Nitrogen fixation seemed relevant enough to add to the private broad bean benefits, as it increases the value of the land, especially in an intercropping system, by lowering the needed fertilizer application for a subsequent crop used on the pasture, and could therefore be explained as a direct private benefit of broad bean production (Aho *et al.,* 2015). It should, because it is already added as a private benefit, not be included in a societal benefit function again, as it would lead to double counting.

Table 1. Parameters private profit broad bean production.

Parameter	Unit	Mean	SD	Source	Notes
Yield [y_1]	kg/ha	3090	216	(Skovbjerg *et al.,* 2020; Peltonen-Sainio & Niemi, 2012)	The standard deviation (SD) is 7% of the mean, based on panel-data by Peltonen-Sainio & Niemi (2012).
Price [p_1]	€/kg	0.23	0.0161		
Subsidy [sub_1]	€/ha	594	_	(Peltonen-Sainio & Niemi, 2012)	Fixed amount per hectare.
Seed costs [sc_1]	€/ha	135	6.75		Not clearly specified for Kontu bean per se.
Fertilizer costs [fc_1]	€/ha	84	11.76		Heavily dependent on the type of farmer and soil quality.
Herbicide costs [hc_1]	€/ha	69	4.83		_
Nitrogen fixation [nf_1]	€/kg	0.00833		(Aho *et al.,* 2015)	The change in land value has been calculated based on the broad bean's ability to fix nitrogen from the air into the soil (~25 kg/ha of the nitrogen is retained in the soil).

For the sake of completeness and keeping track of the core thread. The intermediate construction of b_1 and c_1 is shown in equations (6) and (7).

Benefit broad bean production per ha: $$b_1 = y_1 * (p_1 + nf_1) + sub_1 \quad (6)$$

Costs broad bean production per ha: $$c_1 = sc_1 + fc_1 + hc_1 \quad (7)$$

3.1.2. Dairy farming parameters

This sub-chapter addresses the substantiation of the parameters constructing the benefits (b_2) and costs (c_2) of dairy farming for a Finnish farmer. The Holstein Friesian cattle breed is considered because it is one of the breeds that gives the most milk but also provides a certain quality of meat (Coffey, Hickey & Brotherstone, 2006). Besides, the breed is widely used in Finnish agriculture already and there is accordingly enough data available (Nieme & Väre, 2019).

An important distinction that became apparent while assessing dairy data is that there are two types of conventional outputs from a cow. Namely, the milk supplied throughout the lactation period and the meat retrieved by slaughtering. Based on this property, another assumption had to be made. Every hypothetical hectare houses a cow that gives milk throughout her lactation period and is sold to the abattoir at the end of the year. In the bigger picture, the assumption means that the farmer buys exactly as many new cows as have been sent to the abattoir that year. The farmer thereby has an equal amount of cows in every age group. It is apparent that this does not represent a real-world farm, but on average, the benefits per hectare per year are equal. Averaging the benefits leaves a simpler model that can be assessed easier without compromising its core purpose.

Similar to the broad bean production parameters, Figure 2 is used as a guideline for finding relevant parameters and their values and/or distribution properties. Contradictory to the broad bean producer prices, there is a sufficient amount of historical data on both milk and meat prices. Monthly Finnish raw milk prices have been structurally reported since January 1995 (MMO, 2020) and monthly beef prices since January 2007 (NRIF_a, 2020). Reliable time series data like this can be used in econometric analyses that are able to forecast future prices with a reasonable amount of certainty. Assuming that commodity prices are mean-reverting (Andersson, 2007), a Hull-White/Vasicek Gaussian Diffusion model can be used to forecast the commodity prices over 12 months (Hull, 1993). MATLAB documents the forecasted outcomes of the Monte Carlo run and allows extraction of a normal distribution with mean and standard deviation from it. A million runs are assumed competent, as test outcomes did not differ observably.

The substantiation of the beef yield per cow needs some explanation. The natural resources institute of Finland (LUKE or NRIF) (2020_b) provides data on the monthly slaughterings (in heads) and the amount of meat production from dairy cows specifically (in kg). Dividing the amount of meat production by the number of slaughterings gives the average beef weight of one dairy cow. As there seems to be an upward trend over time, stagnating around January 2016, only the data inputs after that moment are used in constructing a histogram and distribution fit (NRIF, 2020_b). The structural increase in the years before 2016 could be attributed to increased feed conversion efficiency or other agronomic efficiencies that led to higher beef outputs (Hietala & Juga, 2017).

The sources for a well-substantiated cost price for milk cows were rather limited, especially in the case of Finland. The operating costs per unit of milk are substantiated in the following way, assuming that the beef is merely a side product, which is reasonable for the Holstein Friesian breed (Coffey, Hickey & Brotherstone, 2006): The European Commission released a brief on the EU milk margin index estimates up to 2019 (EC, 2020). Wherein the trend of the operating costs for milk production from 2008 up until 2019 is given. Their source is *‘DG AGRI (EU FADN), Model of allocation of costs for milk, Information from market units, and ESTAT price indexes’*. There is no quantification of operating costs present, merely indexes with 2008 as a base year. Additionally, Gołaś (2017) does provide a quantification of the operating costs per unit of milk for Finnish dairy farmers, based on the same data sources as the brief by the European Commission (EC, 2020). By combining the quantified data point of 2013 and the indexes for the years before and after, a value for the operating costs over the timeframe of 2008-2019 can be conducted. Some cost items need to be left out, to leave a fair comparison between broad bean production and raw milk production. For broad bean production, the gross margin of a hectare was calculated and the same thing should be done for dairy farming. For that reason, depreciation and the cost of external factors should not be included in the cost picture as inclusion would leave a net margin instead of a gross margin. Besides, land rents should also be excluded as land is the fixed unit of this assessment.

Based on the findings by Hemme, Uddin & Ndambi (2014), it is assumed that the operating costs are dependent on the yield. In general, higher operating costs led to a higher raw milk yield (Hemme, Uddin & Ndambi, 2014 p.267). Therefore, it is justifiable to multiply the operating costs per kilogram by the yield per kilogram and assume that this value depicts the actual costs that are incurred by the production of raw milk. Note that economies of scale are ignored. This is different from the broad bean case, where the costs were assumed to be the same for every hectare, regardless of the yields.

The parameters and their values relevant for dairy farming are displayed in Table 2. The mathematical notations can be found directly after the parameter name. The parameter 'density' depicts how many cows are housed on a hectare. The total outcome is logically most sensitive to the livestock density (or stocking density) as it is multiplied by the benefits and costs of a cow. Therefore, a distribution of the density parameter is considered to create an overly volatile outcome for the profit per hectare for dairy farming. Creating scenarios and comparing those separately with the broad bean case captures the comparison goal of this assessment better. The scenarios adopted look as follows:

- The current livestock density in Finland (Scenario 1); *0.5*
- The average livestock density in Europe (Scenario 2); *0.8*
- The maximum livestock density in Europe (Scenario 3).; *3.8*

Although the data is from 2016, it has been published in 2019 by Eurostat (Eurostat, 2019). All scenarios are based on this 2016 data, as more recent data is often incomplete. The Livestock

Unit (LSU) density per hectare in Finland lies well below the EU average and the Netherlands top of the EU in terms of density. One dairy cow is the equivalent of one LSU (Upton, 1993).

Table 2. Parameters private profit Dairy farming.

Parameter	Unit	Mean	SD	Source	Notes
Milk Yield [ym_2]	kg/cow	8650	125.31	(Nieme & Väre, 2019; Virtanen & Nousiainen, 2005)	Nieme & Väre (2019) do not give a standard deviation for this mean. However, Virtanen & Nousiainen (2005), acquired similar panel data. This relative standard deviation is assumed to be transferable to the data from 2019. It is assumed that every kg of milk is energy corrected (ECM).
Price Milk [pm_2]	€/kg	0.3872	0.0207	(MMO, 2020)	Retrieved from Monte Carlo (million runs) of Hull-White/Vasicek Gaussian Diffusion model.
Beef Yield [yb_2]	kg/cow	290.3979	7.1885	(NRIF$_b$, 2020)	Based on monthly data from January 2016 onwards.
Price Beef [pb_2]	€/kg	2.5856	0.0480	(NRIF$_a$, 2020)	Retrieved from Monte Carlo (million runs) of Hull-White/Vasicek Gaussian Diffusion model.
Operating Costs [oc_2]	€/kg	0.3756	0.01257	(Gołaś, 2017; EC, 2020)	–
Density s=1 [$d_2(1)$]	cows/ha	0.5	–	(Eurostat, 2019)	Although the data is from 2016, it has been published in 2019 by Eurostat. All scenarios are based on this 2016 data, as more recent data is often incomplete. The LSU per hectare in Finland lies well below the average and the Netherlands top the EU in terms of density.
Density s=2 [$d_2(2)$]	cows/ha	0.8	–		
Density s=3 [$d_2(3)$]	cows/ha	3.8	–		

The intermediate constructions of b2 and c2 are shown in equations (8) and (9). As displayed in Table 2, s ranges from 1 to 3 and depicts the different density scenarios.

Benefits of dairy farming per ha: $$b_2(s) = d_2(s) * (ym_2 * pm_2 + yb_2 * pb_2) \quad (8)$$

Costs of dairy farming per ha: $$c_2(s) = d_2(s) * ym_2 * oc_2 \quad (9)$$

3.1.3. Deterministic private optimization model results

As the deterministic private optimization model uses the mean values of the distribution as a fixed parameter and has no additional constraints, the outcomes of the optimization model are straightforward. As expected, the land allocation choice is binary in the given density scenarios. An extra scenario is added, wherein the profits acquirable from broad bean production and dairy farming are equal. In other words, a density that leaves an indifferent decision for the decision-maker. The model outcomes are displayed in Table 3. The used code (for scenario 1) is displayed in Appendix A. The density parameter is the only aspect differentiating the codes of the scenarios.

Table 3. Outcomes deterministic private optimization model.

Scenario	X_1	X_2	Profit/ha broad bean (€)	Profit/ha dairy farming (€)	Total profit (€)
Density = 0.5	1	0	1042.30	425.96	1042.30
Density = 0.8	1	0	1042.30	681.47	1042.30
Density = 3.8	0	1	1042.30	3237.20	3237.20
Density = ~1.224572	$0 \leq x_1 \leq 1$	$0 \leq x_2 \leq 1$	1042.30	1042.30	1042.30

As shown in Table 3, the fixed private profit per hectare for broad bean production lays around €1040 per year. The yearly private profit margin per cow (density = 1) is approximately €852. At an LSU density of approximately 1.224572, the yearly profits per hectare are equal. This process of increasing the density to find an indifferent situation is visualized in Figure 3.

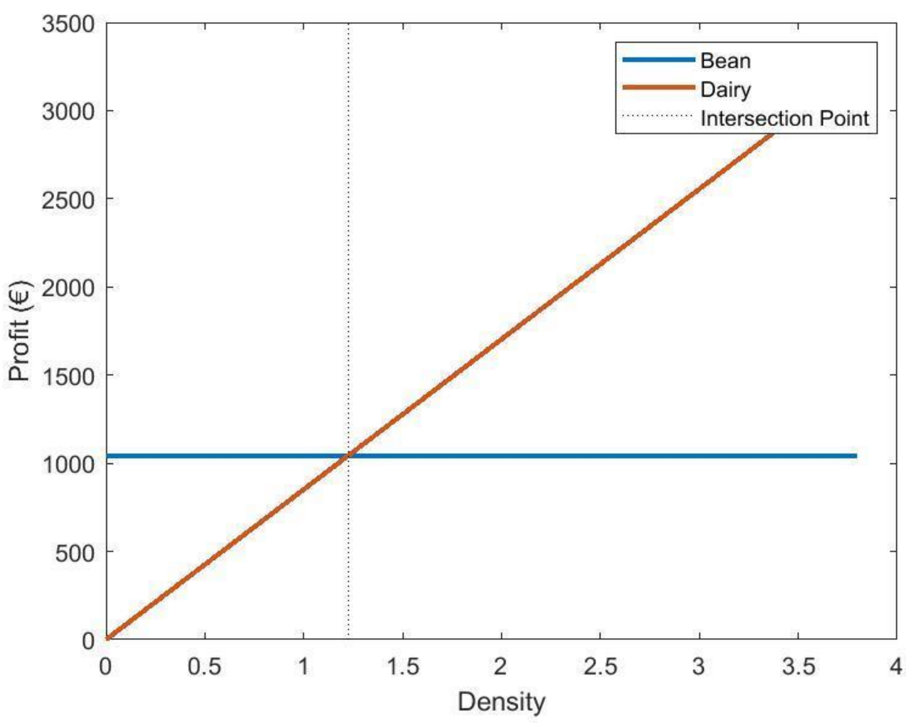

Figure 3. Profits per LSU density. MATLAB output.

3.1.4. Stochastic private optimization model results

With the goal to increase the credibility of the assessment, a stochastic optimization model is employed. By picking random values from the provided distributions, for every run (Table 1 & Table 2) and running the optimization model with them, the outcomes will differ every run. The number of runs is set to 100,000 as more runs would drastically increase the running time, but not increase the specificity of the model substantially. Mathematically, it looks as follows:

Private profit of run *i* for scenario *s*:

$$\Pi\ (i,s) = \ x_1\ (i) * \left(b_1(i) - c_1(i)\right) + x_2(i) * (b_2(i,s) - c_2(i,s)) \qquad (10)$$

Table 4 shows the average land allocation over all the runs, the distribution of the private profit over all the runs, and the private profit of the first and 99th percentile. The code for scenario 1 can be found in Appendix B. Where, again, only the density parameter differentiates the code for different scenarios.

Table 4. Outcomes stochastic private optimization model (Number of runs = 100,000).

Scenario	X_1 (average)	X_2 (average)	Mean (profit €/ha)	Standard deviation (profit €/ha)	1st percentile (profit €/ha)	99th percentile (profit €/ha)
(1) Density = 0.5	1	0	1042.70	73.12	878.87	1219.90
(2) Density = 0.8	0.9746	0.0254	1044.00	72.57	882.76	1220.00
(3) Density = 3.8	0.0034	0.9966	3240.00	803.07	1379.70	5111.90
(4) Density = 1.224572	0.4973	0.5027	Around this density, a normal distribution is not a sufficient fit. A Burr XII seems to fit better to the data. The distribution properties look as follows: **Scale *(alpha)*** = 1023.72 **First shape *(c)*** = 27.35 **Second shape *(k)*** = 0.2988		913.40	1646.66

The distribution outcomes are close to the expectations because there is no constraint and the first three scenarios are not close to the *'indifferent density'*. Besides, all parameter values are either fixed or drawn from a normal distribution, leading to a normal distribution for the outcome value too. This is only true in cases where the land is allocated close to binary. The distribution of the private profit will lose its normal distribution fit when the land is not fully allocated to either bean production or dairy farming. In other words, when the density is close to the '*indifferent* *density'*, the distribution of the private profit is not normally distributed. Subsequently, a Burr XII distribution fits better to the private profit outcomes of the fourth scenario.

As can be observed in Table 4, Figure 4, and Figure 5, the mean profit of scenario 1 and scenario 2 are (almost) equal. Another notable observation is that the distribution of the broad bean profits is denser and has a low relative standard deviation (7%) compared to dairy farming (24.8%), meaning that the outcomes are less uncertain. This is caused by the higher relative standard deviations in the parameters, more specifically the milk yield (ym_2) and the beef yield (yb_2). Further, the profit distribution of scenario 4 is skewed to the right, due to the relative standard deviation differences between broad bean and dairy profits. The MATLAB code for the figures can be found in Appendix C.

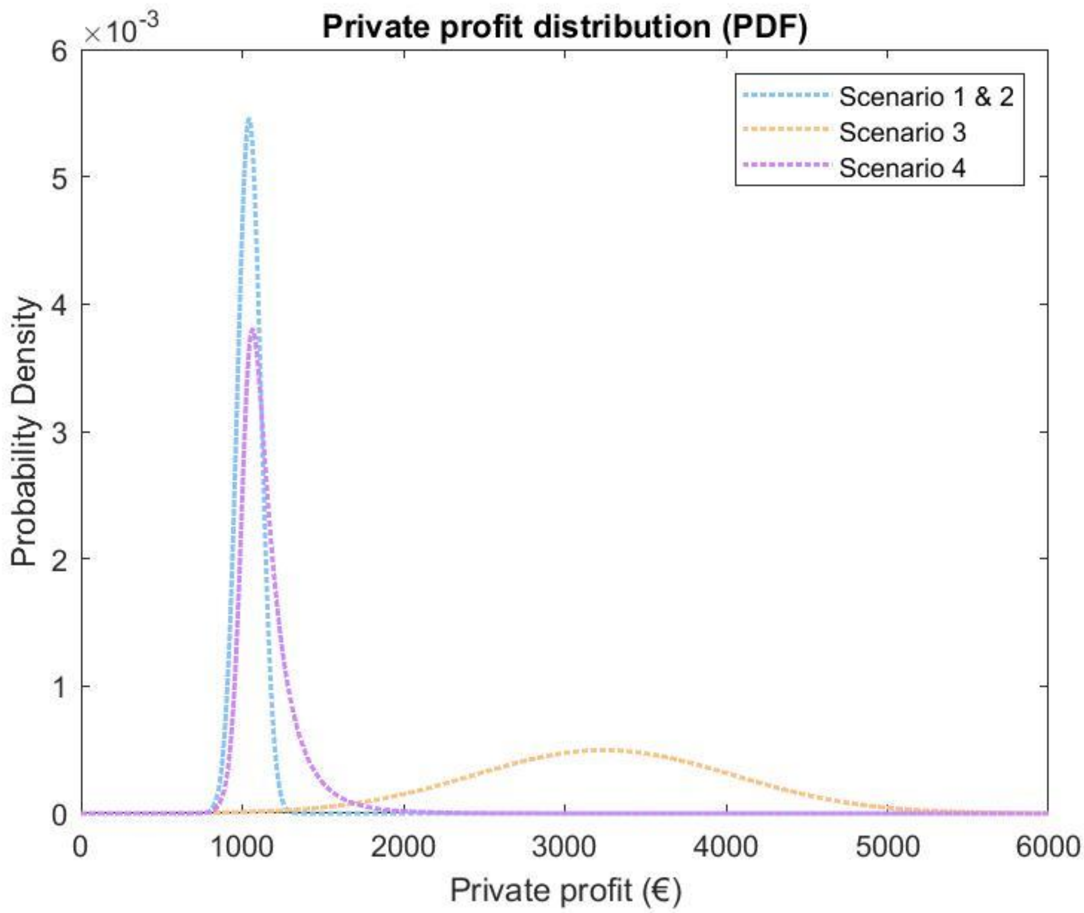

Figure 4. Private profit distribution (PDF) over 100,000 runs. MATLAB output.

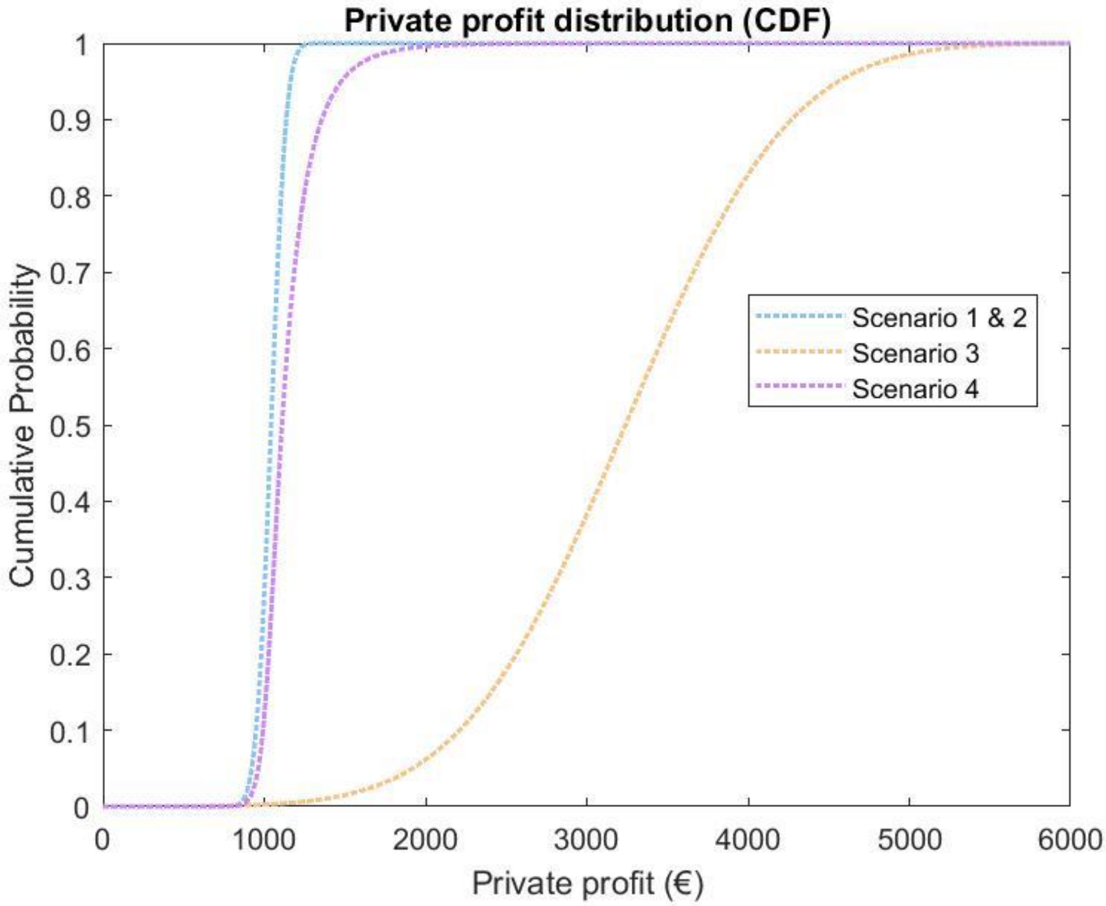

Figure 5. Private profit distribution (CDF) over 100,000 runs. MATLAB output.

3.2. Social optimization model

Moving from a private optimization model (chapter 3.1) towards a social optimization model, various externalities could be included. Externalities can be explained as follows: An externality is a positive or negative effect incurred by producing a good, that is not capitalized on or paid for by the producer of the good (Ayres & Kneese, 1969). The emission of environmental loads is considered to be an obvious externality of agricultural production that is not paid for by the producer or farmer (Pretty *et al.,* 2001). The inclusion of externalities in private optimization models shows the value of production to society, consisting of three major points of interest. First, private profit is seen as a positive value for society. Secondly, the emission of environmental loads can roughly be calculated in monetary terms and could therefore be treated as a monetary cost for society (Vogtländer, Brezet & Hendriks, 2001). Lastly, ecosystem services can be considered as a positive value for society (Daily, 2003).

Environmental externalities are hypothesized to increase the favorability for broad beans, as dairy farming is known for its negative impact on the environment and thereby leaving society with substantial and currently non-internalized costs (Capper, Cady & Bauman, 2009). Subsequent, broad bean production is considered to have minimal negative impacts on the environment and even provide some ecosystem services, like the aforementioned biological nitrogen fixation (Aho *et al.,* 2015; Köpke & Nemecek, 2010).

A conventional way to compare both production opportunities is by comparing their '*Global warming potential'* (GWP). GWP is evaluated in terms of CO_2 -equivalents, where emissions are converted to their CO_2 equivalents through a conversion table (Rao & Riahi, 2006). This conversion table is also called the Kyoto basket. The basket encompasses CO_2, CH_4, N_2O, the F-gases, and SF_6 (Rao & Riahi, 2006). This basket is enough to cover and compare broad bean production and dairy production, since only CO_2, CH_4, and N_2O are considered to be substantial environmental outputs of the production process of both (Heusala *et al.,* 2020; Knudsen *et al.,* 2016).

Based on the long-term impacts a kilogram of CO_2-equivalent has over a timeframe of 100 years, a monetary value has been set by the European Union (eco-costs) for the purpose to include environmental impacts of processes into (optimization) assessments (Vogtländer, Brezet & Hendriks, 2001). The monetary value of a kilogram of CO_2-equivalent has been updated twice since 2001 and is now set at €116 per 1000 kg CO_2-equivalent (Ecocostvalue, 2020). The cost is calculated by finding the point where the demand for CO_2 emissions by society is in equilibrium with the allowed emissions that would exactly comply with the 2 degrees Celsius goal for 2050 (Ecocostvalue, 2020).

3.2.1. Break-even carbon price

But, the actual negative value incurred on society by emitting one kilogram of CO_2-equivalent is considered to be very debatable in literature and practice (Hourcade, Pottier & Espagne, 2018; Bastien-Olvera & Moore, 2020). It is therefore not reasonable to fix the cost of carbon to €116 per 1000 kg CO_2-equivalent. A more applicable approach would be to find a break-even value for a kilogram of CO_2-equivalent within this assessment and compare that to values reported in the literature. More specifically, the carbon price set by the European Union of €116 per 1000 kg CO_2-equivalent (Ecocostvalue, 2020), the price set by the Obama administration of $50 (€40.64) per ton of CO_2-equivalent, and the current American calculating value of $7 (€5.69) (USGAO, 2020; Coren, 2020).

First, it would be relevant to find the break-even price of carbon for dairy farming under different density scenarios. In other words, what is the price of a kilogram of CO_2-equivalent, that leaves the farmer zero profit assuming that he/she internalizes the external costs and benefits. The same break-even price of carbon can be found for broad bean production. Solving $I_1(s) = 0$ and $I_2(s) = 0$ leaves a break-even price of carbon for broad bean production and dairy farming. The break-even price of carbon for dairy farming depends on density, while the break-even price of carbon for broad bean production is constant (i.e. independent from density). Notable is that the break-even carbon price assumes no changes in the market(prices). Thus, all external costs are internalized by the farmer and no price mechanisms are considered.

Break-even broad bean production: $$I_1(s) = b_1 + exb_1 - c_1 - exc_1 \tag{11}$$

Break-even dairy farming: $$I_2(s) = b_2(s) + exb_2(s) - c_2(s) - exc_2(s) \tag{12}$$

The terms exb_1 and exb_2 depict the external benefit of broad bean production and dairy farming respectively. And exc_1 and exc_2 represent the external costs of the products. These external costs and benefits will be explained and quantified in sub-chapter 3.2.3. and 3.2.4.

3.2.2. Indifference carbon price

Besides a break-even price of carbon for both types of production, there is also a carbon price that leaves the decision-maker indifferent between allocating the land to broad bean production and dairy farming. Subtracting equation (12) from (11) creates equation (13). By solving *I(s) = 0* for continuous density values, a continuous indifference carbon price is found.

Ind. point: $$I(s) = (b_1 + exb_1 - c_1 - exc_1) - (b_2(s) + exb_2(s) - c_2(s) - exc_2(s)) \quad (13)$$

3.2.3. Emissions of broad bean production

This paragraph covers the emissions of broad bean production in terms of CO_2-equivalents. An LCA on the carbon footprint of oat and broad bean protein concentrates by Heusala *et al.* (2020) is exploited as a valuable source. Although the paper is focused on an end-product, namely the protein concentrate, it does separate the involved emissions of cultivating broad bean specifically. The cultivation assessment assumes mineral N fertilizer, mineral P fertilizer, and fuel as inputs. The broad bean yield is the output of the cultivation process. The boundaries can be called 'cradle to farmgate' in LCA terms. Heusala *et al.* (2020) identify two amounts of yield (low and high), with a corresponding CO_2-equivalent emission. The high yield scenario considers a yield of 3600 kilograms of broad bean per hectare and the low scenario 1500 respectively. In the high yield scenario, the CO_2-equivalent emission is 0.23 kilograms per kilogram of broad bean produced. The low yield scenario gives a CO_2-equivalent emission of 0.58 kilograms per kilogram of broad bean produced. A question of what the emissions are for yields between these two data points arises, as the MATLAB model adopts a normal distribution for the broad bean yields. This distribution (Table 1) has a mean of 3090 kilograms of broad bean yield per hectare and a standard deviation of 216 kilograms. Meaning that most yield values in the assessment lay between the low and high yield scenario of Heusala *et al.* (2020).

Since there is no specific data available on data points within the two yield scenarios (Heusala *et al.,* 2020; Knudsen *et al.,* 2013), the following assumption has been made: The CO_2-equivalent emissions per kilogram of product is a negative linear function of the yield per hectare. This assumption would cause severe problems when the yields get extremely high or low but seems reasonable within the yield ranges of this assessment. By using the two defined data points, the following equation for the kilogram of CO_2-equivalent emission per kilogram of broad bean production can be constructed:

Kg CO_2-eq. per kg broad bean:

$$Ekg_1 = 0.83 + dt_1 * y_1 \qquad (dt_1 \sim -0.0006667)\ \&\ (1500 \leq y_1 \ \geq 3600) \tag{14}$$

By multiplying equation (14) by the broad bean yield, the CO_2-equivalent emission per hectare can be calculated.

Kg CO_2-eq. per ha of broad bean production: $$E_1 = Ekg_1 * y_1 \tag{15}$$

Figure 6 shows the values for equation (15) within the yield range (*y_1)* of 2660 kilograms and 3522 kilograms (approximately the *mean* ± 2 * *std*). The MATLAB code can be found in Appendix D.

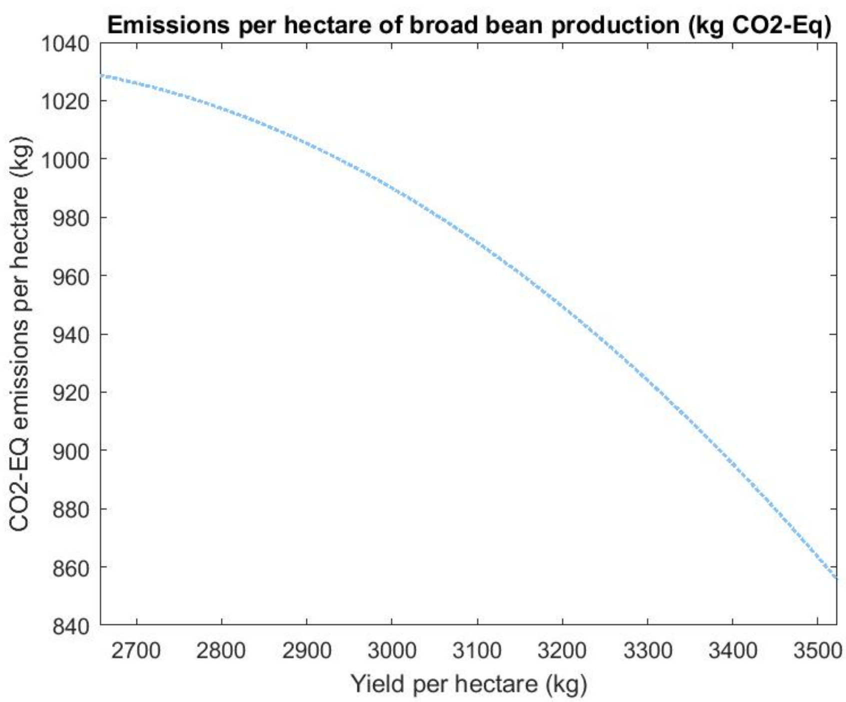

Figure 6. Emissions per hectare of broad bean production in kg CO2-equivalent. MATLAB output.

The externality costs of broad bean production would therefore look as follows:

Externality costs of broad bean production: $exc_1 = E_1 * p_c$ (*p_c = carbon price)* (16)

Broad bean production does not bring additional (monetarily quantifiable) external benefits besides nitrogen fixation (Aho *et al*., 2015). Since BNF is already included as a private benefit (Table 1), the social benefit (exb_1) is equal to zero.

3.2.4. Emission of dairy farming and carbon sequestration

Similar to the broad bean data, papers on dairy farming also report the environmental impact in terms of CO_2-equivalent (Knudsen *et al.,* 2016). Knudsen *et al.* (2016) carried out a research on various farms in Denmark, the United Kingdom, and Finland. Seven of these farms were based in Finland and considered 'organic'. Organic farming is not specified and Knudsen *et al.* (2016) state that the overall emission outcomes, with the inclusion of carbon sequestration, are fairly similar to conventional farming.

The average kilogram of CO_2-equivalent emitted per kilogram of ECM is 1.28 (Ekg_2). This value is considered to be independent of yield per cow. This value depicts the emissions from cradle to farmgate, thus excluding off-farm processing (Knudsen *et al.,* 2016). Due to the dependency of yield per cow and density, the CO_2-equivalent emission per hectare looks as follows:

Kg CO_2-eq. emission per ha of dairy farming: $$EM_2(s) = Ekg_2 * d_2(s) * ym_2 \quad (17)$$

Additionally, dairy farming is considered to incur carbon sequestration (Knudsen *et al.,* 2016). Carbon sequestration can be treated as a benefit to society, as the process decreases the amount of carbon in the atmosphere and therefore negatively affects the global warming potential (Bruce *et al.,* 1999). Knudsen *et al.* (2016) provide carbon sequestration data in a similar fashion as carbon emissions. Subsequently, the data is handled in the same manner. The average kilogram of carbon sequestration per kilogram of ECM is 0.18 ($CSkg_2$).

Kg CO_2-eq. fixed per ha of dairy farming: $$CS_2(s) = CSkg_2 * d_2(s) * ym_2 \quad (18)$$

Subtracting the carbon sequestration from the emission leaves the effective CO_2-equivalent emission per unit of ECM.

Effective CO_2-eq. emission per ha: $$E_2(s) = (Ekg_2 - CSkg_2) * d_2(s) * ym_2 \quad (19)$$

Figure 7 shows the effective CO_2-equivalent emissions per hectare of dairy farming with fixed densities (d_2) per scenario, in line with the mentioned densities in Tables 3 and 4. Note that scenario 3 ($d_2 = 3.8$) is not displayed, as it decreases the clarity of the figure. Apparent is that the density positively influences the slope of the function.

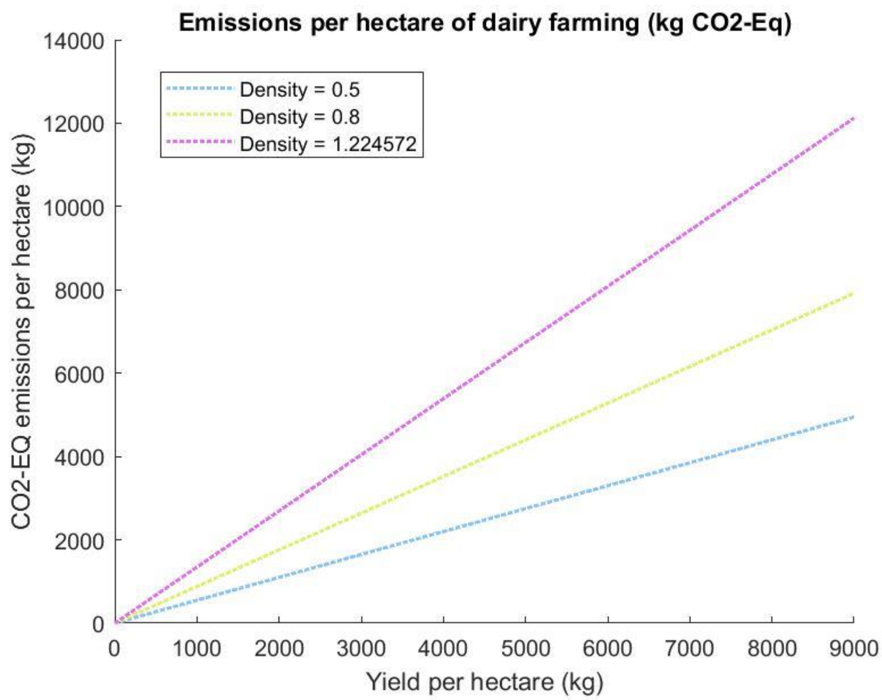

Figure 7. Effective emissions per hectare of broad bean production in kg CO2-equivalent. MATLAB output.

Externality costs of dairy farming: $$exc_2 = EM_2 * p_c \quad (20)$$

Externality benefits of dairy farming: $$exb_2 = CS_2 * p_c \quad (21)$$

The MATLAB code is provided in Appendix E.

3.2.5. Break-even carbon price results

After all the dependent variables constructing equation (11) and (12) are quantified, solving $I_1(s) = 0$ and $I_2(s) = 0$ is quite straightforward by using the code displayed in Appendix F. Table 5 shows the break-even carbon prices of this assessment for both broad bean production and dairy farming. Due to computational constraints, the assessment is run within the deterministic model, as stochastic modeling would increase the running times tremendously, but leaving the same average outcome. Additionally, all inputs are either deterministic or normally distributed, yielding a normal distribution for the dependent variable as well, which is social profit in this case. Besides, these values are compared to the values proposed in the literature.

Table 5. Break-even carbon prices put into perspective. Red depicts negative numbers.

Source	BE-carbon price (€/ton) $\|p_c * 1000\|$	Profit bean production at this carbon price (€/ha) [*€/kg of bean*]	Profit dairy farming at this carbon price (€/ha) [*€/kg of ECM*] Density = 1.224572
Bean production (MATLAB)	1070.92	(0) [*0*]	(1143.58) [*1.3221*]
Dairy farming (MATLAB)	89.46	(955.27) [*0.3092*]	(0) [*0*]
EU (Ecocostvalue, 2020)	116	(929.44) [*0.3008*]	(309.26) [*0.0358*]
Obama administration (USGAO, 2020; Coren, 2020)	40.64	(1002.79) [*0.3245*]	(568.82) [*0.0658*]
USA (USGAO, 2020; Coren, 2020)	5.69	(1036.81) [*0.3355*]	(976.05) [*0.1128*]
None	0	(1042.35) [*0.3373*]	(1042.35) [*0.1205*]

As Table 4 shows, the break-even price of carbon on a broad bean pasture is well above the carbon prices discussed in the literature, for example, almost a tenfold of the European eco-cost value. Meaning that the internalization of external costs would still leave the broad bean farmer a substantial profit. Dairy farming, on the other hand, would be severely affected in a situation where external costs would be internalized. With a break-even carbon price of €89.46 for dairy farming, the European eco-cost price would leave a loss and the carbon price handled by the Obama administration approximately halves the farmer's profit. Note that the profit per hectare of dairy farming depends on the density (private indifference density is used here), but the profit per kilogram of ECM is the same in all density scenarios. In conclusion, internalization of external costs, ceteris paribus, would increase the probability of the farmer choosing broad bean production over dairy farming, as the emissions incurred by broad bean production are substantially less than the emissions by dairy farming.

3.2.6. Indifference carbon price results

As discussed in section 3.2.2., there is a certain carbon price that equalizes the social profits of broad bean production and dairy farming, called the indifference price. The indifference price varies over the density and can be found by solving *I(s) = 0* (13). Figure 8 shows the continuous indifference price over density. The density values start at 0.3, as data points before 0.3 are rather unreasonable, due to mathematical artifacts. This can be explained by the fact that around this density point, the MATLAB solver is not able to give finite values for the indifference price. In extremely low densities, there are both negligible private profits and externalities, leaving the MATLAB solver with irrational calculating values. Luckily, the problematic densities are well below the densities set in the scenarios. The scenario densities are portrayed by the vertical lines.

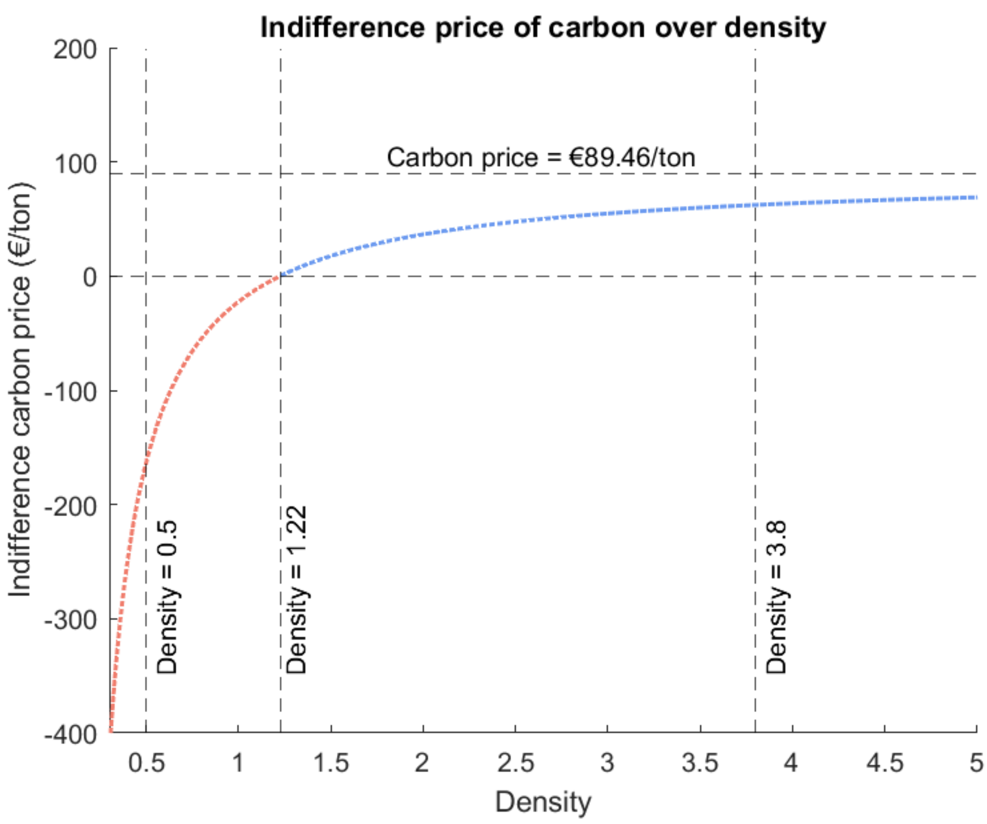

Figure 8. Indifference price of carbon over density. Note that the x-axis starts at a density value of 0.3. MATLAB output.

Figure 8 is interpreted as follows:

- In densities lower than the original indifference density (~1.22), the private profit of dairy farming is lower than the private profit of broad bean production (see Figure 3). Thereby,

the (effective) negative externalities are higher for dairy production. Therefore, to compensate for the lower private profit, the carbon price needs to be negative. Carbon prices can intuitively not be negative, as damaging the environment should not be rewarded. The mathematical interpretation of the conditions is shown underneath:
  - $(b_1 - c_1) > (b_2 - c_2)$
  - $(exb_1 - exc_1) < (exb_2 - exc_2)$
  - $p_c < 0$

- In densities higher than the original indifference density, the private profit of dairy farming is higher than the private profit of broad bean production (see Figure 3). Thereby, the (effective) negative externalities are still higher for dairy production. Therefore, to compensate for the higher private profit, the carbon price needs to be positive, making emitting costly for the producer. The mathematical interpretation of this statement is shown underneath:
  - $(b_1 - c_1) < (b_2 - c_2)$
  - $(exb_1 - exc_1) < (exb_2 - exc_2)$
  - $p_c > 0$

The y-value of the function in Figure 8 behaves asymptotically towards the break-even price of carbon for dairy farming (€89.46 per ton of carbon). The ratio between broad bean profit and dairy profit becomes smaller and approaches zero as density progresses because broad bean profit is independent of density. In high-density points, the marginal profit per kilogram of milk should be very small to equal the total profit of broad bean production. Note that density values higher than 3.8 are very unlikely in Finland because this density (scenario 3) is the current average density in the Netherlands, which is the country with the highest density in Europe (Table 2; Eurostat, 2019). The code used to calculate and plot the indifference carbon price can be found in Appendix G. Appendix H houses a deterministic code, that could be employed to find the indifference carbon price for specific densities.

4. Discussion

The chapter entails the major findings of this research and an examination of the implications in contrast with findings from the literature. The differences in findings and the underlying, predominantly methodological, reasons for these differences will be discussed in various relevant themes. Additionally, the stronger and weaker points of this study will be reviewed accordingly.

4.1. Yields and profits of broad bean farming

4.1.1. Broad bean yields

This assessment assumed a normal distribution of the average broad bean yields per hectare, based on a combination of papers (Skovjberg *et al.,* 2020; Peltonen-Sainio & Niemi, 2012). The paper by Skovjberg *et al.* (2020) was used to find average yields in Finland for the Kontu cultivar. This value seemed to be 3090 kilograms per hectare. The provided standard error could not be transferred to a standard deviation due to a lack of underlying information, such as the number of data inputs. Therefore, another research was employed to attain the standard deviation (Peltonen-Sainio & Niemi, 2012). Peltonen-Sainio & Niemi (2012) claim that the standard deviation of the mean of yield per hectare is 7%, based on panel-data acquired on Finnish farms. Skovjberg *et al*. (2020), on the other hand, acquire their data by experimenting in controlled environments. These environments were not controlled to resemble the perfect growing circumstances, but rather average real-world circumstances. Still, the controlled environments would presumably yield higher average yields as the beans are better protected from extreme weather events and other uncalculated risks. Although the research by Skovjberg *et al.* (2020) is the most recent and well-substantiated, farm yields would supposedly be lower on average. For example, the researches by Heusala *et al.* (2020) and Knudsen *et al.* (2013) report two yield scenarios in Finland. Where the low yield scenario was 1500 kilogram of broad bean per hectare and the high yield scenario 3600 respectively (see section 3.2.3.). The scenario range used in this research is quite a bit closer to the high yield scenario of Heusala *et al.* (2020) than the low yield scenario. On the other hand, Aho *et al.* (2014) do state that the yield per hectare is around 3000 kilograms, but this finding is less substantiated than the aforementioned. Therefore, the yields assumed in this assessment could be perceived as higher than average, but within reasonable bounds.

4.1.2. Farmgate broad bean prices and operating costs

As there was no conclusive or recent data available on the producer prices of broad beans, the paper by Peltonen-Sainio & Niemi (2012) was again used to acquire distribution properties. As panel data was assumed to be the most reliable and readily available, the paper's mean value of €0.23 per kilogram of broad beans was adopted. Additionally, the seed, fertilizer, and herbicide costs were adopted from this paper as well. Using these values, without correcting them for time and inflation, could lead to unfair comparison. On the bright side, the selling price and the input prices are from the same year and the same farmers, leaving a fair gross margin (Peltonen-Sainio & Niemi, 2012). The farmgate prices of legumes are considered to be susceptible to volatility (Jouan, Ridier & Carof, 2019), allowing the chosen farmgate price to be reasonable but also debatable. Papers on other types of crops tend to include the projected yield as a negative factor on the producer prices, which is a logical assumption in economics (Nassar *et al.,* 2020; Jain, 2018; Xie & Wang, 2017). Adopting this price-yield relation was not possible in the broad bean case, as there is not nearly enough data collected on the (European nor Finnish) agronomy structure of the crop.

Thus, the data on broad bean yields, prices, and profits is considerably old. New panel data would increase the credibility of this research, although price volatilities for both inputs and outputs would still leave substantial uncertainty. Thereby, the price-yield relationship seems to be important and should therefore be studied in the future, to increase the applicability of comparative assessment outcomes.

4.2. Yields and profits of dairy farming

4.2.1. Dairy and meat yields

Similar to the broad bean yields, the milk yields are also based on two papers. Where the first paper, by Nieme & Väre (2019), provides relevant and current panel data of Finnish dairy farmers. The average adopted dairy yield from Nieme & Väre (2019) was supplemented by a relative standard deviation calculated by Virtanen & Nousiainen (2005). As the methodological paths by these two pieces of research were similar, the relative standard deviation was considered transferable to the current panel data. Important to note is that the amount of milk yield used in this assessment, 8650 kg per cow per year, averages for the Holstein Friesian breed. Although the Holstein Friesian breed is known for its high milk yields and the Finnish gene pool is rather strong, the numbers by Nieme & Väre (2019) seem to be on the high side but within reasonable bounds (Coffey *et al.,* 2016). For example, Zehetmeier *et al.* (2014) report a mean value of 9596 kilograms of corrected milk per annum per Holstein Friesian cow. Coffey *et al.* (2016) observe an average of 5217 kilograms of ECM per Holstein Friesian per year and a substantially lower standard deviation. Various breeds are used in Finland, although the Holstein Friesian is used the most and is documented most deliberately (Coffey, Hickey & Brotherstone, 2006; Nieme & Väre, 2019). The assumption of only using a single breed does push the outcomes to only represent conventional, milk-driven, farm styles. This simplicity disregards other breeds, their trade-offs between milk yield, beef yield, and additional benefits. A more holistic approach towards decision making in cattle farming, by including trade-offs between meat and dairy production was already introduced in 1983 by Konandreas, Anderson & Trail. This specific trade-off is also mentioned by Klapwijk *et al.* (2014) in an attempt to better understand the holistic decision-making process of a farmer. Similarly, Salmon *et al.* (2018) assess this trade-off structure to shed light on nutrient production possibilities within the global food security problem. Considering these breed trade-offs and lower average milk yields would change the perspective of this research significantly, as meat production would not merely be treated as a positive side stream of dairy farming. This leaves an improved optimization model set-up, where any other type of breed or farming style, with its own costs and benefits, could be compared.

4.2.2. Farmgate dairy prices

The farmgate prices of both ECM and conventional beef were assessed through a model called the Hull-White/Vasicek Gaussian Diffusion model (Hull, 1993), with the assumption that commodity prices are mean-reverting (Andersson, 2007). This model was applicable since there were reliable time series available (MMO, 2020; $NRIF_a$, 2020). There are various other ways to forecast prices of commodities, including more explanatory variables, that would consequently lead to different distribution properties and omit the mean-reverting assumption. Hybrid methods (Gonzalez, Contreras & Bunn, 2011), computational intelligence (Cincotti *et al.,* 2014), and univariate shifting-trends models (Radchenko, 2005) are examples of methods that would provide forecasted farmgate prices with less uncertainty. Especially in cases where the model runs for more than one year, less uncertainty would increase the (long-term) decision-exploration power tremendously.

4.2.3. Operating costs

The operating costs of Finnish dairy farming were rather uncertain, as there was no conclusive data available. For that reason, a yearly index (EC, 2020) and a quantification point (Gołaś, 2017) were used to find the relevant values. The employment of a histogram fit led to an assumed normal distribution with a small relative standard deviation. An additional assumption was that increasing yields would not decrease the operating costs. The opposite is backed by various papers on dairy and cattle farming, especially feed costs and manure management are positively susceptible to economies of scale (MacDonald *et al.,* 2007; Mosheim & Lovell, 2009; Datta, Haider & Ghosh, 2019). However, this research assesses the average farm practice, and the used data, therefore, lies within probable ranges.

To summarize, the number of assumptions and lack of conclusive data on-farm practices increase the dubitability of the outcomes of this research. Many researchers advocate for a more holistic assessment of cattle farming. Employing such a view increases the time-demand of the research, but consecutively increases the applicability of the outcomes for more decision-makers. The questions asked in this research can readily be used for a comparison between breeds, types of farms, farm styles, and crops. Collecting panel data from Finnish farmers on the parameters discussed in this research would open up possibilities regarding decision-making tools for both farmers and policymakers with increased exploratory value.

4.3. Density

The density parameter deserves attention in the discussion section, because the private profit and social profit were most sensitive to it, taking into account that all private and social profits were multiplied by the scenario-specific density. Although density is thus a very influential factor on the outcomes and depicts a substantial part of land-use efficiency, it is not widely covered in comparative studies regarding agricultural land use. There are multiple pieces of research available on the economic and ecological impacts of dairy farming, but density is either fixed or not mentioned at all. For example, the paper by Van Calker *et al.* (2008) regarding sustainability maximizing on Dutch dairy farms calculate with values of the average Dutch farm and thereby fix density. An example that does compare various scenarios is written by Oudshoorn, Sørensen & de Boer (2011). They compare dairy production parameters for three scenarios in Denmark. A business-as-usual scenario, an animal welfare scenario, and an environmental scenario. The following densities were used respectively: 1.41, 1.38, and 0.88. The business-as-usual case in 2011 (Oudshoor, Sørensen & de Boer, 2011) is quite similar to the mentioned average density in 2016 by the source used in this assessment (Eurostat, 2019). The adoption of policy-based density scenarios could have been an improvement to this research, but Finnish agricultural briefs do not mention them (Nieme & Väre, 2019). The stocking density is mostly employed in assessments on cattle behavior, comfort, and the social environment of a farm (Krawczel *et al.,* 2008; Talebi *et al.,* 2014; Huzzey *et al.,* 2006). Therefore, the employment of various density scenarios based on data provided by Eurostat (2019), including a break-even case, successfully depicts the density possibilities in Finland without making restricting assumptions. Decision-makers can apply this research by choosing the density that fits best to their case study.

4.4. Break-even carbon prices

4.4.1. Calculating carbon pricing values

As discussed, the substantiation of appropriate carbon prices is heavily debated in the field of environmental economics. A simple 'Google Scholar' search for papers including '*carbon pricing mechanism'* published in or after 2020 yields about 13,000 results. There are various carbon pricing mechanisms existent, of which all have their pros and cons (Thisted & Thisted, 2020). For this research, the substantiation of the carbon price and the underlying methodology are not of great importance. More important are the calculating values set by governmental bodies, as they are most probable to be translated to future policy measures. The carbon prices set by governmental bodies, such as the EU and the US government have been discussed in the body of this research (Ecocostvalue, 2020; USGAO, 2020; Coren, 2020). Thereafter, the break-even carbon prices for broad bean production and dairy farming were compared with these values. In explanation, the research goal was not to find a legitimate calculating carbon price but to compare break-even carbon prices for the hypothetical scenarios with calculating values found in the literature.

4.4.2. Environmental loads of broad bean production

The break-even carbon price calculation depends on multiple parameters. Namely, the previously argued private costs, benefits, and profits (sections 4.1.2. & 4.1.3.) and the calculated environmental loads. Heusala *et al.* (2020) report on emissions of broad bean production in their farmgate LCA. It showed that input efficiency and yield scenarios have a substantial impact on the relative emissions per kilogram of product. Two data points were provided: With a yield of 3600 kilograms per hectare, the CO_2-equivalent emission is 0.23 kilograms per kilogram of broad bean and with a yield of 1500 per hectare, the CO_2-equivalent emission is 0.58 kilograms per kilogram of broad bean (Heusala *et al.,* 2020; Knudsen *et al.,* 2013). As intermediate points were not quantified, the assumption was made to assume a negative linear relationship between yield and emissions per kilogram of product. Within the yield ranges adopted in this research, the relationship is not compromising the outcomes. Future research should focus on finding a relationship between yields, input-efficiency, and the carbon footprint of broad beans, as there is not any literature available that specifically addresses this. Outcomes of such an assessment would increase the substantiation of the consideration to include broad beans in farm practice optimizations.

4.4.3. Environmental loads of dairy farming

Data on environmental loads of dairy farming were more widely available and more divided, as boundaries and methodologies within LCAs are differentiated (Baldini, Gardoni & Guarino, 2017). LCAs on dairy products differ on the following aspects: country, functional unit, system boundaries, and impact coverage (Baldini, Gardoni & Guarino, 2017). The average LCA looks as follows: the functional unit is fat and protein corrected milk (FPCM), which is closely related to ECM, the system boundary is the farm, and the GWP is the used impact category. The outcomes of these particularly similar studies, set in Northern Europe, can be compared to this assessment and add perspective. The research used was by Knudsen *et al.* (2016) as it was case-specific for Finland and M.T. Knudsen is a known expert on LCAs and farm practices with over 60 publications on the topic. The calculating value adopted from Knudsen *et al.* (2016) was 1.28 kg of CO_2-equivalent emission and 0.18 kg of carbon sequestration per kilogram of ECM. Thus, effectively an emission of 1.10 kg of CO_2-equivalent per kg of ECM. Other values found in the literature are 1.23 (Yan, Humphreys & Holden, 2013), 1.10 – 1.66 (Guerci *et al.,* 2013), 0.97 - 1.57 (Kristensen *et al.,* 2011), and 0.79 – 1.20 (Zehetmeier *et al.,* 2014). Important to note is that these papers do not include carbon sequestration and solely add up the emission incurred by feed production, energy consumption, and farm practices. As can be observed, the CO_2-equivalent emission per kg of ECM varies within researches and countries. The value adopted, by Knudsen *et al.* (2016), with and without the inclusion of carbon sequestration, lies well within the values depicted in the literature and can therefore be considered reasonable.

4.4.4. Break-even carbon prices in perspective

In order to add perspective to the break-even carbon prices of broad beans, there is additional literature needed. But in line with the lack of data on emissions of broad bean farming, there is no literature available on this topic yet. The break-even price found by MATLAB is well above the calculating values found in the used literature, leaving proportional yields after internalization. The break-even price was calculated by setting the social profit functions (11) & (12) to zero and solve with carbon price as its only independent variable. For broad bean production, a value of €1070.92 was found. The break-even carbon price for dairy farming was, as expected, much lower and was calculated at €89.46, due to substantially higher emissions. Important to note is that the break-even carbon price is non-dependent on density because both the private and social profits are equally dependent on it. The dairy break-even carbon price found in this assessment lies between the value used by the Obama administration and European Union (Ecocostvalue, 2020; USGAO, 2020; Coren, 2020). This means that the internalization of environmental externalities would leave the farmer a loss if the calculating value of the European Union is implemented and a 45% drop in profits if the calculating value of the Obama administration is implemented.

The literature mostly addresses the effects of hypothetical carbon prices. The methodology of finding break-even carbon prices for production and compare those with given carbon values is not widely adopted. The comparison between BAU-cases and the implementation of mitigation and adaption practices is studied more deliberately (Dumbrell, Kragt & Gibson, 2016; Mosnier *et al.,* 2019; Kaparaju & Rintala, 2011). This leaves an insufficient amount of literature to compare the outcomes of this assessment with. Ozkan *et al.* (2011) do find that a carbon charge of approximately €16 equals a 10% to 11% decrease of the total operating profits over five years of operation. Thus, the break-even carbon price would be between €160 and €176 per ton of carbon, assuming constant relationships between emissions, costs, and benefits. The outcomes by Ozkan *et al.* (2011) show a break-even carbon price for dairy farming that almost doubles the value found in this assessment. This means that farmers in their assessment are more resilient to the internalization of the external costs. Some differentiation in the outcomes can be explained by differences in the methodological path and research area. Ozkan *et al.* (2011) conducted their research based on Australian farm data, where a substantial different farming environment is in place, and included discounting over a five-year period.

The term 'break-even carbon price' is interpreted differently in the literature compared to this assessment, as the break-even point is not found by equalizing the total profit to zero, but setting a certain environmental goal and finding the carbon price that would cause society to reach this goal. The European Union set the goal to decrease the CO_2 emissions by 70% in 2050 compared to 2008 (Ecocostvalue, 2020). A price of €116 per ton of carbon would yield this. The World Bank argues that a carbon price range between $40 and $80 by 2020 is competent to reach the goal to limit the increase in temperature to 2 degrees Celsius (S&PGlobal, 2020).

To conclude, fair carbon pricing is a very debatable subject and relies on many different goals and methodologies. The break-even price of carbon in dairy farming is not widely studied, contradictory to the effects of carbon pricing in numerous sectors. Therefore, a lack of comparison data is recognized. The gross margins and CO_2-equivalent data does seem to resemble other papers on this subject, which gives reasons to believe that the break-even carbon prices calculated in this research lie within reasonable bounds. The written code that can be found in the Appendices can still function as a tool to calculate the basal impacts of hypothetical carbon prices.

4.5. Agricultural efficiency

An assumption that has been made numerous times in this research regards constant returns to scale. In other words, every extra kilogram of production, for both broad bean and ECM, yields a constant amount of benefits, costs, and emits an equal amount of CO_2-equivalent. Only broad bean emissions diminished as yield increased. Although uncertainty was partly accounted for by including parameter distributions, it is lacking applicability for different farm scales. This is important to mention as agronomy research does take efficiency and returns to scale into account. This property becomes even more important when environmental impacts are included (Coluccia *et al.,* 2020; Baum & Bieńkowski, 2020; Czyżewski, Smędzik-Ambroży & Mrówczyńska-Kamińska, 2020). Future research on this topic should therefore include economies of scale and efficiency structures. Calculating with average farm values is very useful for policy-makers and does represent fair explorative values for policy directions, but misses the connection with the on-farm decision-making process. On the other hand, the MATLAB code, with its parameter values and relations, could function as a base code for farm-specific models.

5. Conclusions and recommendations

This research was conducted to answer the question of whether broad bean production could be considered a viable way of using Finnish agricultural land compared to dairy farming while considering private and societal profits. Answers were found by identifying, modeling, and quantifying relevant agronomical and ecological parameters for both production processes.

In a private model, where environmental externalities are not taken into account, broad beans do perform better per hectare than dairy farming. With the current Finnish livestock density of 0.5 cows per hectare, broad bean production outperforms dairy production by €616.34 per hectare. The density for which both profits are equal is about 1.22, yielding a private profit per hectare of €1042.30. Additionally, the private profit of dairy farming has a considerably larger relative standard deviation than the private profit of broad beans. Adding environmental externalities, by retrieving and implementing data found in the literature, showed that the break-even price of carbon for a broad bean farmer (€1070.92) is almost 12 times higher than the break-even price of carbon for a dairy farmer (€89.46). This means that a broad bean farmer is less prone to the hypothetical internalization of externalities than a dairy farmer. Especially the European calculating value for the carbon price would leave a dairy farmer without a profit margin, while it is only a tenth of the break-even price of broad bean.

Thus, broad beans are, based on the optimization model adopted in this research, a viable way of land-use compared to dairy farming in Finland. Including environmental externalities increased the favorability of broad beans even more.

In order to increase the applicability of assessment outcomes, future research should focus on proper panel data collection. In the best case, the data would come directly from Finnish farms within the region of interest. Knowing the yield distributions, input costs, uncertainties, and substitution possibilities of farmers would increase the reliability of the outcomes. Thereby, more distinct parameters could be included, such as the costs and emissions of product processing and transportation. The addition of more relevant parameters would widen the boundaries of the research and therefore increase the applicability of the assessment even further.

Additionally, considering that a social utility function depends on more than just monetary profits and environmental valuation, future research should assess the nutritional impacts of land-use change. Feeding the increasing population is a challenge more complex than just comparing the monetary values of different products and production processes. Parameters like protein, fat, and vitamin content could become of great importance and could be assessed alongside the private and social profits.

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Appendix A: Deterministic private optimization model (MATLAB code)

```
%% SET UP

clear xopt Total_Private_Profit Protein_Supply;
% Clear the pre-allocated matrices for the outcome variables.
clear
clc
close all
options = optimoptions('fmincon');
options.Algorithm = 'interior-point';
options.Display = 'notify-detailed';
% Turned off the display of every iteration in the Command
Window.

%% Access data from external sources and compute important
values. Dedicated software needed (Econometrics Toolbox). The
obtained values are fixed in the code underneath. Data and code
acquirable [barendkok@hotmail.com].

% Milk_Prices
% Beef_Prices
% Beef_Production
% Operating_Costs

%% DENSITY (Parameter defined by scenario (s).

density_C       = 0.5;

%% Distributions of the parameter (for the deterministic
optimization, only the mean values are used).

% price_B = norminv(rand(-1,1), 0.23, 0.0161)
m_price_B            = 0.23;
sd_price_B           = 0.0161;
dist_price_B         = makedist('Normal', m_price_B, sd_price_B);
% yield_B = norminv(rand(-1,1), 3090, 216.3)
m_yield_B            = 3090;
sd_yield_B           = 216.3;
dist_yield_B         = makedist('Normal', m_yield_B, sd_yield_B);
% seedc_B = norminv(rand(-1,1), 135, 6.75)
m_seedc_B            = 135;
sd_seedc_B           = 6.75;
dist_seedc_B         = makedist('Normal', m_seedc_B, sd_seedc_B);
% fertc_B = norminv(rand(-1,1), 84, 11.76)
m_fertc_B            = 84;
sd_fertc_B           = 11.76;
dist_fertc_B         = makedist('Normal', m_fertc_B, sd_fertc_B);
```

```
% herbc_B = norminv(rand(-1,1), 69, 4.83)
m_herbc_B           = 69;
sd_herbc_B          = 4.83;
dist_herbc_B        = makedist('Normal', m_herbc_B, sd_herbc_B);
% prot_cont_B = norminv(rand(-1,1), 0.309, 0.004)
m_prot_cont_B       = 0.309;
sd_prot_cont_B      = 0.004;
dist_prot_cont_B    = makedist('Normal', m_prot_cont_B,
sd_prot_cont_B);
% yield_CD = norminv(rand(-1,1), 8650, 1253.154129)
m_yield_CD          = 8650;
sd_yield_CD         = 125.31;
dist_yield_CD       = makedist('Normal', m_yield_CD,
sd_yield_CD);
% yield_CM = external, see Beef_Production.
m_yield_CM          = 290.3979;
sd_yield_CM         = 7.1885;
dist_yield_CM       = makedist('Normal', m_yield_CM,
sd_yield_CM);
% price_CD = external, see Milk_Prices.
m_price_CD          = 0.3872;
sd_price_CD         = 0.0207;
dist_price_CD       = makedist('Normal', m_price_CD,
sd_price_CD);
% price_CB = external, see Beef_Prices.
m_price_CM          = 2.5856;
sd_price_CM         = 0.0480;
dist_price_CM       = makedist('Normal', m_price_CM,
sd_price_CM);
% cost_C = external, see Operating Costs.
m_cost_C            = 0.3756;
sd_cost_C           = 0.01257;
dist_cost_C         = makedist('Normal', m_cost_C, sd_cost_C);

%% Parameters & Run

nit_fix_B               = 0.0083;
subs_B                  = 594;
price_B                 = m_price_B;
yield_B                 = m_yield_B;
seedc_B                 = m_seedc_B;
fertc_B                 = m_fertc_B;
herbc_B                 = m_herbc_B;
prot_cont_B             = m_prot_cont_B;
yield_CD                = m_yield_CD;
price_CD                = m_price_CD;
price_CM                = m_price_CM;
yield_CM                = m_yield_CM;
```

```
cost_C                  = m_cost_C;

% Intermediates profit function
benefitkg_B     = price_B + nit_fix_B;
benefitha_B     = yield_B * benefitkg_B + subs_B;
costha_B        = seedc_B + fertc_B + herbc_B;
benefitkg_CD    = price_CD;
benefitha_CD    = yield_CD * density_C * benefitkg_CD;
benefitkg_CM    = price_CM;
benefitha_CM    = yield_CM * density_C * benefitkg_CM;
benefitha_C     = benefitha_CD + benefitha_CM;
costha_C        = density_C * cost_C * yield_CD;

% Profit function, minimizing this is the objective.
Total_Profit    = @(x)( -x(1) * (benefitha_B - costha_B) - x(2)
* (benefitha_C - costha_C));
Total_Profit_B  = @(x)(x(1) * (benefitha_B - costha_B));
Total_Profit_C  = @(x)(x(2) * (benefitha_C - costha_C));

% Inputs for fmincon.
Guess   = [0.5 0.5];
LB      = [0 0];
UB      = [1 1];
Aeq     = [1 1];
beq     = 1;

% FMINCON
xopt =
fmincon(Total_Profit,Guess,[],[],Aeq,beq,LB,UB,[],options);

% Relevant Outputs
PROFIT_B  = xopt(1) * (benefitha_B - costha_B);
PROFIT_C  = xopt(2) * (benefitha_C - costha_C);
Profit_C  = benefitha_C - costha_C;
Profit_B  = benefitha_B - costha_B;
PROFIT = PROFIT_B + PROFIT_C;

display(xopt)
display(Profit_B)
display(Profit_C)
display(PROFIT)
```

Appendix B: Stochastic private optimization model (MATLAB code)

```
%% SET UP

clear xopt Total_Private_Profit Protein_Supply;
% Clear the preallocated matrices for the outcome variables.
clear
clc
close all
options = optimoptions('fmincon');
options.Algorithm = 'interior-point';
options.Display = 'notify-detailed';
% Turned off the display of every iteration in the Command
Window.


%% Access data from external sources and compute important
values. Dedicated software needed (Econometrics Toolbox). The
obtained values are fixed in the code underneath. Data and code
acquirable [barendkok@hotmail.com].

% Milk_Prices
% Beef_Prices
% Beef_Production
% Operating_Costs

%% DENSITY

density_C       = 0.5;

%% Distributions

% price_B = norminv(rand(-1,1), 0.23, 0.0161)
m_price_B           = 0.23;
sd_price_B          = 0.0161;
dist_price_B        = makedist('Normal', m_price_B, sd_price_B);
% yield_B = norminv(rand(-1,1), 3090, 216.3)
m_yield_B           = 3090;
sd_yield_B          = 216.3;
dist_yield_B        = makedist('Normal', m_yield_B, sd_yield_B);
% seedc_B = norminv(rand(-1,1), 135, 6.75)
m_seedc_B           = 135;
sd_seedc_B          = 6.75;
dist_seedc_B        = makedist('Normal', m_seedc_B, sd_seedc_B);
% fertc_B = norminv(rand(-1,1), 84, 11.76)
m_fertc_B           = 84;
sd_fertc_B          = 11.76;
dist_fertc_B        = makedist('Normal', m_fertc_B, sd_fertc_B);
% herbc_B = norminv(rand(-1,1), 69, 4.83)
```

```
m_herbc_B           = 69;
sd_herbc_B          = 4.83;
dist_herbc_B        = makedist('Normal', m_herbc_B, sd_herbc_B);
% prot_cont_B = norminv(rand(-1,1), 0.309, 0.004)
m_prot_cont_B       = 0.309;
sd_prot_cont_B      = 0.004;
dist_prot_cont_B    = makedist('Normal', m_prot_cont_B,
sd_prot_cont_B);
% yield_CD = norminv(rand(-1,1), 8650, 1253.154129)
m_yield_CD          = 8650;
sd_yield_CD         = 125.31;
dist_yield_CD       = makedist('Normal', m_yield_CD,
sd_yield_CD);
% yield_CM = external, see Beef_Production
m_yield_CM          = 290.3979;
sd_yield_CM         = 7.1885;
dist_yield_CM       = makedist('Normal', m_yield_CM,
sd_yield_CM);
% price_CD = external, see Milk_Prices.
m_price_CD          = 0.3872;
sd_price_CD         = 0.0207;
dist_price_CD       = makedist('Normal', m_price_CD,
sd_price_CD);
% price_CB = external, see Beef_Prices.
m_price_CM          = 2.5856;
sd_price_CM         = 0.0480;
dist_price_CM       = makedist('Normal', m_price_CM,
sd_price_CM);
% cost_C = external, see Operating Costs.
m_cost_C            = 0.3756;
sd_cost_C           = 0.01257;
dist_cost_C         = makedist('Normal', m_cost_C, sd_cost_C);

%% Fixed Parameters

nit_fix_B               = 0.0083;
subs_B                  = 594;

%% RUN

% Set number of runs
runs = 100000;

% Pre-allocation to diminish running time.
xopt                    =nan(runs,2);
Total_Profit_Bean       =nan(runs,1);
Total_Profit_Cattle     =nan(runs,1);
Protein_Supply_Bean     =nan(runs,1);
```

```
Protein_Supply_Cattle   =nan(runs,1);

nsamples = 1:runs;
for i = 1:length(nsamples)

% Draw a value from the distribution for every run.
price_B     = random(dist_price_B);
yield_B     = random(dist_yield_B);
seedc_B     = random(dist_seedc_B);
fertc_B     = random(dist_fertc_B);
herbc_B     = random(dist_herbc_B);
prot_cont_B = random(dist_prot_cont_B);
yield_CD    = random(dist_yield_CD);
price_CD    = random(dist_price_CD);
yield_CM    = random(dist_yield_CM);
price_CM    = random(dist_price_CM);
cost_C      = random(dist_cost_C);

% Intermediates profit function
benefitkg_B     = price_B + nit_fix_B;
benefitha_B     = yield_B * benefitkg_B + subs_B;
costha_B        = seedc_B + fertc_B + herbc_B;
benefitkg_CD    = price_CD;
benefitha_CD    = yield_CD * density_C * benefitkg_CD;
benefitkg_CM    = price_CM;
benefitha_CM    = yield_CM * density_C * benefitkg_CM;
benefitha_C     = benefitha_CD + benefitha_CM;
costha_C        = density_C * cost_C * yield_CD;

% Profit function (negative as the fmincon optimizes by
minimization).
Total_Profit    = @(x)( -x(1) * (benefitha_B - costha_B) - x(2)
* (benefitha_C - costha_C));
Total_Profit_B  = @(x)(x(1) * (benefitha_B - costha_B));
Total_Profit_C  = @(x)(x(2) * (benefitha_C - costha_C));

% Inputs for fmincon.
Guess   = [0.5 0.5];
LB      = [0 0];
UB      = [1 1];
Aeq     = [1 1];
beq     = 1;

% Minimization
xopt (i, :) =
fmincon(Total_Profit,Guess,[],[],Aeq,beq,LB,UB,[],options);

Total_Profit_Bean       (i, :)  = benefitha_B - costha_B;
```

```
Total_Profit_Cattle     (i, :)  = benefitha_C - costha_C;
Private_Profit = Total_Profit_Bean .* xopt(:,1) +
Total_Profit_Cattle .* xopt(:,2);
end

%% Compute and display values relevant for reporting.

Average_x1 = sum(xopt(:,1))/runs;
Average_x2 = sum(xopt(:,2))/runs;
mu = (mean(Private_Profit));
sigma = std(Private_Profit);
LBCI = prctile(Private_Profit, 1);
UBCI = prctile(Private_Profit, 99);

display(mu)
display(sigma)
display(Average_x1)
display(Average_x2)
display(LBCI)
display(UBCI)
```

Appendix C: Distribution plotting (MATLAB code)

```
%% INPUT PRIVATE

% Scenario 1
mu_s1        = 1042.7;
sd_s1        = 73.12;
dist_s1      = makedist('Normal', mu_s1, sd_s1);

% Scenario 2
mu_s2        = 1044;
sd_s2        = 72.57;
dist_s2      = makedist('Normal', mu_s2, sd_s2);

% Scenario 3
mu_s3        = 3240;
sd_s3        = 803.07;
dist_s3      = makedist('Normal', mu_s3, sd_s3);

% Scenario 4
alpha_s4     = 1023.72;
c_s4         = 27.35;
k_s4         = 0.2988;
dist_s4      = makedist('Burr', alpha_s4, c_s4, k_s4);

x = 0:0.1:6000;

% pdf
s1 = pdf(dist_s1, x);
s2 = pdf(dist_s2, x);
s3 = pdf(dist_s3, x);
s4 = pdf(dist_s4, x);

% cdf
s1_cdf = cdf(dist_s1, x);
s2_cdf = cdf(dist_s2, x);
s3_cdf = cdf(dist_s3, x);
s4_cdf = cdf(dist_s4, x);

%% PDF PRIVATE

figure(1);
plot(x,s1, ':', 'LineWidth', 1.5, 'Color', '#86C3F9')
hold on
plot(x,s3, ':', 'LineWidth', 1.5, 'Color', '#F9C386')
hold on
plot(x,s4, ':', 'LineWidth', 1.5, 'Color', '#CE86F9')
legend('Scenario 1 & 2', 'Scenario 3', 'Scenario 4')
title('Private profit distribution (PDF)')
```

```
xlabel('Private profit (€)')
ylabel('Probability Density')
hold off
```

%% CDF PRIVATE

```
figure(1);
plot(x,s1_cdf, ':', 'LineWidth', 1.5, 'Color', '#86C3F9')
hold on
plot(x,s3_cdf, ':', 'LineWidth', 1.5, 'Color', '#F9C386')
hold on
plot(x,s4_cdf, ':', 'LineWidth', 1.5, 'Color', '#CE86F9')
legend('Scenario 1 & 2', 'Scenario 3', 'Scenario 4')
title('Private profit distribution (CDF)')
xlabel('Private profit (€)')
ylabel('Cumulative Probability')
hold off
```

Appendix D: CO2-eq. bean (MATLAB code)

```
A = [0.23 0.58];
B = [3600 1500];
C = 0.23-0.58;
D = 3600-1500;
Delta = C/D;
Mean = 3090;
SD   = 216.3;
Xmin = 3090 - 2*SD;
Xmax = 3090 + 2*SD;

x = 0:0.5:5100;
y = 0.83 + Delta * x;

hold on
figure (1);
plot    (x,y, ':', 'LineWidth', 1.5, 'Color', '#86C3F9')
xlim    ([0 5100])
xline   (Xmin, '--', 'LineWidth', 1.3, 'Color', '#CE86F9')
xline   (Xmax, '--', 'LineWidth', 1.3, 'Color', '#CE86F9')
title   ('Emissions per kg of broad bean over yield (kg CO2-
EQ)')
xlabel  ('Yield per hectare (kg)')
ylabel  ('Emissions per kg of broad bean (kg CO2-EQ)')
hold off


z = x .* y;

hold on
figure (2);
plot    (x,z, ':', 'LineWidth', 1.5, 'Color', '#86C3F9')
xlim    ([Xmin Xmax])
title   ('Emissions per hectare of broad bean production (kg
CO2-Eq)')
xlabel  ('Yield per hectare (kg)')
ylabel  ('CO2-EQ emissions per hectare (kg)')
hold off
```

Appendix E: CO2-eq. dairy (MATLAB code)

```
Mean     = 8650;
SD       = 125.31;
Xmin     = Mean - 2*SD;
Xmax     = Mean + 2*SD;
CO2kg    = 1.28;
seq      = 0.18;
density_1 = 0.5;
density_2 = 0.8;
density_4 = 1.224572;


x = 0:20:9000;
y1 = (CO2kg - seq) * density_1 * x;
y2 = (CO2kg - seq) * density_2 * x;
y4 = (CO2kg - seq) * density_4 * x;



hold on
figure (1);
plot    (x,y1, ':', 'LineWidth', 1.5, 'Color', '#86C3F9')
plot    (x,y2, ':', 'LineWidth', 1.5, 'Color', '#DFF06D')
plot    (x,y4, ':', 'LineWidth', 1.5, 'Color', '#E26DF0')
xlim    ([0 9000])
title   ('Emissions per hectare of dairy farming (kg CO2-Eq)')
xlabel  ('Yield per hectare (kg)')
ylabel  ('CO2-EQ emissions per hectare (kg)')
legend  ('Density = 0.5', 'Density = 0.8',  'Density = 
1.224572')
hold off
```

Appendix F: Break-even carbon price (MATLAB code)

```
density_C    = 1.224572;
CO2_Cost     = 0/1000;

%% Distributions
% price_B = norminv(rand(-1,1), 0.23, 0.0161)
m_price_B            = 0.23;
sd_price_B           = 0.0161;
dist_price_B         = makedist('Normal', m_price_B, sd_price_B);
% yield_B = norminv(rand(-1,1), 3090, 216.3)
m_yield_B            = 3090;
sd_yield_B           = 216.3;
dist_yield_B         = makedist('Normal', m_yield_B, sd_yield_B);
% seedc_B = norminv(rand(-1,1), 135, 6.75)
m_seedc_B            = 135;
sd_seedc_B           = 6.75;
dist_seedc_B         = makedist('Normal', m_seedc_B, sd_seedc_B);
% fertc_B = norminv(rand(-1,1), 84, 11.76)
m_fertc_B            = 84;
sd_fertc_B           = 11.76;
dist_fertc_B         = makedist('Normal', m_fertc_B, sd_fertc_B);
% herbc_B = norminv(rand(-1,1), 69, 4.83)
m_herbc_B            = 69;
sd_herbc_B           = 4.83;
dist_herbc_B         = makedist('Normal', m_herbc_B, sd_herbc_B);
% prot_cont_B = norminv(rand(-1,1), 0.309, 0.004)
m_prot_cont_B        = 0.309;
sd_prot_cont_B       = 0.004;
dist_prot_cont_B     = makedist('Normal', m_prot_cont_B,
sd_prot_cont_B);
% yield_CD = norminv(rand(-1,1), 8650, 1253.154129)
m_yield_CD           = 8650;
sd_yield_CD          = 125.31;
dist_yield_CD        = makedist('Normal', m_yield_CD,
sd_yield_CD);
% yield_CM = external, see Beef_Production
m_yield_CM           = 290.3979;
sd_yield_CM          = 7.1885;
dist_yield_CM        = makedist('Normal', m_yield_CM,
sd_yield_CM);
% price_CD = external, see Milk_Prices.
m_price_CD           = 0.3872;
sd_price_CD          = 0.0207;
dist_price_CD        = makedist('Normal', m_price_CD,
sd_price_CD);
% price_CB = external, see Beef_Prices.
```

```
m_price_CM          = 2.5856;
sd_price_CM         = 0.0480;
dist_price_CM       = makedist('Normal', m_price_CM,
sd_price_CM);
% cost_C = external, see Operating Costs. --> Calculated in
tons, so divide by thousand.
m_cost_C            = 0.3756;
sd_cost_C           = 0.01257;
dist_cost_C         = makedist('Normal', m_cost_C, sd_cost_C);

%% Parameters & Run

% Benefit & Damage parameters
CO2_Delta_B             = -1.6667e-04;
CO2_K_B                 = 0.83;
CO2_L                   = 1.28;
CO2_Sec                 = 0.18;
nit_fix_B               = 0.0083;
subs_B                  = 594;
prot_cont_CD            = 0.035;
prot_cont_CM            = 0.26;
price_B                 = m_price_B;
yield_B                 = m_yield_B;
seedc_B                 = m_seedc_B;
fertc_B                 = m_fertc_B;
herbc_B                 = m_herbc_B;
prot_cont_B             = m_prot_cont_B;
yield_CD                = m_yield_CD;
price_CD                = m_price_CD;
price_CM                = m_price_CM;
yield_CM                = m_yield_CM;
cost_C                  = m_cost_C;


%% Intermediates profit function
benefitkg_B     = price_B + nit_fix_B;
benefitha_B     = yield_B * benefitkg_B + subs_B;
costha_B        = seedc_B + fertc_B + herbc_B;
benefitkg_CD    = price_CD;
benefitha_CD    = yield_CD * density_C * benefitkg_CD;
benefitkg_CM    = price_CM;
benefitha_CM    = yield_CM * density_C * benefitkg_CM;
benefitha_C     = benefitha_CD + benefitha_CM;
costha_C        = density_C * cost_C * yield_CD;
socbenefit_B    = 0;
soccosts_B      =(CO2_K_B + CO2_Delta_B * yield_B) * yield_B *
CO2_Cost;
```

```
socbenefit_C    = CO2_Sec * density_C * yield_CD * CO2_Cost;
soccosts_C      = CO2_L * density_C * yield_CD * CO2_Cost;


%% Equations
eqn_cattle = benefitha_C + socbenefit_C - costha_C - soccosts_C;

eqn_bean = benefitha_B + socbenefit_B - costha_B  - soccosts_B;

margin_bean = eqn_bean/yield_B;

margin_cattle = eqn_cattle/yield_CD;
```

Appendix G: Indifference carbon price (MATLAB code)

```
%% Distributions (Do not want to delete them, as I can change
them out easier.
% price_B = norminv(rand(-1,1), 0.23, 0.0161)
m_price_B          = 0.23;
sd_price_B         = 0.0161;
dist_price_B       = makedist('Normal', m_price_B, sd_price_B);
% yield_B = norminv(rand(-1,1), 3090, 216.3)
m_yield_B          = 3090;
sd_yield_B         = 216.3;
dist_yield_B       = makedist('Normal', m_yield_B, sd_yield_B);
% seedc_B = norminv(rand(-1,1), 135, 6.75)
m_seedc_B          = 135;
sd_seedc_B         = 6.75;
dist_seedc_B       = makedist('Normal', m_seedc_B, sd_seedc_B);
% fertc_B = norminv(rand(-1,1), 84, 11.76)
m_fertc_B          = 84;
sd_fertc_B         = 11.76;
dist_fertc_B       = makedist('Normal', m_fertc_B, sd_fertc_B);
% herbc_B = norminv(rand(-1,1), 69, 4.83)
m_herbc_B          = 69;
sd_herbc_B         = 4.83;
dist_herbc_B       = makedist('Normal', m_herbc_B, sd_herbc_B);
% prot_cont_B = norminv(rand(-1,1), 0.309, 0.004)
m_prot_cont_B      = 0.309;
sd_prot_cont_B     = 0.004;
dist_prot_cont_B   = makedist('Normal', m_prot_cont_B,
sd_prot_cont_B);
% yield_CD = norminv(rand(-1,1), 8650, 1253.154129)
m_yield_CD         = 8650;
sd_yield_CD        = 125.31;
dist_yield_CD      = makedist('Normal', m_yield_CD,
sd_yield_CD);
% yield_CM = external, see Beef_Production
m_yield_CM         = 290.3979;
sd_yield_CM        = 7.1885;
dist_yield_CM      = makedist('Normal', m_yield_CM,
sd_yield_CM);
% price_CD = external, see Milk_Prices.
m_price_CD         = 0.3872;
sd_price_CD        = 0.0207;
dist_price_CD      = makedist('Normal', m_price_CD,
sd_price_CD);
% price_CB = external, see Beef_Prices.
m_price_CM         = 2.5856;
```

```
sd_price_CM         = 0.0480;
dist_price_CM       = makedist('Normal', m_price_CM,
sd_price_CM);
% cost_C = external, see Operating Costs. --> Calculated in
tons, so divide by thousand.
m_cost_C            = 0.3756;
sd_cost_C           = 0.01257;
dist_cost_C         = makedist('Normal', m_cost_C, sd_cost_C);

%% Parameters & Run
% Benefit & Damage parameters
CO2_Delta_B             = -1.6667e-04;
CO2_K_B                 = 0.83;
CO2_L                   = 1.28;
CO2_Sec                 = 0.18;
nit_fix_B               = 0.0083;
subs_B                  = 594;
prot_cont_CD            = 0.035;
prot_cont_CM            = 0.26;
price_B                 = m_price_B;
yield_B                 = m_yield_B;
seedc_B                 = m_seedc_B;
fertc_B                 = m_fertc_B;
herbc_B                 = m_herbc_B;
prot_cont_B             = m_prot_cont_B;
yield_CD                = m_yield_CD;
price_CD                = m_price_CD;
price_CM                = m_price_CM;
yield_CM                = m_yield_CM;
cost_C                  = m_cost_C;

% Starting value density
density_C = 0;

% Setting a symbolic value for CO2_Cost
syms CO2_Cost

i = 0:0.01:10;

Equilibrium                 = nan(1,numel(i));
Density                     = nan(1,numel(i));

for k1 = 1:numel(i)

density_C = density_C + 0.01;

% Intermediates profit function
```

```
benefitkg_B      = price_B + nit_fix_B;
benefitha_B      = yield_B * benefitkg_B + subs_B;
costha_B         = seedc_B + fertc_B + herbc_B;
benefitkg_CD     = price_CD;
benefitha_CD     = yield_CD * density_C * benefitkg_CD;
benefitkg_CM     = price_CM;
benefitha_CM     = yield_CM * density_C * benefitkg_CM;
benefitha_C      = benefitha_CD + benefitha_CM;
costha_C         = density_C * cost_C * yield_CD;
socbenefit_B     = 0;
soccosts_B       =(CO2_K_B + CO2_Delta_B * yield_B) * yield_B *
CO2_Cost;
socbenefit_C     = CO2_Sec * density_C * yield_CD * CO2_Cost;
soccosts_C       = CO2_L * density_C * yield_CD * CO2_Cost;

eqn = (benefitha_B + socbenefit_B - costha_B  - soccosts_B) -
(benefitha_C + socbenefit_C - costha_C - soccosts_C) == 0;
EQ_CO2_Cost = solve (eqn, CO2_Cost);

EQ_CO2_Cost_Ton = EQ_CO2_Cost .* 1000;
Equilibrium(:,k1) = double(EQ_CO2_Cost_Ton(:));
Density(:,k1) = double(density_C(:));
end

%% Plotting
Equilibrium1 = Equilibrium;
Equilibrium1(Equilibrium1 < 0) = nan;
Equilibrium2 = Equilibrium;
Equilibrium2(Equilibrium2 >= 0) = nan;

hold on

plot (Density, Equilibrium1, ':', 'LineWidth', 1.5, 'Color',
'#6D9BF0')
plot (Density, Equilibrium2, ':', 'LineWidth', 1.5, 'Color',
'#F07D6D')

xlim ([0.3 5])
ylim ([-400 200])

xline   (0.5, '--', 'LineWidth', 0.02, 'Color', '#000000')
xline   (1.224572, '--', 'LineWidth', 0.02, 'Color', '#000000')
xline   (3.8, '--', 'LineWidth', 0.02, 'Color', '#000000')

yline   (0, '--', 'LineWidth', 0.02, 'Color', '#000000')
yline   (70, '--', 'LineWidth', 0.02, 'Color', '#000000')
```

```
txt1 = 'Density = 0.5';
txt2 = 'Density = 1.22';
txt3 = 'Density = 3.8';
txt4 = 'Carbon price = €70/ton';

text(0.6, -350, txt1, 'rotation', 90)
text(1.3, -350, txt2, 'rotation', 90)
text(3.9, -350, txt3, 'rotation', 90)
text(1.8, 86, txt4)

xlabel('Density')
ylabel('Indifference carbon price (€/ton)')
title('Indifference price of carbon over density')

hold off
```

Appendix H: Indifference carbon price check (MATLAB code)

```
%% Distributions
% price_B = norminv(rand(-1,1), 0.23, 0.0161)
m_price_B           = 0.23;
sd_price_B          = 0.0161;
dist_price_B        = makedist('Normal', m_price_B, sd_price_B);
% yield_B = norminv(rand(-1,1), 3090, 216.3)
m_yield_B           = 3090;
sd_yield_B          = 216.3;
dist_yield_B        = makedist('Normal', m_yield_B, sd_yield_B);
% seedc_B = norminv(rand(-1,1), 135, 6.75)
m_seedc_B           = 135;
sd_seedc_B          = 6.75;
dist_seedc_B        = makedist('Normal', m_seedc_B, sd_seedc_B);
% fertc_B = norminv(rand(-1,1), 84, 11.76)
m_fertc_B           = 84;
sd_fertc_B          = 11.76;
dist_fertc_B        = makedist('Normal', m_fertc_B, sd_fertc_B);
% herbc_B = norminv(rand(-1,1), 69, 4.83)
m_herbc_B           = 69;
sd_herbc_B          = 4.83;
dist_herbc_B        = makedist('Normal', m_herbc_B, sd_herbc_B);
% prot_cont_B = norminv(rand(-1,1), 0.309, 0.004)
m_prot_cont_B       = 0.309;
sd_prot_cont_B      = 0.004;
dist_prot_cont_B    = makedist('Normal', m_prot_cont_B,
sd_prot_cont_B);
% yield_CD = norminv(rand(-1,1), 8650, 1253.154129)
m_yield_CD          = 8650;
sd_yield_CD         = 125.31;
dist_yield_CD       = makedist('Normal', m_yield_CD,
sd_yield_CD);
% yield_CM = external, see Beef_Production
m_yield_CM          = 290.3979;
sd_yield_CM         = 7.1885;
dist_yield_CM       = makedist('Normal', m_yield_CM,
sd_yield_CM);
% price_CD = external, see Milk_Prices.
m_price_CD          = 0.3872;
sd_price_CD         = 0.0207;
dist_price_CD       = makedist('Normal', m_price_CD,
sd_price_CD);
% price_CB = external, see Beef_Prices.
m_price_CM          = 2.5856;
sd_price_CM         = 0.0480;
```

```
dist_price_CM        = makedist('Normal', m_price_CM,
sd_price_CM);
% cost_C = external, see Operating Costs. --> Calculated in
tons, so divide by thousand.
m_cost_C             = 0.3756;
sd_cost_C            = 0.01257;
dist_cost_C          = makedist('Normal', m_cost_C, sd_cost_C);

%% Parameters & Run
% Benefit & Damage parameters
CO2_Delta_B                  = -1.6667e-04;
CO2_K_B                      = 0.83;
CO2_L                        = 1.28;
CO2_Sec                      = 0.18;
nit_fix_B                    = 0.0083;
subs_B                       = 594;
prot_cont_CD                 = 0.035;
prot_cont_CM                 = 0.26;
price_B                      = m_price_B;
yield_B                      = m_yield_B;
seedc_B                      = m_seedc_B;
fertc_B                      = m_fertc_B;
herbc_B                      = m_herbc_B;
prot_cont_B                  = m_prot_cont_B;
yield_CD                     = m_yield_CD;
price_CD                     = m_price_CD;
price_CM                     = m_price_CM;
yield_CM                     = m_yield_CM;
cost_C                       = m_cost_C;

% Starting value density
density_C = Fill in the density here;

% Setting a symbolic value for CO2_Cost
syms CO2_Cost

% Intermediates profit function
benefitkg_B      = price_B + nit_fix_B;
benefitha_B      = yield_B * benefitkg_B + subs_B;
costha_B         = seedc_B + fertc_B + herbc_B;
benefitkg_CD     = price_CD;
benefitha_CD     = yield_CD * density_C * benefitkg_CD;
benefitkg_CM     = price_CM;
benefitha_CM     = yield_CM * density_C * benefitkg_CM;
benefitha_C      = benefitha_CD + benefitha_CM;
costha_C         = density_C * cost_C * yield_CD;
socbenefit_B     = 0;
```

```
soccosts_B      =(CO2_K_B + CO2_Delta_B * yield_B) * yield_B *
CO2_Cost;
socbenefit_C    = CO2_Sec * density_C * yield_CD * CO2_Cost;
soccosts_C      = CO2_L * density_C * yield_CD * CO2_Cost;

eqn_Bean = (benefitha_B + socbenefit_B - costha_B  - soccosts_B)
== 0;

eqn_Cattle = (benefitha_C + socbenefit_C - costha_C -
soccosts_C) == 0;

eqn_Total = (benefitha_B + socbenefit_B - costha_B  -
soccosts_B) - (benefitha_C + socbenefit_C - costha_C -
soccosts_C) == 0;


BE_CO2_Cost_Bean = solve (eqn_Bean, CO2_Cost);
BE_CO2_Cost_Cattle = solve (eqn_Cattle, CO2_Cost);
IP_CO2_Cost = solve (eqn_Total, CO2_Cost);

display(IP_CO2_Cost)
```