Report *Rapport*

# Carbon Footprint of Table Potatoes – Uncertainties and Variations

*Klimatgasutsläpp från matpotatis – osäkerheter och variationer*

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Keywords: Carbon footprint, carbon labelling, table potatoes, life cycle assessment, LCA, greenhouse-gas emissions, Monte Carlo simulation, uncertainty analysis

## ABSTRACT

Carbon footprint (CF) has become a hot topic as public awareness of climate change is placing demands on manufacturers to declare the climate impact of their products. Calculating the CF of food products is complex and associated with unavoidable uncertainty due to the inherent variability of natural processes. This study quantifies the uncertainty of a common food product and discusses the results in relation to different types of CF systems for food product labelling.

A detailed life cycle inventory (LCI) with global warming potential (GWP) as the only impact category was performed on King Edward table potatoes grown in the Östergötland region of Sweden. Parameters were described using one probability distribution for spatial and temporal variation and one separate distribution describing measuring/data uncertainty, allowing the effect of parameter resolution on CF uncertainty to be studied. Monte Carlo simulation was used to quantify the overall uncertainty. The influence of individual parameters on the CF was analysed and differences in CF for food products from different production systems, with and without climate impact reduction rules, were simulated.

The potato CF fell in the range 0.10-0.16 kg $CO_2$e per kg potatoes, with 95% certainty for an arbitrary year and field. Emissions of $N_2O$ from soil dominated both the emissions and the uncertainty of the CF. Locking the temporal variation to a specific year lowered the uncertainty range by 19%. Parameter collection on a spatial scale of one field did not reduce the uncertainty. The most sensitive parameters were the yield, the soil humus content and the emission factor used for $N_2O$ emissions from soil. Potatoes grown according to climate rules lowered the CF by 9% with a probability of 53% for an arbitrary year and field.

The importance of yield, which proved to be the most influential parameter, is a common characteristic of agricultural products in general, since the accumulated emissions from a cultivated area are divided across the yield from that area. Maximising the yield reduces the CF but could have negative impacts on other environmental aspects. The purpose of the CF labelling scheme, together with uncertainty analysis, needs to be considered when determining how the CF should be calculated, as an average or for a specific year, farm, field, region, etc.

The CF of potato calculated for an arbitrary year and field varied between approximately -17% and +30% of the average value with 95% certainty, showing that uncertainty analysis in the design, calculation and evaluation of food product CF labelling schemes is important to ensure fair and effective comparisons.

## SAMMANFATTNING

### Bakgrund

Livsmedelskonsumtionen står för ca 25 % av växthusgasutsläppen som en medelsvensk orsakar per år (SEPA, 2008a). I och med att medvetenheten kring klimatfrågan ökar hos allmänheten, visar individer intresse av att sänka sina utsläpp från bland annat livsmedelskonsumtion (Toivonen, 2007; L.E.K., 2008; SEPA, 2008b). Klimatdeklaration och kolavtryck/klimatavtryck (engelska ”carbon footprint”) är termer som använts för att beskriva den mängd växthusgaser som en viss produkt eller tjänst orsakar under dess livstid. Enheten gram eller kilogram koldioxidekvivalenter ($CO_2e$) används för att räkna ihop utsläppen av koldioxid ($CO_2$), metan ($CH_4$) och lustgas ($N_2O$) till en enhet.

Livscykelanalys (LCA, ISO, 2006a; ISO, 2006b) är en metod som används för att bedöma en produkts eller tjänsts totala miljöpåverkan under hela dess livstid. I en livscykelanalys inkluderas tillverkning, användning och avfallshantering av produkten; från råvaruutvinning till dess att produkten slängs eller återvinns. Miljöpåverkan i form av övergödning, försurning, påverkan på ozonskiktet, land- och vattenanvändning, klimatpåverkan osv. studeras. En klimatdeklaration kan ses som en delmängd av en livscykelanalys där endast påverkan på klimatet beaktas (SETAC, 2008; Weidema et al., 2008; Finkbeiner, 2009).

För att möjliggöra för konsumenter att göra aktiva klimatsmarta val kan klimatdeklarationen kommuniceras till konsumenter genom olika märkningssystem, via marknadsföring eller webbsidor. Även då det är svårt att beräkna och framförallt kommunicera klimatdeklarationer, och trots att sådana system ifrågasätts, finns på marknaden idag flera system i begränsad användning (Berry et al., 2008; Olofdotter & Juul, 2008; Schmidt, 2009).

Brittiska livsmedelskedjan Tesco var en föregångare inom området och introducerade klimatdeklarationer på några av sina produkter redan 2007 (Olofdotter & Juul, 2008). Som ett försök att tillhandahålla en enhetlig metod för att beräkna klimatdeklarationer utvecklade British Standards Institute en specifikation över en metod, PAS 2050, ”Specification for assessment of the life cycle GHG of goods and services” (BSI, 2008). Den bygger på befintlig LCA-metodik enligt standarderna ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b).

I Sverige driver KRAV och Svenskt Sigill tillsammans projektet Klimatmärkningen för mat (CLfF) (CLfF, 2009). De har valt att angripa problemet från en annan vinkel. Istället för att beräkna ett numeriskt värde på klimatgasutsläppen, bygger systemet på ett antal regler som producenten måste rätta sig efter för att få klimatmärka sina produkter. Under hösten 2008, startade även ISO utvecklingen av en internationell standard för klimatdeklarationer för produkter (ISO 14067), som även den bygger på de befintliga ISO-standarderna för LCA.

Det återstår att se hur klimatmärkningssystem kommer att utformas, vilka standarder som kommer att användas och huruvida det är möjligt att utforma ett system som får en signifikant påverkan på konsumtionsmönster. Med tanke på uppmärksamheten och intresset kring klimatdeklarationer är det dock troligt att klimatdeklarationer kommer att användas av företag för att stärka sitt varumärke och differentiera sina produkter (Carbon Trust, 2008b). Då klimatdeklarationerna kommer att sammankopplas med ekonomiska värden, kommer fokus på korrekthet, precision och tillförlitlighet i de beräknade siffrorna att öka.

Att beräkna klimatdeklarationer är komplext av flera anledningar. En av utmaningarna är variationen i naturliga processer. Variation är en inbyggd egenskap hos ett system och kan inte, till skillnad från osäkerhet, minskas med mer tillförlitlig modellering eller datainsamling. Utöver variationen i de naturliga processerna bidrar olika typer av osäkerhet i modeller och data till den totala osäkerheten i resultatet. Detta har beskrivits av Björklund (2002) och Heijungs & Huijbregts (2004) med flera. Osäkerhets- och känslighetsanalys kan användas för att beräkna olika parametrars bidrag till den totala osäkerheten (Heijungs & Huijbregts, 2004). Resultat från sådana studier kan användas för att bedöma om ett klimatdeklarationssystem har en acceptabel nivå av precision. Resultaten från osäkerhetsanalyser kan också användas för att bedöma var fokus bör ligga när modeller förbättras, samt hjälpa till med att bedöma hur troliga förutspådda resultat, i detta fall utsläppsminskningar, är.

## Syfte och mål

Målet med denna studie var att för ett typiskt livsmedel beräkna osäkerheten i klimatdeklarationen beroende på naturliga variationer samt osäkerheter i indata och i viss mån beräkningsmodeller. Målet var också att utreda vilka parametrar (inklusive deras upplösning i tid och rum) och processer som påverkar osäkerheten i slutresultatet. Matpotatis valdes som exempelgröda, dels eftersom det är ett av våra vanligaste svenska livsmedel och dels eftersom potatis är en produkt som säljs med liten förädling, samt att potatis är lätt att spåra. Det gör att en fallstudie på potatis blir illustrativ för hur osäkerhetsanalys på livsmedel kan utföras, samt relevant för en allmän diskussion kring osäkerheter i klimatdeklarationer av livsmedel.

Att förstå hur naturliga variationer och osäkerheter i livsmedelsproduktion påverkar resultatet av klimatdeklarationer är viktigt. Framförallt kan produktjämförelser, det slutgiltiga målet med klimatdeklarationer, inte göras utan att man känner till hur tillförlitliga resultaten är. Som ett exempel på en jämförelse av produkter från olika produktionssystem inkluderar denna studie en kvantifiering av sannolikheten att en godtycklig påse potatis som producerats enligt CLfFs regler har lett till en minskning av utsläppen av växthusgaser, i jämförelse med med en påse som producerats utan hänsyn till dessa regler.

## Material och metoder

En LCA-studie innefattande omfattande osäkerhet och känslighetsanalyser utfördes på den funktionella enheten ett kilogram King Edward matpotatis förpackad i en 2-kilos papperspåse tillgänglig för försäljning i en svensk mataffär. Den del av livscykeln som sker efter leverans till butiken ingår ej.

Eftersom det är vanligt att sort och produktionsplats anges på potatispåsen i Sverige låstes dessa parametrar till King Edward och Östergötland. I Östergötland sker odling på sandjordar med låga mullhalter. Det antogs att endast konstgödsel användas. Utsäde köptes in till gårdarna och reproducerade en gång på gården. Skörden lagrade i en kall, oventilerad lagringshall och kördes till förpackningsanläggningen med traktor och kärra. Där tvättades, sorterades och packades potatisen innan den slutligen distribuerades i lastbil till antingen Stockholm eller närområdet för försäljning.

Följande processers utsläpp av växthusgaser togs med i studien:

- Nitrifikation och denitrifikation som ger upphov till lustgasutsläpp från marken
- Ändringar i markens kolbalans som ger upphov till koldioxidutsläpp från marken eller inlagring av kol i marken
- Förbränning av traktorbränsle (diesel)
- Elförbrukning på gården
- Produktion och transport av insatsvaror (gödselmedel, kemikalier, bränsle, utsäde, papperspåse och el)
- Produktion, underhåll och avfallshantering av jordbruksmaskiner och byggnader
- Elförbrukning i paketeringsprocessen
- Transport och distribution av potatisen

Alla utsläpp fördelades jämnt på den del av skörden som gick att använda för någon typ av humankonsumtion, trots att potatis säljs till olika priser beroende på kvalitet. Det antogs att all potatis som inte gick att använda till humankonsumtion spreds på fältet.

För alla parametrar bestämdes ett medelvärde och två sannolikhetsfördelningar, en för variationen, till exempel variationer i ler- och mullhalt mellan fält och avkastningsvariationer mellan år, samt en fördelning över osäkerheten i parametern, dvs. mätosäkerheten.

Alla parametrar, förutom data över maskiner och byggnader, som beskriver odlingssystemet, förädlingsledet och transporter, såsom jordtyper, avkastningsnivåer, gödsel- och energianvändning, transportsträckor (aktivitetsdata, AD) samlades in direkt från rådgivare med expertkunskaper i potatisodling i Östergötland samt från paketeringsanläggningen. Data över maskiner och byggnader togs från den europeiska databasen ecoinvent (ecoinvent Centre, 2007). Aktivitetsdata finns sammanfattad i tabell 1, 7 och 14.

Parametrar för att beräkna klimatgasutsläpp utifrån aktivitetsdata (emissionsfaktorer, EF) samlades in från befintlig litteratur samt genom direktkontakt med vissa tillverkare. Emissionsfaktorerna finns sammanfattade i tabell 15 och 24. Eftersom osäkerhetsmått för litteraturdata oftast saknades beskrevs emissionsfaktorerna med kvalitetsindikatorer och ett osäkerhetsmått beräknades utifrån dessa (Weidema & Wesnaes, 1996; Frischknecht et al., 2004).

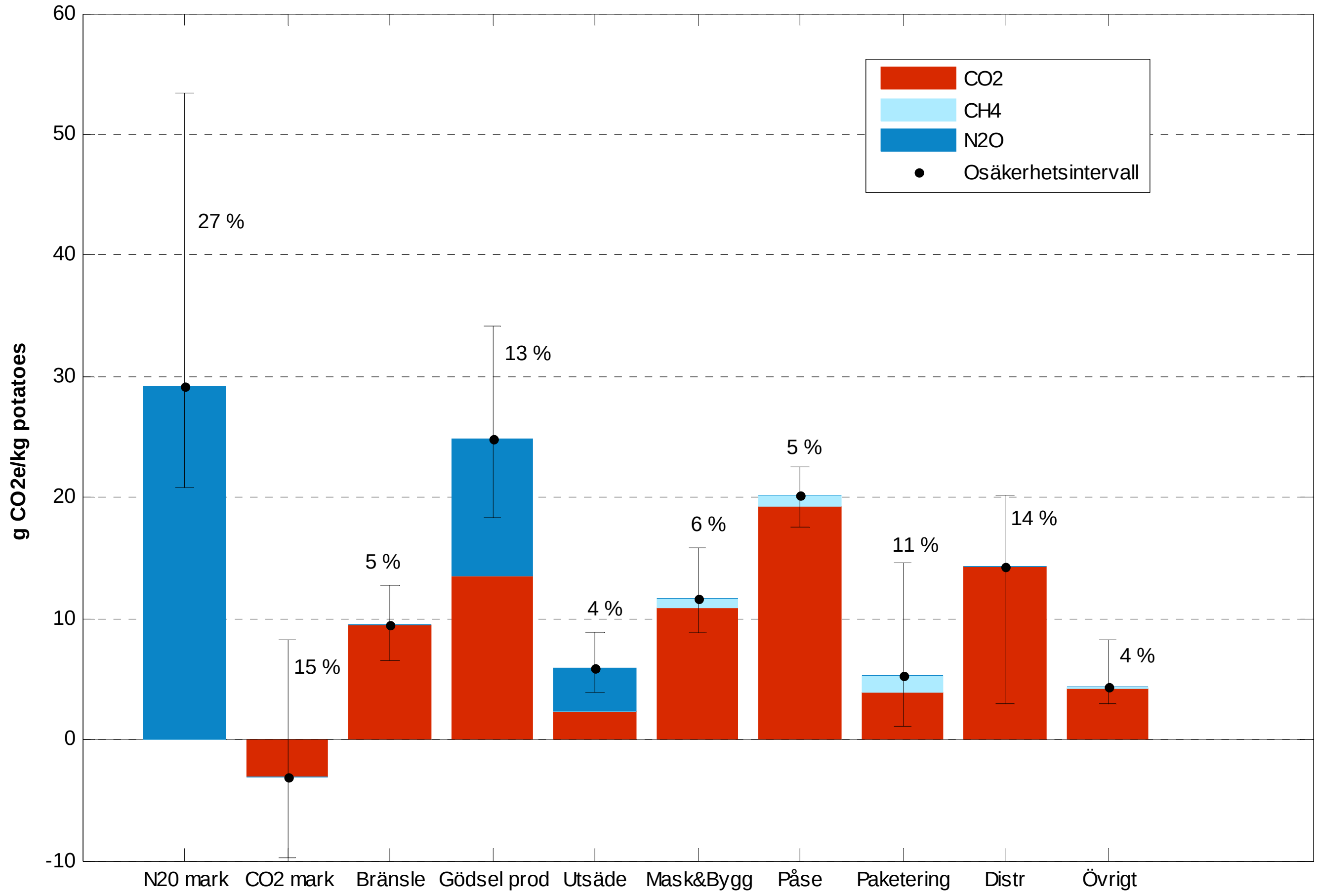
Lustgasavgång från mark beräknades med IPCCs (2006) metodik med vissa av emissionsfaktorerna reviderade enligt Kasimir-Klemedtsson (2001). Koldioxidavgång/kolinlagring i marken beräknades med ICBM-modellen (Andrén et al., 2004).

Referensåret var 2007 och resultaten antas gälla för perioden 2005-2009.

**Resultat**

Potatisens klimatpåverkan beräknades inledningsvis som ett deterministiskt medelvärde där parametrarnas medelvärde användes i beräkningarna. Resultatet blev ett klimatavtryck på 0,12 kg $CO_2$e per kg potatis. Med CLfFs klimatregler (utsläpp från kvävegödsel max 4 kg $CO_2$e/kg N och el från förnybara källor) sjönk medelvärdet med 9 % till 0,11 kg $CO_2$e/kg potatis.

De svarta stolparna i Figur 1 visar osäkerheten i de ingående processerna som ett 95-procentigt konfidensintervall (mellan 2.5-97.5 percentilerna). Relativa osäkerhetsmått beräknades som osäkerhetsintervallet delat med det deterministiska medelvärdet. Markemissioner visade sig stå för de största osäkerheterna, speciellt lustgasemissioner från mark med en relativ osäkerhet på 27 %.




*Figur 1: Klimatgasutsläpp från odling av potatis (King Edward) i Östergötland.*

Två typer av känslighetsanalyser genomfördes. Först gjordesen traditionell känslighetsanalys där parametrarnas värden förändrades med ± 20 %. Denna analys kompletterades med en andra känslighetsanalys där parametervärdena förändrades ± 2 standardavvikelser för normal- och log-normalfördelade parametrar. För diskret fördelade parametrar användes största och minsta värdet.

Den traditionella känslighetsanalysen visade att avkastningen, kvaliteten (andelen av skörden som kan säljas för humankonsumtion) och mängden kvävegödselmedel var de känsligaste parametrarna. Resultatet från känslighetsanalyserna visas i tabell 30. Den andra känslighetsanalysen som använde realistiska osäkerheter avslöjade att även markens humushalt, mängd traktorbränsle, elanvändning i paketeringsprocessen, distributionsavståndet och två av emissionsfaktorerna för lustgas var viktiga för slutresultatet. Detta visar tydligt hur en traditionell känslighetsanalys kan missa att upptäcka känslighet i parametrar som inte är normal- eller uniformt fördelade.

Monte Carlo (MC) - simulering (Rubinstein & Kroese, 2007) användes för att bestämma den totala osäkerheten i slutresultatet. I en MC-simulering beräknas klimatavtrycket ett stort antal gånger (50 000 gånger i denna studie). I varje beräkning dras parametervärden slumpmässigt ur de fördelningar som beskriver parameterns troliga värden. På så sätt fås ur en MC-simulering ett stort antal realistiska slutresultat på klimatavtrycket. För ett fall som beskriver ett godtyckligt år och ett godtyckligt fält (basscenariot a1) hamnade 95 % av resultaten från MC-simuleringen i intervallet 0,10-0,16 kg $CO_2$e/kg potatis. I detta fall har alla variationer och osäkerheter tagits med.

Om den spatiala upplösningen låstes till ett fält, dvs. endast osäkerhet och inte variation i markens ler- och humushalt samt avståndet mellan fält och gård togs med, minskade inte osäkerheten utan den låg kvar på 0,10-0,16 kg $CO_2$e/kg potatis. Om däremot året låstes till ett visst år, dvs. endast osäkerheter och inte variation togs med för avkastning, kvalitet, bränsleförbrukning, gödselmängder etc. sjönk osäkerheten med 19 % (ett intervall på 0,11-0,15).

Produktion enligt CLfF reglerna gjorde att 95 % av resultaten från MC-simuleringen hamnade mellan 0,091-0,15 kg $CO_2$e/kg potatis för ett godtyckligt år och fält. Klimatavtrycket minskade alltså men osäkerheten sjönk endast ytterst marginellt. (Se tabell 27 för fler fallstudier.)

Genom att parvis räkna ut skillnaden i klimatavtryck mellan resultat från basscenariot och scenariot där CLfF-reglerna applicerats, erhölls ett mått på sannolikheten att en påse potatis i affären som producerats enligt CLfF-reglerna orsakat mindre utsläpp än en påse potatis som producerats utan hänsyn till dessa regler. Det visade sig att en påse producerad enligt CLfF-reglerna med 72 % sannolikhet bidragit till minskade utsläpp. En sänkning på 9 %, den deterministiska medelsänkningen, uppnås med en sannolikhet på 53 %.

**Diskussion**

Avkastningen visade sig vara den mest inflytelserika parametern. Detta är gemensamt för alla jordbruksprodukter, eftersom utsläppen från en viss area delas upp på avkastningen från den arean. Maximerade skördar sänker alltså klimatavtrycket. Numeriska märkningssystem inkluderar detta förhållande, men det måste beaktas med vilken upplösning skördestatistik (och annan data) ska samlas in och hur variationer mellan år skall hanteras. Hur detta görs beror på syftet med märkningssystemet. Om syftet är att stimulera individuella producenter att minska sina utsläpp, måste data från varje enskild producent samlas in. Det mest korrekta klimatavtrycket skulle fås om data samlades in för varje år och fält, men det blir knappast meningsfullt och/eller rättvist att använda i ett märkningssystem eftersom skördar kan variera betydligt utan att odlingssättet förändrats, beroende på väder etc. Ett korrekt utformat märkningssystem bör inte straffa producenter pga. faktorer de inte kan styra över, utan skall gynna höga skördar som ett resultat av bra odlingssystem, vilket leder till genomsnittligt bra skördar. Från den synvinkeln är det således bättre att använda ett medelvärde över flera år i ett numeriskt märkningssystem.

Att tillhandahålla konsumentledning som maximerar utsläppsminskningspotentialen från livsmedelsproduktionen som helhet är ett annan möjligt mål med ett märkningssystem. Ett sådant system måste möjliggöra jämförelser mellan olika typer av produkter och där kan det räcka med ett potatisklimatavtryck på nationell eller regional nivå. Genom att bygga vidare på arbetet i denna studie, kan osäkerheten i ett sådant nationellt klimatavtryck bestämmas och man kan avgöra om det är möjligt att ha ett klimatavtrycksvärde för hela Sveriges potatisproduktion med tillräckligt stor noggrannhet att det möjliggör jämförelser med liknande produkter.

Fokusering på att maximera skördenivåerna för att sänka klimatavtrycket kan få allvarliga konsekvenser på andra miljömål. Produktion och användning av växtskyddsmedel har stor miljpåverkan men mycket liten inverkan på klimatavtrycket. Potatis är en gröda som besprutas relativt mycket, speciellt med svampmedel, men detta märks inte i klimatavtrycket. Hur andra miljömål påverkas av olika typer av märkningssystem är ett område där ytterligare forskning behövs.

Mängden kvävegödselmedel är en viktig parameter eftersom den påverkar de två mest bidragande processerna, utsläpp av lustgas från mark och tillverkning av konstgödsel.

Hushållning med kväve är således viktigt inte bara för övergödningen utan även för klimatpåverkan. Vidare bidrar de icke-linjära och svårbedömda markprocesserna till stora osäkerheter i slutresultatet, framför allt lustgasavgång från mark, vilken dessutom är den process som bidrar mest till klimatavtrycket. Metoderna som används idag för att beräkna lustgasavgång från mark är trubbiga och tar inte hänsyn till jordtyp, brukningsmetoder, typ av gröda osv. Detta är ett viktigt forskningsområde för att osäkerheterna i klimatavtrycken av livsmedel ska kunna minska. Kolavgången från, respektive inbindningen i mark skulle kunna beräknas noggrannare än vad som gjorts i denna studie med ICBM-modellen (Andrén, 2004), men det kräver datainsamling på en nivå som idag inte är praktiskt realiserbart i ett kommersiellt jordbruk.

En jämförelse mellan potatis odlad med och utan CLfF klimatregler visade att ungefär hälften av de klimatproducerade potatispåsarna producerats med en sänkning av utsläppen på med 9 % (den deterministiska medelsänkningen). Självklart skall åtgärder som användning av ”ren” gödsel och el alltid genomföras, men exemplet visar att vid införandet av numeriska märkningssystem eller mer komplexa regler, kan osäkerhetsanalys inte försummas.

### Slutsats

Klimatavtrycket för King Edward matpotatis odlad i Östergötland varierade mellan ca -17 % och +30 % från medelvärdet 0,12 kg $CO_2$e per kg potatis med 95 % säkerhet. Beräkningen av klimatavtrycket för ett visst fält minskade inte osäkerheten. Beräkning för ett visst år minskade osäkerhetsintervallet med endast 19 %. Sannolikheten att en klimatproducerad (CLfF regler enligt april 2009) potatispåse producerats med lägre utsläpp som följd visade sig vara 72 %.

En naturlig fråga blir: Vad är en accepterbar nivå av osäkerhet? Frågan är mer filosofisk än naturvetenskaplig. Klart är dock att nivån på osäkerheten som kan godtas beror på målsättningen med märkningssystemet. Osäkerheten måste vara tillräckligt låg för att jämföra potatis från olika producenter, om målsättningen är att stimulera enskilda producenter till att göra utsläppsminskningar. Om målsättningen är att möjliggöra val för konsumenter som får stor inverkan på utsläppsminskningen måste osäkerheten vara tillräckligt låg för att möjliggöra val mellan potatis och andra, med potatis jämförbara, produkter.

## FOREWORD

This report contains background data for the article:

- Röös E., Sundberg C. & Hansson P-A. 2010. Uncertainties in the carbon footprint of food products: A case study on table potatoes, *International Journal of LCA*, accepted for publication 2010-01-17.

The work carried out in the project leading up to this report formed part of my PhD project, *Carbon Declarations of Food Products*, carried out at the Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala. I would like to thank my supervisors and article co-authors Cecilia Sundberg and Per-Anders Hansson for their support throughout the project.

I would also like to thank Dietrich von Rosen and Johannes Forkman for statistical support, Olof Andrén and Thomas Kätterer for help with the soil carbon estimates, and Johan Arvidsson with help on the relationship between soil clay content and tractor fuel consumption.

Finally I would like to thank all experts listed in the reference list for providing the data and knowledge that made this project possible.

Elin Röös

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**CONTENTS**

# 1 BACKGROUND

Consumption of food products contributes approximately 25% of the total greenhouse gas (GHG) emissions caused by the average Swede (SEPA, 2008a). With growing public awareness about climate change, there is an increasing willingness on the part of individuals to lower their GHG emissions due to food consumption (Toivonen, 2007; L.E.K., 2008; SEPA, 2008b). Determining the climate impact caused by a food product is very difficult for consumers, as aspects such as product type, production system, packaging, origin, transport etc. need to be weighed together (Jungbluth et al., 2000).

Carbon footprint (CF) and carbon declaration are terms that have evolved to describe the amount of GHG emissions that a particular product or service will cause during its lifetime, typically expressed in $CO_2$ equivalents ($CO_2e$) and including emissions of $CO_2$, $CH_4$ and $N_2O$. A CF can be seen as a subset of a Life Cycle Assessment (LCA) in which only the global warming potential (GWP) impact category is studied (SETAC, 2008; Weidema et al., 2008; Finkbeiner, 2009). In order to facilitate active choices by individuals, the CF can be communicated to consumers in different ways; through a carbon or climate label on the product package or at the point of sale, in marketing or via a website. Although calculating and, in particular, communicating the CF is difficult and the potential of such systems is being questioned, several climate labelling systems are being discussed and some are already in limited use (Berry et al., 2008; Olofdotter & Juul, 2008; Schmidt, 2009).

The British supermarket Tesco became a forerunner in the area of food product CF by introducing a carbon label with the CF of some of its food products back in 2007 (Olofdotter & Juul, 2008). In an attempt to provide a consistent method for calculating the CF of products and services, the British Standards Institute developed the PAS 2050 Specification for assessment of the life cycle GHG of goods and services (BSI, 2008). It builds on the existing LCA methods standardised in ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b) and adds further principles specific to GHG assessment. The Carbon Trust is now heading the first application of the PAS 2050 in the UK as it helps companies with the calculation and communication of CF and has developed a code of good practice for the PAS 2050 specification (Carbon Trust, 2008a). The focus is currently set on emission reduction of individual products as opposed to comparison between products. The Carbon Label supplied by the Carbon Trust contains a numerical value of the CF, but currently the purpose of the number is to serve as proof that the committed reduction has actually been achieved. The aim of the Carbon Trust activity in the long run is the introduction of a system that will make it possible to distinguish between low and high emitting products, and not only between products for which producers are committed to lower the emissions and those who are not explicitly expressing so, as is the case at present.

In Sweden, KRAV and Seal Quality Systems Ltd[1] are jointly driving the Climate Labelling for Food (CLfF) project (CLfF, 2009). The CLfF project has approached the task from a slightly different angle and instead of calculating a numerical CF, the system builds on a set of rules that the producer has to obey in order to be allowed to label the products. LCA

[1] KRAV is an incorporated association with 28 members representing farmers, producers, trade and consumers, as well as environmental and animal welfare interests. KRAV develops organic standards and promotes the KRAV label for organic products.

Seal Quality Systems Ltd is a wholly owned subsidiary of the Federation of Swedish Farmers (LRF). Seal Quality Systems Ltd owns and develops rules for the Swedish Seal of Quality (Svenskt Sigill) label (conventional farming).

methodology, together with expert opinion, was used when developing the climate rules. During autumn 2008, ISO also initiated the development of an international standard on CF for products (ISO 14067), which will build on the existing ISO standards for LCA.

It remains to be seen how the systems for food CF will be designed, how the standards will be applied and whether it is possible to develop a CF system that will have a significant impact on consumption patterns. However, based on the immense momentum for CF calculations, it is likely that CF values will be used by companies for strengthening their corporate brand and for product differentiation (Carbon Trust, 2008b). As these CF will be connected to economic values, the focus on accuracy, precision and reliability in the numbers presented will be sharpened.

Determining the CF of a food product is complex for several reasons. One of the challenges is the variability in natural processes. Variability is an inherent property of a system and, unlike uncertainty, it cannot be reduced by more accurate modelling of the system or collection of the data. While some variations arise from differences in cultivation practices, others are less easily explained; one example being the difference in yield from similar fields. In addition to variations in the natural crop cultivation processes, there are variations in the subsequent processing and distribution processes. Although these later steps are more predictable, traceability of complex food products is an issue.

In addition to the intrinsic variability of natural processes, the magnitude of the variations in a system also depends on the temporal and spatial boundaries of the system under study. The variations in a cropping system can be reduced if only production from one specific field during one season is studied. The yield, the amounts of fertilisers and chemicals used will show no variation in this case. The other extreme is the study of production of a crop on a regional or national level for an arbitrary year, which will show considerable variation in several variables.

In addition to the spatial and temporal variation in natural processes, different types of uncertainty in models and data contribute to the uncertainty of the overall LCA result, as has been described by Björklund (2002) and Heijungs & Huijbregts (2004) among others. Uncertainty due to choices and mistakes and epistemological uncertainties and model uncertainties can be decreased to some extent by the use of standards and by critical review (Huijbregts, 1998; Björklund, 2002). Minimising inaccuracy in data requires careful data collection, which is often costly and time-consuming and in some cases not even practically possible.

Uncertainty and sensitivity analysis can be used to determine the contribution to the end result uncertainty from uncertainties in the input data and model parameters (Heijungs & Huijbregts, 2004). Results from such studies can be of help when determining whether a CF system provides an acceptable level of precision. Uncertainty analysis also identifies focal points for improving the models and contributes to greater understanding of the processes behind the CF. The results of an uncertainty analysis also help to determine the probability of a predicted reduction potential.

Uncertainty assessments of LCA data can be performed in different ways; by using empirical data to calculate the uncertainty distribution, by using expert judgement to make qualified estimates or by describing the data using quality indicators (Weidema & Wesnaes, 1996). In the ecoinvent database all data are described using seven quality indicators, one being the reliability indicator which describes whether the data are based on verified or unverified measurements, qualified or unqualified assumptions. The seven indicators are put together to form one numerical uncertainty measurement (Frischknecht et al., 2004).

# 2 GOAL AND SCOPE

The main aim of the present study was to quantify the uncertainty in the CF of a common food product resulting from natural variations and model and parameter uncertainty, in accordance with how data collection could be performed in a ‘real-life’ CF labelling system. A secondary aim was to investigate the particular parameters (including their temporal and spatial resolution) and processes influencing the uncertainty in the end result. Table potatoes were chosen as the study object since they are one of the most common staple food products on the Swedish market. They are a product that is sold with little processing and that is easily traced from the farm to the supermarket shelf. This makes a potato case study suitable for illustrating how uncertainty analysis of food products can be carried out and relevant for a general discussion of uncertainties in the CF of agricultural products.

Understanding the natural variation and uncertainties associated with food production and how they affect the CF is important. Most essentially, product comparison, the ultimate goal of CF analysis aimed at influencing consumer behaviour, can only be carried out with confidence if the range of uncertainty is known. As an example of a CF comparison for products from different production systems, this study includes a quantification of the probability that an arbitrary bag of table potatoes available for purchase in a supermarket and produced according to CLfF rules has led to a reduction in GHG emissions during production compared with a bag produced without specific climate actions being taken.

# 3 MATERIALS AND METHODS

## 3.1 Overview

The study consisted of a detailed investigation of the parameter variability and uncertainty in the CF of 1 kg of table potatoes[2] available for purchase in a 2 kg 'kraft' paper bag at a Swedish supermarket.

Since it is common Swedish practice that the information presented to the user on the potato package includes the potato variety and the producer, these parameters were fixed. The common variety King Edward was chosen and the production was assumed to take part at a fictitious but specific farm in Östergötland, Sweden, a region that produces 10% of the Swedish annual consumption of table potatoes (SCB, 2008a).

The CF constitutes a 'cradle to retail' inventory including emissions arising from soil preparation up until the potatoes are available for purchase on the shelf, including the production and transport of all inputs and the waste handling of any potatoes sorted out before transport to the supermarket.

## 3.2 The system and its boundaries

Potatoes are grown in a 4-6 year crop rotation, so the field used for potato cultivation, and hence the clay and humus content and the distance between the field and the farm, was assumed to vary between years. Cultivation on sandy soil with moderate humus content dominates and mineral fertilisers were assumed to be used. No cultivation on organic soil was included, since organic soils are unusual in Östergötland, although potatoes are a common crop on organic soils in other parts of Sweden.

Only synthetic fertilisers were assumed to be used, since only 29% of the potatoes in Sweden are fertilised with organic fertilisers (SCB, 2008c) and animal production is concentrated to other parts of Sweden.

Seed potatoes were assumed to be bought and reproduced on the farm once, before being used in potato production. The harvested potatoes were assumed to be stored on the farm in a cold storage facility and delivered by tractor and trailer to the packaging plant. After washing, sorting and packaging, the majority of the potatoes were assumed to be distributed for sale to Stockholm, the largest city in Sweden, and the rest sold locally.

Emissions from the production, maintenance and waste handling of agricultural machinery and buildings were included, since capital goods have been shown to contribute considerably (approximately 10%) to the climate impact of the production of agricultural products (Frischknecht et al., 2007).

Storage at the supermarket, transport from supermarket to household, preparation in the household and waste handling in the household of non-consumed potatoes, peelings and the paper bag were not included. The system boundaries are illustrated in Figure 1.

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[2] Fresh potatoes are not included in either the calculations or the discussion section.

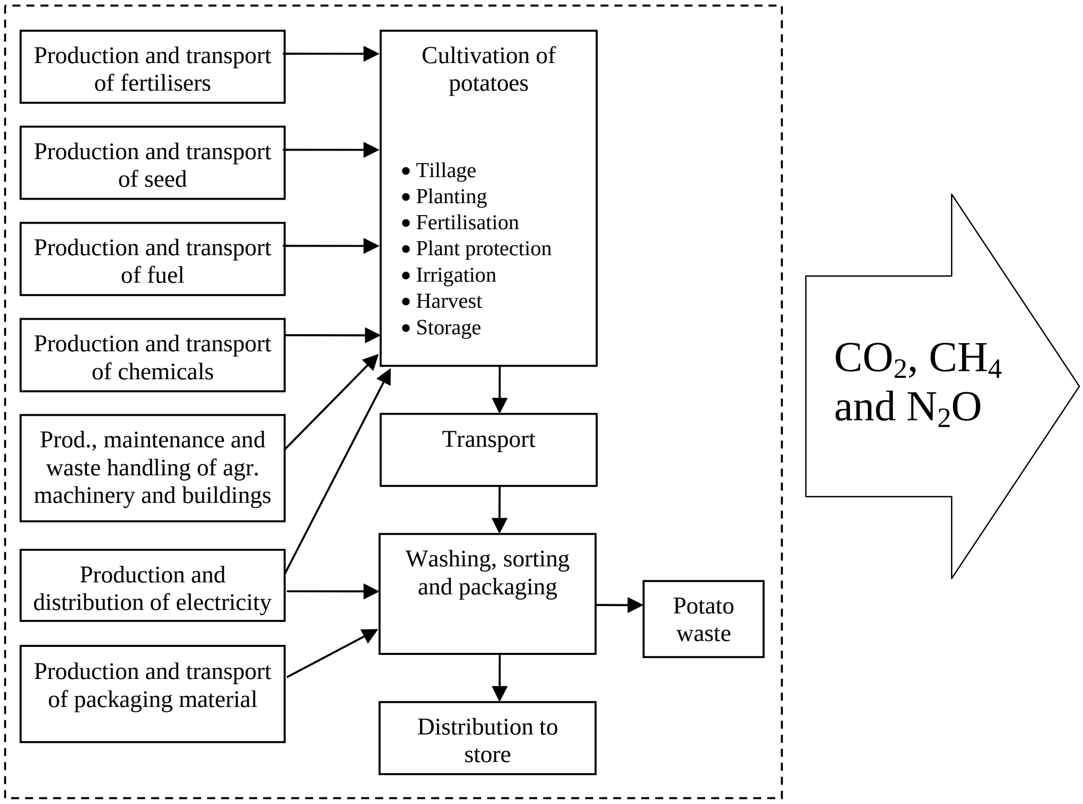



*Figure 1: Boundaries of the potato production system.*

The potato production system included in this study gives rise to GHG emissions through the following processes:

- Denitrification and nitrification in soil – giving rise to $N_2O$ emissions from soil
- Changes in the soil carbon pool – giving rise to $CO_2$ emissions or sequestration from/to soil
- Fuel combustion during field operations
- Electricity consumption on the farm
- Production and transport of inputs
  - Fertilisers
  - Chemicals
  - Tractor fuel
  - Seed
  - Packaging paper
  - Electricity
- Production, maintenance and waste handling of agricultural machinery and buildings
- Electricity consumption during the packaging process
- Transport and distribution of the potatoes

### 3.3 Functional unit

Functional unit (f.u.) was set to 1 kg of potatoes in a 2 kg ‘kraft’ paper bag ready for sale at a supermarket selling potatoes from the Östergötland region.

## 3.4 Allocations and system expansion

All GHG emissions were allocated to the marketable potatoes uniformly, disregarding the fact that potatoes are sold at different prices for different qualities. All potatoes not marketable as table potatoes were assumed to be spread on the field according to common practice. During reproduction of seed potatoes, fractions of suitable sizes were assumed to be used as seed and the rest sold as table potatoes minus the unmarketable fraction, which was removed. An equal burden was allocated to the seed potatoes and the fraction sold as table potatoes.

## 3.5 Data collection

The parameter data in this study were collected in accordance with how data could realistically be collected from the existing Swedish potato production chain for use in a CF system, without the introduction of extended accounting regulations or measuring equipment. This gives an estimate of the precision of the table potato CF if introduced into the current Swedish production system and calculated using existing and practically applicable models. The reference year was 2007, but the data are approximately applicable for at least two preceding and subsequent years.

The uncertainty in the data depends on the circumstances under which the data were collected. For example, in the case of performing a field trial, in order to study the tractor fuel consumption during different field operations, the tractor would be equipped with fuel measurement equipment and the consumption would be closely monitored, leading to a low degree of uncertainty. However, in the case of normal crop cultivation the uncertainty in the tractor fuel consumption would be larger due to the lack of precise measurement equipment and continuous recording of the consumption during operations for different crops and purposes.

The parameters were split into two types: 1) activity data and 2) emission factors. Activity data (AD) were directly measurable parameters describing for example the amounts of inputs spent, such as the amount of fuels, fertilisers and chemicals, and descriptive parameters such as the soil humus content and the transport distance. The emission factors (EF) included: 1) EF for emissions caused by the production and transport of inputs (EF-inputs), 2) EF for soil emissions (EF-soil) and EF for transport of potatoes (EF-transport). AD, except for capital goods, were collected as primary data, while secondary data were used to calculate the EF. This corresponds to how data would realistically be collected in a practical CF calculation. AD such as yield, fertiliser use, field operations performed, energy spent, etc. are already being recorded on farms, as this is a requirement from several certification programmes to which the majority of the producers in Östergötland belong. As long as the inputs themselves are not climate-labelled, it is realistic to assume that EF values need to be collected from the available literature.

The variations and uncertainties were assessed separately using probability distributions for all parameters individually. The distributions for variation outline the variability between years and fields for AD and between different ways of production for EF-inputs. The uncertainty distributions for AD describe the precision that can realistically be assumed when collecting the data from the potato production chain. Due to the large uncertainties in the models for calculating the soil emissions, it was not possible to divide the uncertainties in EF-soil into variations and uncertainties and hence both variations and uncertainties are grouped under uncertainties for these. Variations in EF-transport take into consideration the size of trailer used and the degree of loading.

### *3.5.1 Activity data overview*

The AD for potato production are summarised in Table 1. The confidence interval is 95%. These data, including the data used to estimate the distributions for the variations and uncertainties, were mostly collected directly from agricultural advisors, producers and the packaging plant, while some data were collected from the detailed Swedish table potato LCA conducted by Mattsson et al. (2001). In the present study it was not possible to use database or literature values for AD, since the goal was to estimate the uncertainty as accurately as possible for the specific situation of potato cultivation in Östergötland.

The AD describe fictitious but realistic production of King Edward potatoes in this region. On the spatial scale chosen, cultivation on a specific farm, it is realistic to assume that most parameters are independent, for example soil clay and humus content and yield. On the national level, however, or if the potato variety had not been specified, independency in the AD would not have been a realistic assumption, since yields vary considerably between potato varieties and different geographical locations in Sweden (SCB, 2008a). Examples of parameters that are correlated are the fuel consumption during tillage operations and the soil clay content, as heavier soils require more fuel, and amount of machinery used depending on the type of field operations performed. These correlations were included in the study. The distributions were truncated for unrealistic values, e.g. fertiliser values < 0. A detailed description of how the parameter distributions were assessed can be found in subsequent sections.

The AD describe a fictitious but realistic production situation, but do not claim to represent a true average or majority of the production of King Edward potatoes in the Östergötland region. However, that has no effect on the outcome or purpose of the study, which was to determine the variations and uncertainties for a specific but representative production situation.

*Table 1: Activity data (AD) on potato production*

| | Mean | Variation | | Uncertainty | |
|---|---|---|---|---|---|
| | | Distribution | Confidence interval 95%/ discrete values | Distribution | Confidence interval 95% |
| **Field-bound:** | | | | | |
| Clay content | 1.7% | Lognormal | 0.1-10% | Normal | ± 40% |
| Humus content | 1.8% | Lognormal | 0.8-3.6% | Normal | ± 40% |
| Distance farm-field | 0.75 km | Lognormal | 0.1-3 km | Normal | ± 7% |
| **Cultivation:** | | | | | |
| Yield | 45 ton/ha | Normal | ± 7 ton/ha | Normal | ± 2% |
| Quality | 85% | Normal | ± 3.5%-units | Normal | ± 1% |
| Fuel tillage operations | 142 l diesel/ha | Mix* | 70-266 l diesel/ha | Mix* | 70-266 l diesel/ha |
| Amount of N fertiliser | 145 kg/ha | Normal | ± 20 kg/ha | Normal | ± 10% |
| Amount of P fertiliser | 50 kg/ha | Normal | ± 10 kg/ha | Normal | ± 10% |
| Amount of K fertiliser | 250 kg/ha | Normal | ± 50 kg/ha | Normal | ± 10% |
| Amount of seed | 2.5 ton/ha | Normal | ± 0.5 ton/ha | Normal | ± 2% |
| Chemical treatments | 102 g/ha | Discrete | 0-202 g/ha | Normal | ± 5% |
| Amount of irrigation | 50 mm/ha | Discrete | 0, 25, 50, 75, 100 mm | Normal | ± 5% |
| Amount of agr. machinery | 83 kg/ha | Mix** | 48-130 | Mix** | ± 10% |
| Amount of agr. Buildings | 0.32 $m^2$/ f.u. | Negligible | - | Normal | ± 10% |
| **Processing:** | | | | | |
| Energy use in packaging process | 0.22 MJ/f.u. | Lognormal | 0.07-0.54 MJ/f.u. | Normal | ± 5% |
| Amount of ‘kraft’ paper | 23.6 g | Negligible | - | Normal | ± 0.5% |
| **Transport:** | | | | | |
| Distance, farm to packaging plant | 20 km | Normal | ± 10 km | Normal | ± 7% |
| Distance, packaging plant to store | 210 km | Discrete | 80% - 250 km<br>20% - 50 km | Normal | ± 7% |

* The distribution for fuel consumption variation is a mixture of a discrete distribution of the number of repetitions for different operations and normal distributions describing variation due to the soil clay content, different driving styles and the combination of tractor and equipment.

* The distribution for the variation in the amount of machinery is a mixture of a discrete distribution of the number of repetitions for different operations and normal distributions describing variation due to the soil clay content, weight and lifetime differences.

### 3.5.2 *Activity data – field-bound*

#### *3.5.2.1 Overview*

Field-bound AD are parameters that describe a specific field. Included in this study are the soil clay and humus contents, as well as the distance from the field to the farm. The average field size was set to 5 ha (H. Augustinsson, P. Gustafsson, A. Kronhed, pers. comm. 2009).

It was assumed that the uncertainty in assessing the soil clay and humus content is the measurement uncertainty associated with soil mapping carried out in accordance with the principles drawn up by the Swedish Board of Agriculture (SJV). These include point mapping with at least one measurement point per hectare. At each point, 10 boreholes should be made down to a depth of 20 cm within an area with a radius of 3-5 m (SJV, 2002).

However, measurements of clay and humus content during soil mapping are only recommended in special cases in order to determine the need for calcium. However, in this study it was assumed that such measurements were performed during the ordinary soil mapping, since potato growers often have better knowledge of the soil conditions than the average farmer, due to the quality of the potatoes being very sensitive to the soil nutrient balance (P. Gustafsson, A. Kronhed, E. Winding, pers. comm. 2009).

#### *3.5.2.2 Clay content*

The soil clay content was used for calculating the fuel consumption during field operations, since tillage of soil with higher clay content requires more traction power (see section 3.5.3.4).

Potatoes are most commonly grown on light soils (Fogelfors, 2001). Cultivation on organic soils also exists (H. Augustinsson, P. Gustafsson, A. Kronhed, pers. comm. 2009), but was not included in this study, since organic soils are not common in the Östergötland region.

<u>Variation</u>

The variation in the clay content is the variation between different fields, since this was the finest geographical granularity used in this study.

In order to assess the variations in soil clay content between different fields, opinions from the experts listed in Table 2 were taken into account.

*Table 2: Variation in clay content, expert opinion*

| Expert | Variation |
|---|---|
| Eric Winding | Sandy soils and organic soils, cannot give a limit for clay content, mentions that further south, some cultivation on lighter clay soils does exist. |
| Andreas Kronhed | Sandy soil cultivation dominates, some cultivation on clay soils up to 15%, even some rare cases up to 20-25%. |
| Hans Augustinsson | Confirms information from Andreas Kronhed. |
| Pirjo Gustafsson | Confirms information from Andreas Kronhed. |

In order to reflect the fact that the vast majority of potato cultivation in the Östergötland region takes place on sandy soils, which by definition contain less than 2% clay, a lognormal distribution was chosen with a mean of 1.7% and a 95% confidence interval between 0.1 and 10% clay. The distribution includes the less common cultivation on clay soils in its tail.

Uncertainty

The relevant uncertainty in the soil clay content is the Standard Error of the Mean (SEM) on a per field basis. The SEM is a measurement of how well the mean represents the true value and is defined as standard deviation divided by the square root of the number of observations.

The SEM gives a measurement of the accuracy in the soil clay content mean value that is reported for a specific field.

- Uncertainty due to intra-field variation

The intra-field variation is needed in order to calculate SEM. Since this study did not examine variations down to specific parts of the field, it is not important how the clay is spread across the field.

The intra-field variations in several nutrients in Swedish agricultural soils were investigated by Söderström (2008), who showed that the level of K-HCl is correlated to the soil clay content. Measurements of K-HCl presented in Söderström (2008) were used to estimate the coefficient of variation to 30%, which thus describes a typical intra-field variation for soil clay content.

- Measuring uncertainty

The measuring uncertainty in the laboratory is ± 20% (95% confidence interval, normal distribution). Additional uncertainty is introduced during the actual gathering of the soil samples in the field, which is larger than the laboratory measuring uncertainty. Numbers as high as ± 100% have been recorded, but are rare (P-O. Persson, pers. comm. 2009). An uncertainty of ± 50% (95% confidence interval, normal distribution) was assumed for the sample gathering.

- Total uncertainty

The recommendation for soil mapping is to take one sample per hectare. The average field size of 5 ha gave a SEM of approximately 40% (95% confidence interval, normal distribution).

*3.5.2.3 Humus content*

The soil humus content was used when calculating the soil carbon content, which was needed in order to determine how the soil carbon balance is affected by potato cultivation (see section 3.5.9.2).

Variation

The light soils used for potato cultivation are low in humus content.

In order to assess the variations in humus content in soil types used in potato cultivation in Östergötland, opinions from the experts listed in Table 3 were taken into account.

*Table 3: Variation in humus content, expert opinion*

| Expert | Variation |
|---|---|
| Jan Ericsson | Has never experienced a soil with less than 0.8% humus, humus content follows the clay content. |
| Andreas Kronhed | Usually very low humus content, very seldom more than 3%. |
| Hans Augustinsson | Confirms information from Andreas Kronhed. |
| Pirjo Gustafsson | Confirms information from Andreas Kronhed. |

In order to reflect the fact that the overwhelming majority of potato cultivation in the Östergötland region takes place on sandy soils with a low humus content, which seldom exceeds 3%, a lognormal distribution with a mean of 1.8% and a 95% confidence interval of 0.8-3.6% was used in the calculations.

<u>Uncertainty</u>

- Uncertainty in the mean value

Following the same reasoning as for soil clay content, the SEM for the humus content was also estimated to 30% based on data presented in Söderström et al. (2008).

- Measuring uncertainty

The measuring uncertainty for humus content in the laboratory is 15% (95% confidence interval, normal distribution). Additional uncertainty is introduced during the actual gathering of the soil samples in the field, which is larger than the measuring uncertainty. Numbers as high as ± 100% have been recorded but are rare (P-O. Persson, pers. comm. 2009). An uncertainty of ± 50% (95% confidence interval, normal distribution) was assumed for the sample gathering.

- Total uncertainty

The recommendation for soil mapping is to take one sample per hectare. The average field size of 5 ha gave a SEM of approximately 40%.

#### *3.5.2.4 Distance farm-field*

The distance between the farm and the field affects the fuel consumption when transporting machinery, fertilisers and the harvested produce to/from the field.

<u>Variation</u>

Information from the experts in Table 4 was used when assessing the variation in the distance between the farm and the field.

*Table 4: Variation in distance farm-field, expert opinion*

| Expert | Variation |
|---|---|
| Eric Winding | 2-1500 m (for far away fields, the inputs are delivered by lorry instead of tractor). |
| Andreas Kronhed | 50- 3000 m, |
| Hans Augustinsson | Approx. 1 km, larger farms have larger distances due to the need for new land in order to follow the crop rotation. |
| Pirjo Gustafsson | Confirms information from Andreas Kronhed and Hans Augustinsson. |

A lognormal distribution was used for the distance between the farm and the field, assuming that the majority of the fields used for potato cultivation are located at an average distance of 0.75 km from the farm (or input storage). Fields can be located further away, past the 95%-limit of 3 km with less probability.

It can happen that a farmer rents farm land from surrounding farmers in order to be able to handle a 4-6 year crop rotation. In that case and in cases where the farmer owns land further away, the distances could be considerably larger than 3 km, as in the case reported by Eric

Winding above. However, the inputs and the harvest are then delivered to/from the field using a lorry or a tractor with a high capacity trailer, and not by individual tractor runs, making it realistic to cover those cases with the lognormal distribution between 0.1 and 3 km.

Uncertainty

See uncertainty distribution of the distance between plant and store, section 3.5.5.2.

### 3.5.3 Activity data – cultivation

#### 3.5.3.1 Overview

AD related to potato cultivation, or primary production, are described in this section.

#### 3.5.3.2 Yield

Emissions calculated per hectare were divided across the usable yield (yield times quality factor) in order to calculate emissions per f.u.

Variation

The yield level used in Mattsson et al. (2001) was 45 ton/ha for King Edward from the Östergötland region. That showed good agreement with the yield data collected from the experts (see Table 5).

*Table 5: Variation in yield, expert opinion*

| Expert | Variation |
|---|---|
| Andreas Kronhed | Average 45 ton/ha, varies between 38 and 52 to/ha with 95% confidence. |
| Hans Augustinsson | Average 45 ton/ha, varies between 35 and 50 ton/ha with 95% confidence. |
| Pirjo Gustafsson | Average 45 ton/ha, varies between 38 and 52 ton/ha with 95% confidence, based on data from GROs test digging. |

The yield was assumed to follow a normal distribution with a mean of 45 ton/ha and a 95% confidence interval of ± 7 ton/ha.

Uncertainty

The yield uncertainty gives a measurement of the precision with which the producer can estimate the yield size. During harvest, wooden boxes are filled with potatoes and transported to storage. The farmer knows the weight of a box filled with potatoes and the yield is estimated by calculating the number of boxes. All experts in Table 5 stated that the measuring uncertainty in the yield is small, approximately a few percent.

The yield uncertainty was assumed to be normally distributed with a 95% confidence interval of ± 2%.

#### 3.5.3.3 Quality

A non-negligible amount of the yield is not used for human consumption due to diseases, mechanical damage or the potatoes being too small or too big. In the Östergötland region the most common practice is for the entire yield to be delivered to the packaging facility, where it is sorted. Therefore, all loss occurred at the packaging plant in the system studied here.

The quality parameter is the percentage of the yield that is sold for human consumption in some form. This quality parameter differs between potato varieties and also due to the geographical location of the cultivation site, since different parts of Sweden have different possibilities to utilise potatoes not used for human consumption. For example, small fractions in the Östergötland region are used for delicacy potatoes, since that is a product manufactured by the packaging facility Swegro in Skänninge, while in the Uppland region there is no use for these fractions and they are given as feed to wild animals (E. Winding, A. Magnusson, pers. comm. 2009).

The same burden was allocated to all potatoes, including delicacy potatoes, although potatoes are sold at different prices for different qualities.

Variation

Expert opinion on quality is summarised in Table 6.

*Table 6: Variation in quality, expert opinion*

| Expert | Variation |
|---|---|
| Anders Magnusson | 75% sold as table potatoes, 5% sorted as a large fraction and sold as such, and 5% sorted as a small fraction and sold as delicacy potatoes, small variations. |
| Andreas Kronhed | 70-75% sold as table potatoes, approx 15% used as delicacy potatoes and large potatoes, 10% waste. |
| Hans Augustinsson | 70-75% sold as table potatoes, confirms the information from Anders Magnusson. |
| Pirjo Gustafsson | Confirms information from the above, based on GRO statistics. |

SCB presents potato yield statistics as reduced yield per hectare. The reduced yield is calculated by decreasing the yield for potatoes not used by a standard factor of 9.5% (SCB, 2008b). Since King Edward is a potato variety known to show lower quality compared with other varieties, the 15% loss assumed in this study is equivalent to the 9.5% used by SCB.

The mean value of the quality parameter was set at 85%, which includes the approximately 75% sold as table potatoes and the approximately 10% large and small fraction sold for other human consumption.

The quality parameter was assumed to vary normally with a mean of 85% and a 95% confidence interval of ± 3.5%-units (99% confidence interval of ± 5%)

Uncertainty

The uncertainty in the quality parameters was interpreted as the measuring uncertainty when packaging the potatoes into the bags. This is done in an automated process that weighs the potatoes on a scale with high precision (A. Agard, pers. comm. 2009). Hence the uncertainty in the quality parameter was assumed to be less than in the yield parameter and it was set to ±1%.

#### *3.5.3.4 Fuel consumption - field operations*

Potato cultivation requires a number of mandatory field operations regardless of the cultivation system used. Hence, these operations were assumed to always be performed. For professional cultivation these have to be complemented with a varying number of additional operations (Table 7).

*Table 7: Field operations in potato cultivation, and fuel consumption with its variations on soil with clay content 1.7%*

| Mandatory operations | Mean Rep | Discrete variation with equal probab. | Mean fuel consumption | Variation (95 % conf. interval) | Substance | Doses per repetition |
|---|---|---|---|---|---|---|
| Ploughing * | 1 | None | 10 l diesel/ha[1] | Variation due to driving manner: ± 30%<br><br>Variation due to the combination of tractor and equipment : ± 10%<br><br>Variation due to the soil clay content for operations marked with * , variation according to Pettersson & Arvidsson (2009) | n/a | n/a |
| Harrowing* | 1 | None | 3.7 l diesel/ha[1] | | n/a | n/a |
| Spreading of fertiliser | 1 | None | 2.0 l diesel/ha[2] | | Synthetic fertiliser | *** |
| Handling of fertiliser | 1 | None | 0.003 l diesel/ ha and kg NPK[2] | | n/a | n/a |
| Planting* | 1 | None | 10 l diesel/ha[1] | | n/a | n/a |
| Top-killing | 1 | None | 15 l diesel/ha[2] | | n/a | n/a |
| Harvest* | 1 | None | 62 l diesel/ha[2] | | n/a | n/a |
| Transport | 9 | None | 0.3 l diesel/km[3] | | n/a | n/a |
| Complementing operations | | | | | | |
| Inter-row rotary cultivator* | 1 | 0-2 | 3.7 l diesel/ha[1] | | n/a | n/a |
| De-stoner* | 0.5 | 0-1 | 10 l diesel/ha[1] | | n/a | n/a |
| Harrow, herbicides* | 0.5 | 0-1 | 3.7 l diesel/ha[1] | | n/a | n/a |
| Ridging* | 0.5 | 0-1 | 7.0 l diesel/ha[2] | | n/a | n/a |
| Additional fertiliser | 1 | 0-2 | 2.0 l diesel/ha[2] | | Synthetic fertiliser | *** |
| Irrigation | 2 | 0-4 | 3.3 l diesel/ha[2] 10 MJ electricity /(mm*ha) | | Water | 25 mm/ha |
| Spraying herbicides | 1 | 0-2 | 1.2 l diesel/ha[2] | | Titus | 0.0125 g/ha |
| Spraying fungicides | 8 | 4-12 | 1.2 l diesel/ha[2] | | Shirlan/Epok | 0.2 g/ha |
| Spraying insecticides | 1** | 0-1** | 1.2 l diesel/ha[2] | | Sumi-Alpha | 0.015 g/ha |
| Spraying, top-killing | 0.5 | 0-1 | 1.2 l diesel/ha[2] | | Reglone | 200 g/ha |

* Operations affected by soil type
** Done together with spraying for fungicides
*** The fertiliser amounts in sections 3.5.3.5 - 3.5.3.7 can be divided between two spreading occasions
1 From Pettersson & Arvidsson (2009)
2 From Mattsson et al. (2001)
3 From Lindgren et al. (2002)

Variation

- Variations due to soil clay content

For operations like ploughing, harrowing, planting and harvest, the fuel consumption varies with the soil clay content due to the increased energy needed for the tillage operations. The fuel consumption for spraying of pesticides, spreading of fertiliser and irrigation was assumed not to vary with the soil clay content.

The equations given in Pettersson & Arvidsson (2009) were used to adjust the fuel consumption to the clay content (Table 8).

*Table 8: Equations for the relationship between clay content and tractive power (Pettersson & Arvidsson, 2009)*

| Type of machinery | Specific tractive power ($kN/m^2$)<br>x= clay content in% | Depth (m) | Used in this study for: |
|---|---|---|---|
| Ploughing | 29.8+1.36*x | 0.20 | Ploughing<br>De-stoner<br>Planting<br>Harvest* - 95+1.36*x |
| Harrow | 36+1.63*x | 0.06 | Harrowing |
| Cultivator | 42.6+1.93*x | 0.05 | Rotary cultivator |
| Carrier | 48.3+2.19*x | 0.04 | Ridging* - 51+2.19*x |

* The equations for harvest and ridging, which are potato cultivation-specific operations and not covered in Pettersson & Arvidsson (2009), were adjusted to match the fuel consumption in Mattsson et al. (2001)

How the calculation of the fuel consumption was done is exemplified below by the case for ploughing (Arvidsson, pers):

Tractive power = 29.8+1.36*Clay content [$kN/m^2$]

Tractive power width = Tractive power * Depth [kN/m]

Fuel consumption = Tractive power width * 1.6

- Variations due to driving manner

The fuel consumption for field operations varies due to different driving manners. These include the ability to plan the driving, how the vehicle is accelerated and how brakes are applied, the number of revolutions used and how the hydraulics and gear box are used, as well as the level of maintenance of the vehicle.

The variations in fuel consumption due to differences in driving manner were assessed using the results of eco-driving courses for agricultural operations organised by the Swedish National Association of Driving Schools (STR). Fuel consumption before and after attending the course was measured for individual drivers. Since very few farmers have attended an eco-driving course, the variations before such a course were used to estimate the variation. These variations include those between drivers carrying out the different field operations between different years and fields.

From the STR course results, the variation was estimated to be ± 30% (normal distribution, 95% confidence interval).

- Variation due to non-optimal tractor-machinery combination

The fuel consumption also varies depending on how well the tractor fits with the size of the machinery used. When a farmer invests in a new tractor the tendency is to increase the size of the tractor but the machinery is not replaced at the same time, with a non-optimal combination as a result. Danfors (1988) reported that a non-optimal combination can result in as much as 37% higher fuel consumption. Data in Lindgren et al. (2002, Table 49) show a difference of 25%.

In the fuel consumption data from Pettersson & Arvidsson (2009) and Mattsson (2001), some effects of non-optimal combinations are assumed to be included, so a reasonable number for maximum variation due to non-optimal tractor-machinery combination is ± 10%.

<u>Uncertainties</u>

Detailed monitoring of fuel consumption on a per field and per crop basis is not practically feasible in everyday farming today. In a practical situation of calculating the CF, literature data would be used for fuel consumption, making the uncertainty as large as the variation.

However, in the case of including both uncertainty and variation in the simulation, as for simulating the CF for an arbitrary year and an arbitrary field, only one of the distributions for variation/uncertainty is used and the other is kept fixed in order not to double-count the variation/uncertainty in the fuel consumption. This means that the fuel consumption variation/uncertainty is the same for an average year as for a specific year, since even for the specific year, literature data would be used to estimate the fuel consumption instead of actual measurement.

#### *3.5.3.5 Amount of N fertiliser*

The amount of N fertiliser is used for calculating the emissions during production of the fertiliser and for determining the amount of $N_2O$ emitted from the soil.

The Swedish Board of Agriculture (SJV) recommends an N fertiliser rate of 150 kg/ha for King Edward with an expected yield of 45 ton/ha (SJV, 2006). This number was slightly adjusted for the present study based on the expert opinions summarised in Table 9.

<u>Variation</u>

The amount of N fertiliser can vary between fields due to the soil history, previous crop, use of de-stoner, etc., but it was assumed to be independent of other parameters in this study. This assumption was ratified by the experts, since no general pattern can be found between these parameters and the amount of N fertiliser, as the amount used also depends on traditions and factors that are difficult to pin-point.

*Table 9: Variation in the amount of N fertiliser, expert opinion*

| Expert | Variation |
|---|---|
| Andreas Kronhed | 150 kg N with little variation. |
| Hans Augustinsson | 140 kg N, varies between 110-170 kg N. |
| Pirjo Gustafsson | 138 kg N, varies ± 20 kg<br>(calculated using the GRO crop advisory programme). |

The variation in the amount of N fertiliser spread was assumed to be normally distributed with a mean value of 145 kg N/ha and a 95% confidence interval of ± 20 kg N/ha.

Uncertainty

The uncertainty in the amount of N fertiliser used, as well as other types of fertilisers, describes the amount of the planned fertiliser amount that is actually spread to the field. A set of six different trials performed by the Swedish Institute of Agricultural and Environmental Engineering (JTI) showed that the precision in the amount of fertiliser spread was within a ± 10% range for five of the trials (Thylén, 1994). The trial that exceeded ± 10% was performed on a very uneven ley field and was deemed not representative of potato fields.

The uncertainty in the amount of N fertiliser spread was assumed to be normally distributed with a 95% confidence interval of ± 10%.

#### *3.5.3.6 Amount of P fertiliser*

The amount of P fertiliser was used for calculating the emissions during production of the fertiliser.

SJV recommends a P fertiliser rate of between 27.5 and 107.5 kg/ha for an expected yield of 45 ton/ha (SJV, 2006) depending on the soil P-AL class. The experts in Table 10 stated that the mean amount of P fertiliser applied to potatoes in the study region is 50 kg/ha. Since the P fertiliser covers the demand for P for two subsequent crops, the amount of P was divided by 3 in the calculations.

Variation

*Table 10: Variation in the amount of P fertiliser, expert opinion*

| Expert | Variation |
|---|---|
| Andreas Kronhed | 50 kg P with little variation. |
| Hans Augustinsson | 55 kg P, varies between 50-60 kg N. |
| Pirjo Gustafsson | 58 kg P, varies ± 20 kg<br>(calculated using the GRO crop advisory programme). |

The variation in the amount of P fertiliser spread was assumed to be normally distributed with a mean value of 50 kg P/ha and a 95% confidence interval of ± 10 kg P/ha.

Uncertainty

Same as uncertainty for N fertiliser (see section 3.5.3.5).

#### *3.5.3.7 Amount of K fertiliser*

The amount of K fertiliser was used for calculating the emissions during production of the fertiliser.

SJV recommends a K fertiliser rate of between 0 and 320 kg/ha for an expected yield of 45 ton/ha depending on the soil K-AL class (SJV, 2006). Since cultivation on sandy soils with low contents of K dominates potato production, the lower levels of the amount of K in the recommendations were deemed not relevant. No correlation with soil clay content was taken into account, although soil clay content was a parameter included in the study, since the emissions from production of K fertiliser were small.

Variation

*Table 11: Variation in the amount of K fertiliser, expert opinion*

| Expert | Variation |
|---|---|
| Andreas Kronhed | 250 kg K with little variation. |
| Hans Augustinsson | 300 kg K, varies ± 50 kg. |
| Pirjo Gustafsson | 235 kg K, varies ± 50 kg.<br>(calculated using the GRO crop advisory programme). |

The variation in the amount of K fertiliser spread was assumed to be normally distributed with a mean value of 250 kg K/ha and a 95% confidence interval of ± 50 kg K/ha.

Uncertainty

Same as uncertainty for N fertiliser (see section 3.5.3.5).

*3.5.3.8 Fertilisation strategy*

It is necessary to use fertilisers low in chloride content for potato cultivation, since chloride has a negative affect on tuber quality. It was confirmed by all the experts cited in Table 9 that the fertiliser type ProMagna from Yara dominates the Swedish market more or less completely when it comes to low-chloride fertilisers.

The most common practice (90% of farmers) in Östergötland is to spread 1000 kg ProMagna 11-5-18 before or at planting (A. Kronhed, pers. comm. 2009). That gives an N amount of 110 kg and a P amount of 50 kg. For soils with low P-AL class, complementary P is given using the fertiliser P20. The mean amount of K for King Edward is 250 kg/ha. The standard amount of ProMagna gives an amount of 180 kg/ha and the rest is given in the form of either Kalimagnesia or potassium sulphate. In this study, Kalimagnesia was assumed. Additional N fertiliser is given using N27, N34 or calcium nitrate (CN). This fertiliser strategy was the one used in the calculations.

*3.5.3.9 Amount of seed*

Data on the amount of seed were needed in order to calculate the emissions from the production of seed potatoes (see section 3.5.6.4).

Variation

The amount of seed varies with the size of the seed potatoes and the distance between plants and rows (Fogelfors, 2001). Table 12 lists expert opinions used when determining these distributions.

*Table 12: Variation in the amount of seed, expert opinion*

| Expert | Variation |
|---|---|
| Hans Augustinsson | 2.2-2.3 ton/ha, varies ± 0.4 ton. |
| Pirjo Gustafsson | 2.5 ton/ha, varies ± 0.5 ton. |

The variation in the amount of seed used was assumed to be normally distributed with a mean value of 2.5 ton/ha and a 95% confidence interval of ± 0.5 ton/ha.

Uncertainty

Assumed to be the same as for yield, following the same reasoning, see section 3.5.3.2.

#### *3.5.3.10 Chemical treatments*

Potatoes are a crop that is chemically treated for weeds, fungi and insects. The potato haulm is often chemically killed in order for the potatoes to mature and form peel in the ground before harvest (Fogelfors, 2001). Data on the number of applications with chemical treatments were needed in order to calculate the fuel consumption for application, and on the amount of active chemical substances in order to calculate the emissions from production of the chemicals.

Variation

The variation included was the number of chemical treatments per field and per pesticide; herbicides, fungicides, insecticides and for haulm-killing. The variation is a discrete distribution per pesticide (Table 7). Variation in the size of the doses was not accounted for, since it has very limited effect on the GHG emissions.

Uncertainty

No uncertainty was accounted for in the number of repetitions. The chemical treatments are registered by the farmers with assumed good precision, since this is a requirement from the Swedish Environmental Protection Agency (SEPA, 1997), so the uncertainty in dose size was set to ± 5 % (normal distribution, 95% confidence interval).

#### *3.5.3.11 Amount of irrigation*

In order to achieve a high yield, continuous application of water is important in potato cultivation. The amount of irrigation used depends on the precipitation during a certain year. The farms described in Mattsson et al. (2001) were irrigated with 50-75 mm/year.

Variation

Table 13 lists expert opinion regarding the amount of irrigation during potato cultivation in Östergötland. The variation describes the temporal variation between years with different amounts of precipitation.

*Table 13: Variation in irrigation, expert opinion*

| Expert | Variation |
|---|---|
| Andreas Kronhed | Average 60 mm, varies between 0-100 mm. |
| Hans Augustinsson | Between 0-4 times per year, 20-30 mm per time. |
| Pirjo Gustafsson | Between 0 and 100 mm. |

The amount of irrigation was assumed to follow a discrete uniform distribution with the values 0 mm, 25 mm, 50 mm, 75 mm and 100 mm.

Uncertainty

The uncertainty describes the measuring uncertainty in the amount of irrigation applied. As the irrigation equipment used is often automated, the precision was assumed to be high. However, since no reference data on irrigation equipment were found the uncertainty was set to ± 5%. This is presumably too high, but since the contribution from irrigation to the total CF was small, this assumed distribution was deemed acceptable.

#### 3.5.3.12 Amount of machinery

The emissions caused by the production of the machinery necessary for potato cultivation were calculated as the amount of machinery (AM) per hectare needed for a certain operation, times an emission factor for the production of 1 kg of machinery. AM was calculated as follows:

AM (kg/ha) = Weight of the machinery (kg) * Operation time per operation (h/ha)/

Lifetime of the machinery (h)

The background data for the ecoinvent data v2.0 (Nemecek & Kägi, 2007) were used as activity data in order to calculate the emissions from the production of machinery, except for tractors, for which a survey of 429 different tractor models was used (Emgardsson, 2009). The values are summarised in Table 14.

*Table 14: Weight (rounded to two significant digits), operation time per hectare, lifetime and shed size of machinery used in potato cultivation (ecoinvent Centre, 2009; Emgardsson, 2009)*

| Type of machinery | Weight (kg) | Operation time per hectare (h/ha) | Lifetime (h) | Lifetime (years) | Shed size ($m^2$) |
|---|---|---|---|---|---|
| Plough | 1000 | 2.1 | 1000 | 12 | 13.3 |
| Harrow | 540 | 0.8 | 430 | 12 | 12.2 |
| Fertiliser broadcaster | 190 | 1.5 | 1500 | 10 | 3.8 |
| Potato planter | 450 | 5.3 | 1600[1] | 10[1] | 7.9 |
| Mobile sprinkler | 1300 | 1 | 1500[2] | 10[2] | 14.6 |
| Field sprayer | 480 | 0.7 | 1500[2] | 10[2] | 6.1 |
| Haulm cutter | 540 | 1.5 | 1600[1] | 10[1] | 7.0 |
| Harvester | 3200 | 13.4 | 1600 | 10 | 24.4 |
| Trailer | 4000 | 4.8[3] | 1200 | 15 | 43.6 |
| Rotary cultivator | 900 | 1.5 | 700 | 12 | 6.8 |
| De-stoner[4] | 900 | 1.5 | 700 | 12 | 6.8 |
| Ridger | 500 | 1.1 | 1600[1] | 10[1] | 10.2 |
| Tractor 47 kW | 3400[5] | Sum of the above including no of repetitions | 7800 | 12 | 12.0 |

[1] Values for potato harvester used
[2] Values for fertiliser broadcaster used
[3] The trailer is used during transport of the potatoes to/from field and to packaging facility
[4] Same as for rotary cultivator
[5] From Emgardsson (2009)

Variation

- Variation due to the use of different machinery types

The variation accounted for in terms of calculating the tractor fuel consumption (see section 3.5.3.4) based on the type of machinery used and the number of repetitions was used in calculation of the impact from production of machinery.

- Variation due to different machinery sizes

The size of the machinery used affects the weight and the operation time per hectare. The operation times per hectare in Table 14 are applicable when using a tractor with size 30-64 kW. A larger tractor would decrease the operation time. The effect of using a larger tractor or machinery, e.g. a 5-furrow plough instead of a 4-furrow plough, was assumed to be cancelled out by the decrease in operation time per hectare following a 1:1 relationship.

However, tractor weight varies across tractor brands for the same power. From the weight of 10 different tractors with power 44-49 kW, an average weight of 3400 kg for a 47 kW tractor was calculated (Emgardsson, 2009). The standard deviation was 270 kg. This variation in tractor weight was included in the calculations.

In order to calculate the variation in weight for the weight class of machinery suited to the 30-62 kW tractor, the variation in weight for 4-furrow ploughs was calculated. Using data on the weights of 4-furrow Överum and Kverneland ploughs (Kongskilde, 2009; Kverneland, 2009), an average weight of 1500 kg and a standard deviation of 320 kg were calculated (coefficient of variation 21%). The rest of the machinery was assumed to vary in size to a similar extent as the ploughs, and a coefficient of variation of 21% (corresponding to a 95% confidence interval of ± 42%) was used for all other machinery except tractors.

- Variation due to differences in draught requirement for different soil types

Heavy soils lead to longer operation times per hectare for tillage operations, planting and harvest. The increase in operation time on soils with higher clay content was assumed to follow the increased demand for diesel due to higher soil clay content with a 1:1 relationship.

- Variation due to differences in lifetime

Based on the data in Wetterberg et al. (2007), the average lifetime of a Swedish tractor was set to 7800 h with a variation of ± 10% (95% confidence interval, normal distribution). The same lifetime variation of ± 10% was used for the rest of the machinery.

Variation in the lifetime in years was not included, since it was only used in calculation of the emissions from the construction of buildings, which had little effect on the end-result.

Uncertainty

Using the Swedish motor-vehicle register, it would be feasible to get very accurate information on the weight of the tractors of a specific farmer. However, since producers often have more than one tractor, there would still be uncertainty about the tractor used for different operations. By asking the farmer about the type, brand and variety of machinery used, it would be possible to calculate the weight of the machinery and the operation times per hectare with good precision. Lifetimes of machinery and tractors are more difficult to assess.

Based on the fact that weight and operation time per hectare would be possible to assess with little uncertainty and that lifetime is associated with greater uncertainty, the total uncertainty added on top of the variation was set to ± 10% (95% confidence interval, normal distribution).

*3.5.3.13 Amount of buildings*

Emissions from the production of on-farm buildings were calculated for a shed for the machinery and tractor and the cold potato storage building.

The background data for the ecoinvent data v2.0 (Nemecek & Kägi, 2007) were used to determine the area needed to house the machinery. The areas are summarised in Table 14. The average shed size was calculated to 175 $m^2$ using the average number of repetitions in Table 7 and the areas in Table 14. The lifetime of the shed was set to 50 years, which is the same figure used in the ecoinvent report (Nemecek & Kägi, 2007). The amount of shed space needed per hectare (AS) was calculated as:

AS ($m^2$/ha) = Area ($m^2$) * operation time (h/ha) / (lifetime of the shed (years) * annual employment of the machines (h/year))

An average value of the annual employment of 126 h/years across machinery including tractor was calculated from the lifetimes in years and hours in Table 14. Accordingly, the average operation time was 2.8 h/ha.

Using these numbers, the AS for the machinery shed was calculated to 0.078 $m^2$/ha.

It was assumed that storing the average yield from one hectare required an area of 12 $m^2$. The lifetime of the cold storage building was assumed to be 50 years. The area required for storage per hectare and year was hence calculated to be 0.24 $m^2$.

The total building area was calculated to be 0.32 $m^2$.

<u>Variation</u>

No variation was accounted for, since the contribution to the total results from the production of buildings was very small.

<u>Uncertainty</u>

An uncertainty of ± 10% (normal distribution, 95% confidence interval) was accounted for, following similar reasoning as for machinery (see section 3.5.3.12).

### 3.5.4 *Activity data - processing*

#### *3.5.4.1 Energy packaging process*

At the packaging facility the potatoes are washed, sorted and packed in 'kraft' paper bags in one automated process. An inventory performed by the Swedish Institute for Food and Biotechnology (SIK) in 2001 showed that the energy consumption per packed kg of potatoes varied between 0.09-0.97 MJ, with a median of 0.22 MJ (Vinsmo et al., 2001). The large packaging facility Swegro in Skänninge, Östergötland, had an energy consumption per kilo packed potatoes in the lower range of the interval found in Vinsmo et al. (2001) during 2008 (the exact number is confidential information). It was assumed that energy consumption has decreased rather than increased since 2001, when the SIK study was carried out, so the boundaries of the range in Vinsmo et al. (2001) were lowered somewhat in this study.

The variation in energy consumption during the packaging process was assumed to follow a log-normal distribution with a geometric mean of 0.22 MJ/f.u. and a 95% confidence interval between 0.07-0.54 MJ/f.u..

Uncertainty

Measurements of energy consumption at packaging facilities are most commonly made by dividing total annual energy consumption by the amount of packed potatoes. This should give rather good precision on average, since the packaging facilities often specialise in packaging potatoes.

The uncertainty in the energy consumption during the packaging process was assumed to follow a normal distribution with a 95% confidence interval of ± 5%.

#### *3.5.4.2 Amount of packaging material*

The potatoes were assumed to be packed in 2 kg 'kraft' paper bag, which is a common type of packaging for Swedish potatoes. There are only a few vendors of potato paper bags on the Swedish market and the market is dominated by the manufacturer Stenqvist (L. Mårtensson, pers. comm. 2009). The 2 kg 'kraft' paper bag weighs 23.6 g and contains 2% glue and 1% ink, but the latter were not included (I. Norling, pers. comm. 2009).

Variation and uncertainty

The variation and uncertainty in the weight of the packaging material was assumed to be small, since the process is totally automated. A ± 0.5% uncertainty was included (normal distribution, 95% confidence interval).

### 3.5.5 *Activity data - transport*

#### *3.5.5.1 Distance from the farm to the packaging plant*

Variation

Potato production in the Östergötland area is quite concentrated and the packaging facilities are located close to the farms. The majority of the potatoes are delivered to the packaging plants using a tractor and trailer. Maximum transport distance is 20-30 km and the load capacity of the carriage is 10-20 ton (A. Magnusson, pers. comm. 2009).

The load capacity of the trailer used to transport the harvest from the farm to the packaging facility was set to vary uniformly between 10, 15 and 20 ton. The distance from the farm to the packaging plant was assumed to vary between 10 and 30 km (95% confidence interval, normal distribution).

Uncertainty

See uncertainty distribution of the distance between plant and supermarket, section 3.5.5.2.

*3.5.5.2 Distance between the packaging plant and supermarket*

Variation

The majority of the potatoes grown in the Östergötland region are sold in Stockholm and the rest are sold locally. The Swegro packaging plant delivers 85% to Stockholm and 15% locally (A. Magnusson, pers. comm. 2009). It was assumed that smaller packaging facilities deliver locally to a slightly larger extent. The distance from Skänninge, Östergötland, to Stockholm is 230 km. An additional 20 km for distribution within Stockholm was assumed. The distance for local distribution was set to 50 km.

The variation of the distribution distance was assumed to be discretely distributed with the following values: 80% - 250 km, 20% - 50 km in order to represent delivery to Stockholm and locally.

Uncertainty

Gebresenbet & Ljungberg (2001) showed that by optimising the route, transport distances for grain could be cut by approximately 7%. Since incorrect route choices, traffic jams, road construction work, etc. can also make distances longer, the uncertainty in the distribution distance was set to ± 7% (95% confidence interval, normal distribution).

### *3.5.6 Emission factors for inputs*

The emission factors for the inputs (EF-inputs) used in potato cultivation are summarised in Table 15. The EF-inputs include the production and transport of the inputs to the farm. The values were mainly taken from the literature, which corresponds to how data on EF-inputs would be collected in a practical CF labelling system, since the inputs themselves are not (yet) carbon-labelled.

The distribution of variation outlines the variability between different ways of production for EF-inputs and the uncertainty describes the accuracy in the actual numbers for a specific production technique. Since the data used to determine the EF-inputs did not include any uncertainty assessment, as is most commonly the case with LCA data, the methodology based on quality indicators was used to assess the uncertainty (Weidema & Wesnaes, 1996; Frischknecht et al., 2004). See section 3.5.8 for a more detailed explanation of the uncertainty assessment for EF-inputs.

A detailed description of how the data were collected and how the distributions for the variation were estimated can be found in the following sub-sections.

*Table 15: Emission factors for the production and transport of inputs (EF-inputs)*

| | Mean | Variation | | Uncertainty | |
|---|---|---|---|---|---|
| | | Distribution | Distribution parameters | Distribution | Geo. Std |
| NPK fertilisers | 6.8 kg $CO_2$e/ kg N* | None** | - | Lognormal | 1.15 |
| N fertilisers | 5.5 kg $CO_2$e/kg N* | Discrete | 53% - 6.8 kg<br>38% - 4.0 kg<br>9% - 4.2 kg | Lognormal | 1.15 |
| Chemicals | 5.4 kg $CO_2$e/kg active substance* | Negligible | - | Lognormal | 1.15 |
| Diesel | 0.125 kg $CO_2$e/ l diesel | Negligible | - | Lognormal | 1.02 |
| Seed | 0.090 kg $CO_2$e/kg seed | Included in the uncertainty | | Simulated | n/a |
| Packaging paper | 1.7 kg $CO_2$e/kg paper bag | Negligible | - | Lognormal | 1.08 |
| Electricity consumption | 0.024 kg $CO_2$e/MJ | Normal | Standard deviation:<br>0.008 g $CO_2$e/MJ | Lognormal | 1.07 |
| Machinery | 3.8-5.8 kg $CO_2$e/kg | Included in the uncertainty | | Lognormal | 1.06 |
| Buildings | 186 kg $CO_2$e/m$^2$ | Included in the uncertainty | | Lognormal | 1.06 |

* Only production

** NPK for potatoes on the Swedish market are manufactured at one plant only

#### 3.5.6.1 Fertilisers

Production

The production of synthetic fertilisers is energy-demanding and the production of nitric acid used in N fertilisers also emits considerable amounts of $N_2O$. Through the use of different techniques, the emissions of GHG can be reduced. Table 16 shows the variation in emissions from the production of N fertilisers using different techniques.

*Table 16: Emissions of GHG from production of N fertilisers*

| Technique (source) | kg $CO_2$e per kg N |
|---|---|
| AN[3] 'Old tech' (Jenssen & Kongshaug, 2003) | 7.3 |
| AN Average 2003 (Jenssen & Kongshaug, 2003) | 6.8 |
| AN BAT 2003 (Jenssen & Kongshaug, 2003) | 3 |
| AN BAT 2007 (Erlingsson, 2008a) | 2.5 |
| BAT according to Yara (Erlingsson, 2008b) | 4 |

Sales statistics from Lantmännen in combination with knowledge of the plants that are equipped with $N_2O$ reduction techniques were used to determine the distribution of the GHG emissions caused by the production of the fertilisers on the Swedish market.

All fertilisers are imported to Sweden and the production is dominated by Yara. ProMagna is only produced by Yara at the Finnish plants in Nystad and Siilinjärvi. These plants will be equipped with $N_2O$ reduction technique during 2009 (M. Erlingson, pers. comm. 2009). Hence for the season of 2007 it was assumed that the Finnish plants caused emissions corresponding to those of average European plants (6.8 kg $CO_2$e per kg N), as described in Jenssen & Kongshaug (2003) with no variation.

Only use of ProMagna 11-5-18 was considered, in order to simplify the calculations. This had little effect on the end results, since the emissions are correlated to the N content. However, it did give slightly higher emissions for transport, but these are negligible in the total results.

N27 and NS27-4 fertilisers on the Swedish market are produced at the Yara plant in Rostock, Germany and at plants in Poland, Lithuania and Russia. The production of CN is carried out at the Yara plant in Porsgrunn, Norway (M. Erlingson, pers. comm. 2009). The Yara plants in Porsgrunn, Norway and Rostock, Germany, are equipped with $N_2O$ reduction techniques (M. Erlingson, pers. comm. 2009), so the emissions from these were assumed to cause emissions of 4 kg $CO_2$e per kg corresponding to BAT 2007 technique (EC, 2007) and the information from Yara (Erlingson, 2008b). Plants in Poland, Lithuania and Russia were assumed to cause emissions corresponding to the European average (Jenssen & Kongshaug, 2003; R. Ramel, pers. comm. 2009).

Lantmännen dominates the Swedish market, with a market share of approximately 60% (R. Ramel, pers. comm. 2009), and its statistics were assumed to be representative for the entire Swedish market. Lantmännen provided sales statistics for the years 2006 and 2007. The data for 2007 were used when determining the distribution.

[3] Ammonium nitrate (AN)

*Table 17: Distribution of GHG emissions from production of pure N fertilisers on the Swedish market and used for potato production*

| Discrete distribution | % | kg $CO_2$e per kg N |
|---|---|---|
| N27, N34 Average European | 53 | 6.8 |
| N27, NS27-4 BAT 2007 | 38 | 4.0 |
| Calcium nitrate BAT 2007 | 9 | 4.2 |

Production of the P and K fertilisers (P20, Kalimagnesia and potassium nitrate) was assumed to cause emissions corresponding to the average European level reported in Jenssen & Kongshaug (2003). Since the production of one of these fertilisers contributed to less than 1% of the total emissions from the production of fertilisers, variations in the emission factors for these fertilisers were not included in the study.

<u>Transport</u>

Transport distances used in this study are summarised in Table 18. Fertilisers are shipped from the production site to Norrköping for further distribution in the Östergötland area (M. Erlingson, pers. comm. 2009). The distance for distribution from Norrköping to the farm was set to 90 km. No variation or uncertainty was included in the fertiliser transport distances because of the low contribution to the final result. Emissions from transport were obtained by multiplying the distances by the EF for transport (see section 3.5.7).

*Table 18: Transport distances for fertilisers*

| | Road outside Sweden (km) | Sea (km) | Road in Sweden (km) | Comment |
|---|---|---|---|---|
| Nystad and Siilinjärvi, Finland (ProMagna) | 275 | 300 | 90 | 50% from Nystad (70 km) and 50% from Siilinjärvi (480 km) assumed. Boat to Norrköping. |
| Poland, Lithuania, Russia (N27 Average European and N34) | 100 | 550 | 90 | Average 100 km of road transport outside Sweden assumed for all countries. Boat to Norrköping. |
| Rostock, Germany (N27 BAT 2007) | 0 | 700 | 90 | Boat to Norrköping. |
| Possgrunn, Norway (CN BAT 2007) | 0 | 1000 | 90 | Boat transport to Norrköping around Sweden assumed. |

#### *3.5.6.2 Chemicals*

Although chemical treatment during potato cultivation is substantial, the chemical substances are concentrated and the emission of GHG from the production of the chemicals is limited. Hence, no variation was taken into account. For uncertainty see section 3.5.8.

<u>Production</u>

Emission factors for the production of pesticides (Kaltschmitt & Reinhardt, 1997) are summarised in Table 19.

*Table 19: Emissions from production of pesticides*

| Emission | kg $CO_2$e/kg active substance |
|---|---|
| $CO_2$ | 4.921 |
| $CH_4$ | 0.0045 |
| $N_2O$ | 0.450 |
| Total | 5.376 |

<u>Transport</u>

Crop protection chemicals are produced at plants in Europe as well as in India and China. Since the mass of the chemicals used is low, the transport of the chemicals contributes very little to the end result of the GHG emissions. Production in China without variation was assumed to cover the case with the longest transport.

The distance between Stockholm and Shanghai, 8040 km, without variation was used in order to calculate the contribution from transport.

*3.5.6.3 Fuel*

<u>Production and transport</u>

The GHG emissions caused by the production and transport of diesel are 3.5 g $CO_2$ and 0.002 g $CH_4$ per MJ diesel (Uppenberg et al., 2001). One $m^3$ of diesel contains 9800 kWh, or 35,280 MJ of energy. This gives emission factors as presented in Table 20.

*Table 20: Emissions from production of diesel*

| Emission | kg $CO_2$e/l diesel |
|---|---|
| $CO_2$ | 0.123 |
| $CH_4$ | 0.00176 |
| $N_2O$ | - |
| Total | 0.125 |

No variation was accounted for due to the low influence of this process on the end result.

For uncertainty see section 3.5.8.

*3.5.6.4 Seed*

<u>Production and transport</u>

Seed was assumed to be bought and reproduced on the farm once before being used in potato production. For the calculation of seed cultivation emissions, the AD in Table 1 and Table 7 were used with the following adjustments; 20% reduction in yield, 80% of the amounts of N fertiliser, and one additional chemical treatment for virus (A. Kronhed, pers. comm. 2009). No transport or packaging was included in the seed production calculations.

The potatoes not used as seed potatoes were assumed to be sold as consumable potatoes according to the description in section 3.5.3.3.

The distribution for the seed production was calculated by performing a Monte Carlo simulation (see section 3.6.4) with the AD values adjusted for seed production and using the numerical outcome of that simulation as input for the rest of the simulations. The outcome from the Monte Carlo simulation includes both variations and uncertainties, since these are included in the input parameters.

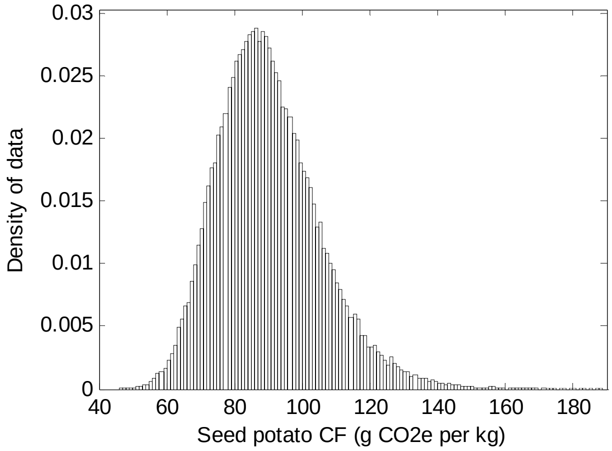



*Figure 2: Histogram of the emissions from seed production.*

### *3.5.6.5 Packaging material*

Production and transport

Swedish potatoes are sold in a variety of paper bag sizes and also commonly in bulk. In this study the potatoes were assumed to be packaged in 2 kg 'kraft' paper bags. The Swedish market for paper bags for potatoes and vegetables is dominated by the manufacturer Stenqvist and it was deemed realistic to assume that the bags were bought from the same vendor year after year (I. Norling, pers. comm. 2009). Hence, no variation was accounted for.

'Kraft' paper production emissions were taken from the ecoinvent v.2.0 database (ecoinvent Centre, 2007) and found to be 1.67 kg $CO_2$e per kg 'kraft' paper. The production of the bag caused emissions corresponding to 0.05 kg $CO_2$e per kg paper bag (ecoinvent Centre, 2007), resulting in an emission factor of 1.71 kg $CO_2$e per kg 'kraft' paper potato bag.

For uncertainty see section 3.5.8.

### *3.5.6.6 Electricity*

In the Nordic countries, except Iceland, electricity is traded on a common electricity market. Electricity is also imported from and exported to Estonia, Russia, Poland and Germany on a small scale. New transmission links with these countries will soon enable electricity trade on an even larger scale. In this study, however, the electricity was assumed to come from the Nordic market, which is a realistic scenario for the period 2005-2009 (Nordel, 2005; Swedenergy, 2009).

The electricity mix on the grid varies throughout the year, mostly depending on the amount of hydropower available. Emission data for the period 2005-2008 (Table 21) were taken from the calculations of the Nordic electricity mix presented by Swedenergy (2009). The variation during the period 2005-2008 was assumed to be representative for the period 2005-2009, since no data for 2009 were available at the time of this study.

*Table 21: Emissions of GHG from electricity consumption (Swedenergy, 2009)*

| Year | GHG emissions (g $CO_2$e/kWh) |
|---|---|
| 2005 | 60 |
| 2006 | 120 |
| 2007 | 100 |
| 2008 | 70 |

The variation in the electricity emissions was assumed to follow a normal distribution with a mean value of 88 g $CO_2$e/kWh (0.024 kg $CO_2$e/MJ) and a standard deviation of 28 g $CO_2$e/kWh (0.008 kg $CO_2$e/MJ) calculated from the data in Table 21.

#### *3.5.6.7 Machinery*

The emission factors for machinery were taken from the ecoinvent database v2.0 (ecoinvent Centre, 2007) and are summarised in Table 22. These emission factors take into account emissions caused during production, maintenance and disposal of the machinery, for details see Nemecek & Kägi (2007). Only uncertainty was accounted for (see section 3.5.8).

*Table 22: Emissions from the production of machinery (ecoinvent, 2007)*

| Type of machinery: | Emissions (kg $CO_2$e per kg machinery) | | | |
|---|---|---|---|---|
| | $CO_2$ | $CH_4$ | $N_2O$ | Total: |
| Agricultural machinery, tillage | 4.2 | 0.3 | - | 4.5 |
| Agricultural machinery, general | 3.6 | 0.2 | - | 3.8 |
| Tractor, production | 5.5 | 0.3 | - | 5.8 |
| Trailer, production | 3.9 | 0.5 | - | 4.4 |
| Harvester, production | 4.1 | 0.3 | - | 4.4 |

#### *3.5.6.8 Buildings*

The emission factors for buildings, shed and cold storage facility were taken from the ecoinvent database v2.0 (ecoinvent Centre, 2007) and are summarised in Table 23. These emission factors take into account emissions caused during construction, utilisation (repair and energy consumption) and disposal of the construction material, for details see Nemecek & Kägi (2007). Only uncertainty was accounted for (see section 3.5.8).

*Table 23: Emissions from the production of buildings (ecoinvent, 2007)*

| Type of building: | Emissions (kg $CO_2$e per $m^2$ shed) | | | |
|---|---|---|---|---|
| | $CO_2$ | $CH_4$ | $N_2O$ | Total: |
| Shed | 180 | 5.7 | - | 186 |

### 3.5.7 *Emission factors for transport*

#### *3.5.7.1 Overview*

Emissions factors for transport are summarised in Table 24. Data for road transport by truck and sea transport were collected from the NTM Calc website (NTM, 2009).

*Table 24: Emission factors for transport of the potatoes*

| | Average (g $CO_2$e /tonkm) | Variation (g $CO_2$e /tonkm) | | Uncertainty | |
|---|---|---|---|---|---|
| | | Distribution | Distribution parameters | Distribution | Standard deviation: |
| Road transport, tractor | 800 | Mix* | 100/3% - 80<br>100/3% - 53<br>100/3% - 40<br>and ± 30% | Lognormal | 1.05 |
| Road transport, truck | 68 | Normal | ± 10 | Lognormal | 1.05 |
| Sea transport | 22 | Normal | ± 18 | Lognormal | 1.05 |

* varies with the size of the carriage

#### *3.5.7.2 Road transport tractor*

The transport from the farm to the packaging facility is predominantly by tractor and trailer with a load of 10-20 ton (A. Kronhed, H. Augustinsson, pers. comm. 2009). Fuel consumption for road transport with a tractor and a load of 11 ton in one direction and empty in the other direction has been measured as 6.4 kg/h (Lindgren et al., 2002). The speed was assumed to be 25 km/h, which gives a fuel consumption of 0.31 l/km, resulting in an EF of 800 g $CO_2$e/km.

Variation was accounted for using a uniform discrete distribution corresponding to trailer sizes of 10, 15 and 20 ton and a ± 30% variation (normal distribution) due to differences in driving manner.

#### *3.5.7.3 Road transport truck*

The emissions from the road transport by truck were assumed to vary normally with a 95% confidence interval between data from using a heavy truck (40 ton) with a load level of 50%, 58 g $CO_2$e/tonkm, and from a lighter truck (26 ton) with a load level of 50%, 78 g $CO_2$e/tonkm.

#### *3.5.7.4 Sea transport*

The emissions from sea transport were assumed to vary normally with a 95% confidence interval between data from using a large freight vessel (> 8000 dwt) with a load level of 80%, 4 g $CO_2$e /tonkm, and from a smaller freight vessel (< 2000 dwt) with a load level of 80%, 40 g $CO_2$e/tonkm.

### *3.5.8 Uncertainties in emission factors for inputs and transports*

Since the EF for inputs are based on literature data and not primary sources as for the activity data, the uncertainties are much more difficult to assess.

In order to assess the uncertainties in the EF for inputs, the same methodology as in the ecoinvent database was used (Weidema & Wesnaes, 1996; Frischknecht et al., 2004). This methodology assumes a lognormal distribution of uncertainties based on the work by Hofstetter (1998) and the fact that emissions cannot show negative numbers.

In order to assess the standard deviation of the lognormal distribution describing the uncertainty, the quality of the data was determined by the following six indicators: reliability, completeness, temporal correlation, geographical correlation, further technological correlation, sample size and a basic uncertainty indicator depending on the type of process.

For the EF for fertilisers, the basic uncertainty was a weighted average of 1.3 between the value of 1.05 for emissions of $CO_2$ and 1.50 for the emissions of $N_2O$[4]. For all other emission factors the basic uncertainty was set to 1.05, since these are dominated by $CO_2$ emissions. The other six factors were determined from the Pedigree matrix in Frischknecht et al. (2004) and are presented in Table 25.

The total geometric standard deviation was calculated using the formula in Frischknecht et al. (2004).

*Table 25: Uncertainties in the emission factors for inputs*

| | Basic | Relia-bility | Comp-leteness | Temp corre-lation | Geograf. corre-lation | Techno-logy | Sample size | Total |
|---|---|---|---|---|---|---|---|---|
| | $U_b$ | $U_1$ | $U_2$ | $U_3$ | $U_4$ | $U_5$ | $U_6$ | U |
| Fertilisers | 1.30 | 1.05 | 1.05 | 1.03 | 1.00 | 1.00 | 1.02 | 1.15 |
| Chemicals | 1.05 | 1.05 | 1.10 | 1.20 | 1.02 | 1.00 | 1.20 | 1.15 |
| Fuel | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.02 |
| Paper bag | 1.05 | 1.05 | 1.10 | 1.00 | 1.02 | 1.00 | 1.10 | 1.08 |
| Electricity | 1.05 | 1.00 | 1.05 | 1.05 | 1.00 | 1.00 | 1.10 | 1.07 |
| Transport | 1.05 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.10 | 1.05 |
| Machinery | 1.05 | 1.05 | 1.03 | 1.00 | 1.00 | 1.00 | 1.10 | 1.06 |
| Buildings | 1.05 | 1.05 | 1.03 | 1.00 | 1.00 | 1.00 | 1.10 | 1.06 |

### *3.5.9 Emission factors for soil emissions*

Soils emit $N_2O$ due to nitrification and denitrification processes caused by microbial activity in the soil. These processes are stimulated by the additional N added to agricultural soils during cultivation in the form of fertilisers, crop residuals and deposited N.

During cultivation, $CO_2$ is either lost from or sequestered in the soil depending on the initial carbon content in the soil, the amount of organic content that is applied to the soil and a number of climatologically dependent parameters such as the soil water content and soil temperature.

[4] Approximately 50% of the emissions from fertiliser production are $N_2O$ and 50% are $CO_2$.

Due to the large uncertainties in the models for calculating the soil emissions, it was not possible to divide the uncertainties in EF-soil into variations and uncertainties. Hence, both variations and uncertainties are grouped under uncertainties for these.

#### *3.5.9.1 Emission factors for $N_2O$*

The amount of $N_2O$ emitted from agricultural soils during cultivation depends on a number of parameters such as the N content of the soil, the soil temperature and water content, the soil carbon content, the tillage intensity and the technique for spreading and type of fertiliser (Kasimir-Klemedtsson, 2001; Dobbie & Smith, 2003; Perälä et al., 2006; Vallejo et al., 2006; Lui et al., 2007).

Since the $N_2O$ emissions to a large extent are dependent on soil conditions that vary substantially both within a field depending on the amount of available N, soil texture, drainage etc. and during the cropping season due to available N and precipitation, it is difficult to determine how large the emissions will be for a specific year. Numerous international studies show great variations and only a few show a significant relationship between emissions and different parameters (Ahlgren et al., 2009). Due to the lack of more accurate methods, the method used for determining emissions of $N_2O$ in this study was the methodology developed by the IPCC (IPCC, 2006).

The IPCC method is designed for national reporting of GHG emissions and is associated with large uncertainties. The method builds on a linear relationship between applied nitrogen and $N_2O$ emissions. A percentage of the applied N from synthetic and organic fertilisers as well as from crop residues is assumed to be emitted as $N_2O$. These emissions are called direct emissions. Indirect emissions are caused by the N that leaks out from the field, as well as from N that is volatilised as ammonia and later deposited on the field.

In this study, the modified emission factors suggested by Kasimir-Klemedtsson (2001) were used for emissions caused by synthetic fertilisers. For synthetic fertilisers, the default IPCC EF is 0.01 with an uncertainty range between 0.003-0.03 (IPCC, 2006). Kasimir-Klemedtsson (2001) recommends a decrease to 0.008 (uncertainty 0-0.009). The value suggested by Kasimir-Klemedtsson (2001) was used as a geometric mean in this study and the 95% confidence interval was adjusted to 0.006-0.01 in order to fit a lognormal distribution. For crop residues, the default IPCC EF and uncertainty range was used since Kasimir-Klemedtsson (2001) did not recommend any modified values for crop residues. For the indirect EFs, Kasimir-Klemedtsson (2001) do recommend modified values that are lower than those recommended by the IPCC. However IPCC strongly recommends using the default values due to the lack of knowledge and large variability in the indirect emissions unless the national values are based on thorough research. Therefore, this study used the IPCC EFs for indirect emissions of $N_2O$.

Kasimir-Klemedtsson (2001) recommends the use of an EF for background emission of 0.5 kg $N_2O$-N/ha with an uncertainty range of 0.5-1.5 kg $N_2O$-N/ha. This range was adjusted in order to be used in the simulation. A lognormal distribution was used with a 95% confidence interval between 0.2-1.5 kg $N_2O$-N/ha, which gives an expected value of 0.6 kg $N_2O$-N/ha. The slightly higher expected value was assumed to compensate for the lower value of the lower boundary.

The choice of emission factors in this study corresponds to the EFs used in the Swedish GHG Inventory (SEPA, 2009). The emission factors are summarised in Table 26.

*Table 26: Emission factors for $N_2O$ emissions (kg $N_2O$-N/kg N)*

| | IPCC (2006) | | Kasimir-Klemedtsson (2001) | | SEPA (2009) | | Values used in this study | |
|---|---|---|---|---|---|---|---|---|
| | Default value | Uncert.* | Default value | Uncert. | Used value | Error | Geo mean | Uncert.* |
| Synthetic fertiliser | 0.01 | 0.003-0.03 | 0.008 | 0-0.009 | 0.008 | 80% | 0.008 | 0.006-0.01 |
| Crop residuals | 0.01 | 0.003-0.03 | - | | 0.01 | 80% | 0.01 | 0.003-0.03 |
| Deposited N | 0.01 | 0.002-0.05 | 0.002 | - | 0.01 | 80% | 0.01 | 0.002-0.050 |
| Leached N | 0.0075 | 0.0005-0.025 | 0.0025 | - | 0.0075 | 80% | 0.0075 | 0.0005-0.025 |
| Background emissions, mineral soils | - | - | 0.5 | 0.5-1.5 | 0.5 | 80% | 0.5 | 0.2-1.5 |

* Log-normal distribution

There are studies that indicate that the $N_2O$ emissions from potato fields are considerably higher than from fields cultivated with cereals. Soil compaction and high levels of nitrate have been identified as causes of the increased $N_2O$ emissions (Flessa el al., 2002). However, due to the lack of reliable relationships between crop types and $N_2O$ emissions, it was not possible to make corresponding corrections to the emission factors.

### *3.5.9.2 Model parameters for $CO_2$ soil emissions/sequestration*

For calculation of the $CO_2$ loss or sequestration from soil, the ICBM model (Andrén et al., 2004) was used. The change in the soil carbon stock, dC/dt, is described by the following relationship:

$dC/dt = i - k*C$

where i is the input of carbon (from crop residuals, organic fertilisers etc), k is a constant and C is the amount of carbon in the soil. Since k is a constant, the fraction of carbon that is lost or sequestered is constant, which means that soils rich in carbon require a higher amount of carbon input in order not to lose carbon and vice versa for soils low in carbon content. The ICBM model divides the soil into two carbon pools, the young and the old. The young pool contains the loosely bound carbon that is returned to the air in a short time frame, while the old pool contains stable carbon compounds. It is only changes to the old pool that are taken into account when calculating the $CO_2$ loss or sequestration from soil. Changes in the young pool are part of the biogenic short-time cycle of carbon.

The rate at which carbon is transferred from the young pool to the old pool is described by the humification coefficient, h, in the ICBM model. The humification coefficient normally varies between 0.08 and 0.16 for agricultural crops. For potatoes, h was assumed to vary normally between 0.08 and 0.12 (95% confidence interval, normal distribution) (O. Andrén, T. Kätterer, pers. comm. 2009).

The rate of carbon loss or sequestration is affected by the soil temperature, the soil water content and the intensity of tillage operations. This dependency is summarised in the external influence parameter, $r_e$, in the ICBM model. Potato cultivation increases the loss of soil carbon compared with cultivation of cereals, since the amount of crop residues is less, the tillage operations are more abundant and potatoes are irrigated. Therefore, $r_e$ was set to vary between 1.0 and 1.4 (95% confidence interval, normal distribution). Normally, for cultivation on sandy soils $r_e$ is adjusted to 0.9 due to the limited ability of sandy soils to hold water, but since potatoes are irrigated no such adjustment was made.

The emissions due to changes in the soil carbon balance are seldom included in LCA studies, due to the large uncertainties and complexities in the carbon balance models when used on an entire field. In this study such emissions were included, as they make an interesting and relevant contribution to both the overall result and the uncertainty in the CF. However, there remain methodological issues that need to be solved in order to practically include the emissions in a CF system. The organic input used in the model should be the input from the crop that was cultivated during the previous year. Since potatoes are often grown in a crop rotation, the correct assumption would have been to use cereals as the crop grown in the previous year. This would give a measurement of the actual carbon lost/sequestered during the year of potato cultivation. However, it does not consider the fact that the potatoes will leave less organic input to the next year, which is clearly a consequence of growing potatoes. Therefore, the input was calculated from the potato yield from the year being studied, which does not give the exact measurable emissions of $CO_2$ for that year, but does fairly allocate the input on the crop causing the input (O. Andrén, T. Kätterer, pers. comm. 2009).

The soil carbon content was calculated from the soil humus content. The carbon content in soil is 1/1.73 the soil humus content, which gives a fraction of carbon in the soil of 1.04% for a humus content of 1.8%. The topsoil depth was set to 0.25 m and the density of the soil was set to 1.3 g/cm$^3$, from which the mass of topsoil on an area of 1 m$^2$ was calculated to be 325 kg. The carbon soil content was then 3.38 kg/m$^2$ (O. Andrén, T. Kätterer, pers. comm. 2009).

The amount of organic input was calculated from the function in Andrén et al. (2004).

## 3.6 Analytical methods

This study concentrated on uncertainty introduced by natural variations, variations in production techniques, distribution distances etc. and data uncertainty. Uncertainties on a higher conceptual level such as uncertainty due to choices, epistemological uncertainty or mistakes, or uncertainty introduced by estimating the uncertainty (Björklund, 2002) were not included. Model uncertainty was partly included by considering the emission factor and model parameter uncertainties.

This study only included variation and uncertainty in the inventory phase of the LCA; the uncertainty in empirical data and model parameters. Since the resulting GWP is presented as emissions of GHG in $CO_2$e and no further impact assessment is made, no uncertainty due to the valuation or interpretation phases (Basson & Petrie, 2007) needs to be included.

The LCA methodology itself introduces uncertainties in the result (Reap et al., 2008), which were not accounted for here.

### *3.6.1 Calculation of emissions*

The emissions were calculated by multiplying the AD by the corresponding EF for all processes except emissions of $CO_2$ from soils, for which the ICBM model was used (see section 3.5.9.2). For example, in order to calculate the emissions caused by electricity consumption during the packaging process, the amount of energy spent during the packaging process, 0.22 MJ/f.u., was multiplied by the EF for electricity consumption, 0.024 $CO_2$e/MJ (mean value). For the cultivation processes the emissions per hectare were calculated and divided across the usable yield in order to get emissions per f.u.

The GHG included in the study were $CO_2$, $CH_4$ and $N_2O$. Emissions of other GHG were assumed to be negligible. The emissions of $CH_4$ and $N_2O$ were converted into $CO_2$ equivalents ($CO_2$e) using a factor of 25 for $CH_4$ and a factor of 298 for $N_2O$ (IPCC, 2006).

### *3.6.2 Mean value and uncertainty in contributing processes*

The potato CF was calculated as a deterministic mean using the mean values of all parameters for a base scenario that represented an arbitrary year between 2005 and 2009 and production in an arbitrary field on a farm in the Östergötland region (scenario a1). The calculation was repeated with the CLfF rules applied (scenario c1). The rules mandate fertilisers with a maximum emission factor of 4 kg $CO_2$e/kg N and electricity from sustainable sources (CLfF, 2009).

### *3.6.3 Sensitivity and uncertainty importance analysis*

The uncertainty contribution from individual parameters was examined using a traditional sensitivity analysis of a ± 20% change in the parameter values. This was compared with an uncertainty importance analysis on an individual parameter basis using a change of ± 2 standard deviations for normal and log-normally distributed parameters and highest and lowest value for discretely distributed parameters, including both variation and uncertainty. During the analysis all variables and parameters, except the one under study, were kept fixed.

### *3.6.4 Uncertainty analysis*

Uncertainty analysis was performed for all scenarios using Monte Carlo (MC) simulation (Rubinstein & Kroese, 2007). MC simulation is a numerical method used to study the propagation of uncertainty over a choice of parameters or all of the uncertain parameters. Characterising each parameter to be included in the simulation with a probability density function (PDF) allows random values of the parameter to be drawn during a large number of simulations, resulting in a PDF of the end result.

Payraudeau et al. (2007) describe the limitations and problems with applying Monte Carlo simulation LCAs of agricultural activities. One factor is the difficulty in using bibliographic data, since these seldom contain more than the mean value and in some cases the uncertainty range, but not the distribution, resulting in the introduction of subjectivity. Furthermore, Payraudeau et al. (2007) point out the difficulty in determining the dependencies between parameters. On the spatial scale chosen, cultivation on a specific farm, it is realistic to assume that all parameters are independent. On the national level, however, or if the potato variety was not fixed, independency in the AD would not have been a realistic assumption, since yields vary considerably between potato varieties and different geographical locations in Sweden (SCB, 2008a). Examples of parameters that are correlated are the fuel consumption during tillage operations and the soil clay content, as heavier soils require more fuel and machinery use varies depending on the type of field operations performed. These correlations were included in the study. For a detailed description of the parameters that were assumed to be correlated and independent, see the description of the collection of different data in section 3.5.

The MC simulations were run using 50,000 iterations.

#### *3.6.4.1 Scenarios*

Uncertainty analysis was carried out for a number of different scenarios. All scenarios used 1) the level of detail in empirical data available from normal Swedish potato production processing and distribution, without the introduction of extended accounting regulations or measuring equipment; and 2) the existing models applicable for calculation of the carbon footprint based on this data. This gave an estimate of the precision of the table potato CF if introduced into the current Swedish production system and calculated using existing and practically applicable models. The scenarios showed how the uncertainty in the CF was affected by using numbers on different temporal and spatial scales.

The base scenario (scenario a1) represented the use of an average CF value, as it took into account all variations and uncertainties for all parameters. In scenario b1, the variations in field-bound parameters were fixed, hence representing an average temporal value but for a specific field. Scenarios c1 and d1 were the same as a1, except that the CLfF project rules were applied. The rules mandate fertilisers with a maximum emission factor of 4 kg $CO_2$e/kg N and electricity from sustainable sources (CLfF, 2009).

Scenarios a2, b2, c2 and d2 represented calculating the CF for a specific year in which the yield, the amount of fertilisers and energy etc. spent are known, and hence only uncertainties were included for these parameters. In scenario b2 the variation in the field-bound parameters was also fixed. In scenarios c2 and d2, CLfF rules were applied.

### *3.6.5 Comparison of carbon footprints*

Table potatoes grown according to the CLfF rules were compared against the base scenario in order to calculate the probability that the CF for CLfF-grown potatoes from an arbitrary year and an arbitrary field was lower than that from the base scenario. By calculating the differences between individual samples from the CLfF MC simulation (scenario c1) and the base scenario MC simulation (scenario a1), a distribution of the difference between arbitrary bags of potatoes from the two production systems was obtained. This distribution was used to determine the probability that the CF of a bag of potatoes cultivated according to the CLfF system caused lower emissions (in grams) at different levels than those from the base scenario.

# 4 RESULTS

## 4.1 Mean value and contributing processes

The mean value was calculated with and without the application of the CLfF rules and the result was 0.12 and 0.11 kg $CO_2$e per kg respectively. The CLfF rules lowered the emissions by 11 g per kg (9%). The emissions from the contributing processes are listed in Table 29 in Appendix A, and the proportions are illustrated in *Figure 3*.

The processes that contributed most to the outcome were:

- $N_2O$ emissions from soil
- $CO_2$ sequestration to soil
- Production of fertilisers
- Production of seed
- Production, maintenance and waste handling of capital goods (machinery and buildings)
- Combustion of diesel fuel on the farm
- Electricity spent during processing
- Production of the paper bag
- Distribution of the potatoes

The sum of the emissions from the remaining processes was less than 5%.

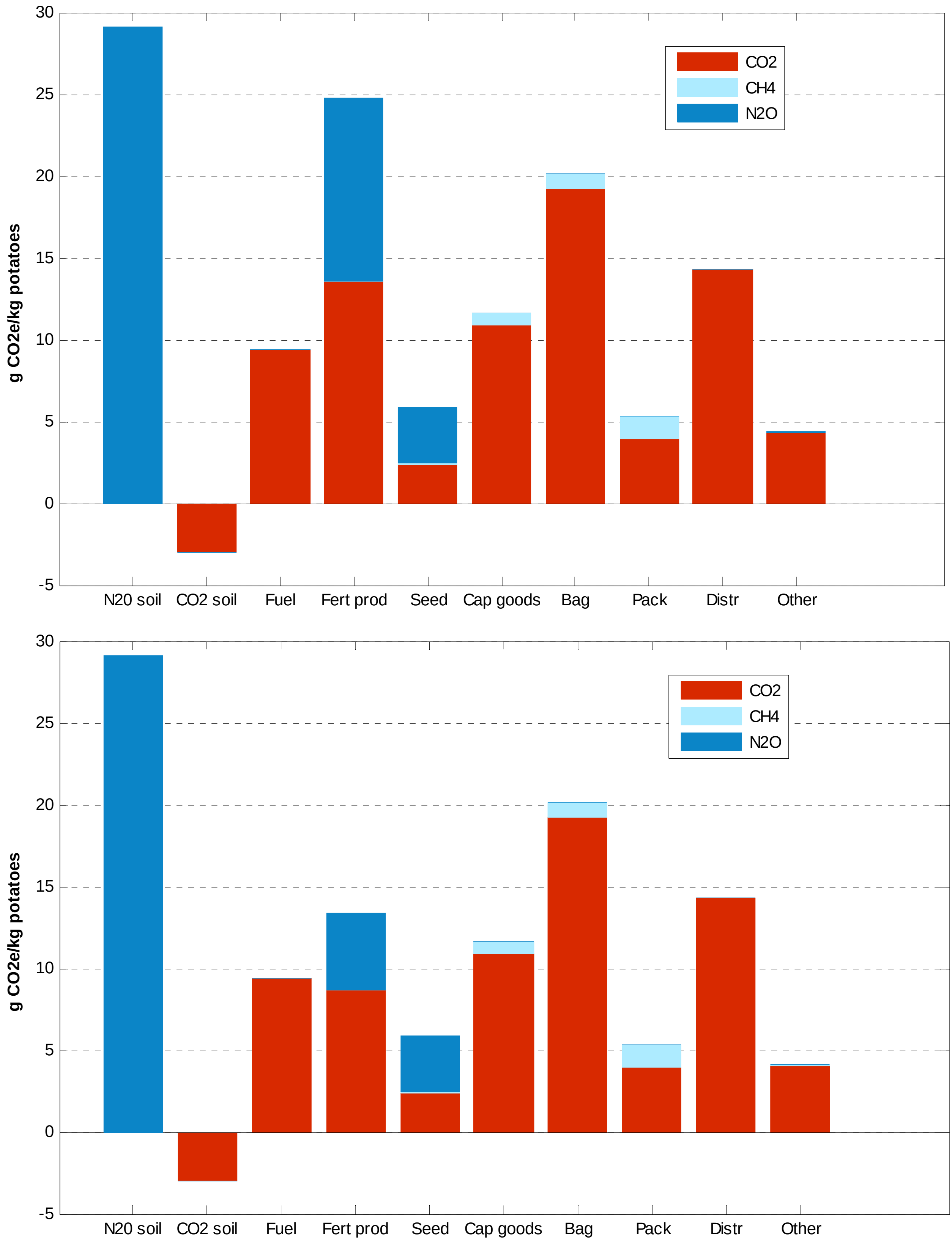



*Figure 3: Contribution to the total potato CF from the main contributing processes, cultivation without (upper diagram) and with (lower diagram) CLfF rules, deterministic mean values.*

## 4.2 Sensitivity and uncertainty importance analysis

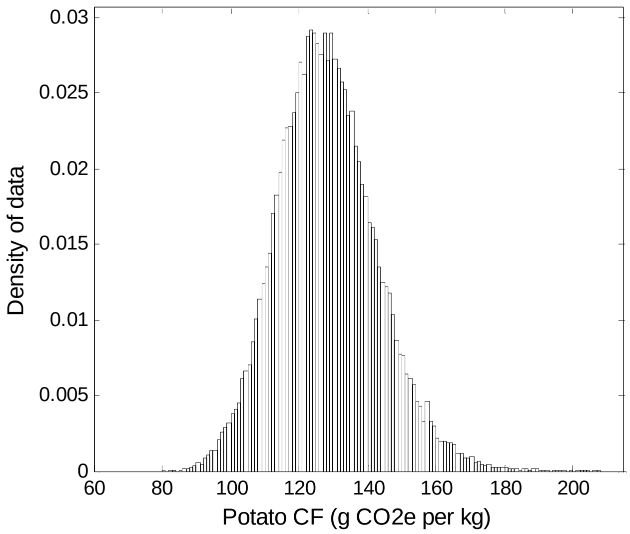
The results from the sensitivity and uncertainty importance analysis are shown in Appendix A.

The sensitivity analysis showed that the most sensitive parameters were potato yield and quality and the amount of N fertiliser used. The uncertainty importance analysis revealed that the soil humus content, the fuel spent during tillage operations, the amount of electricity spent during the packaging process, the distribution distance, and two of the EF used for soil emissions were also important for the end result. The results clearly show how a traditional sensitivity analysis can fail to recognise the sensitivity in the parameters that are not normally or uniformly distributed. Examples of such in this study included the log-normally distributed EF for $N_2O$ emissions and the energy spent during packaging.

## 4.3 Uncertainty analysis

The outcome of the MC simulation of the base scenario (a1), in which variations and uncertainties for all parameters were included, was that 95% of the results fell within a range of 0.10-0.16 kg $CO_2$e per kg table potatoes. For the simulation in which the CLfF rules were applied, the potato CF fell in the range of 0.091-0.15 kg $CO_2$e per kg table potatoes.

a1)




c1)

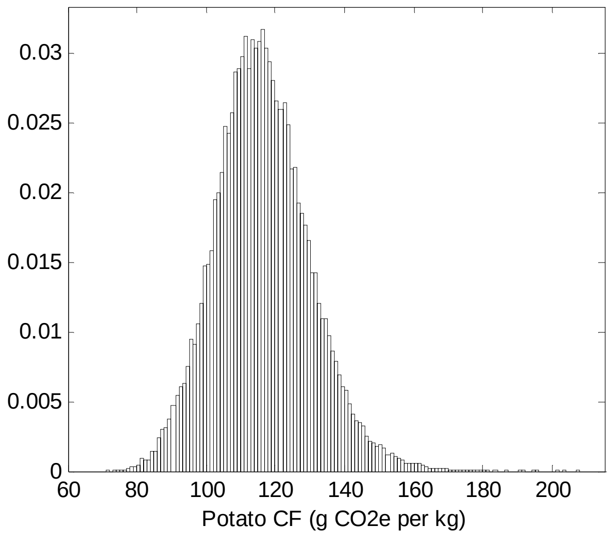



*Figure 4: Histogram of the MC simulation of the base scenario (a1) and with CLfF rules applied (c1).*

The relative uncertainty contributions from the main processes are illustrated as black bars in *Figure 5*. (See Table 31 in Appendix A for a more detailed numbers.)

The black bars show the uncertainty as a 2.5-97.5 percentile range in each individual process due to variations and uncertainty in the input parameters. Soil emissions showed a relative uncertainty contribution of 27% and 15% of the total CF for $N_2O$ and $CO_2$ emissions, respectively. The production of fertilisers, the packaging process and the distribution of the potatoes to the supermarket contributed to the uncertainty by similar magnitudes (13, 11 and 14%), while the remaining processes showed a relative uncertainty that was 6% or less.

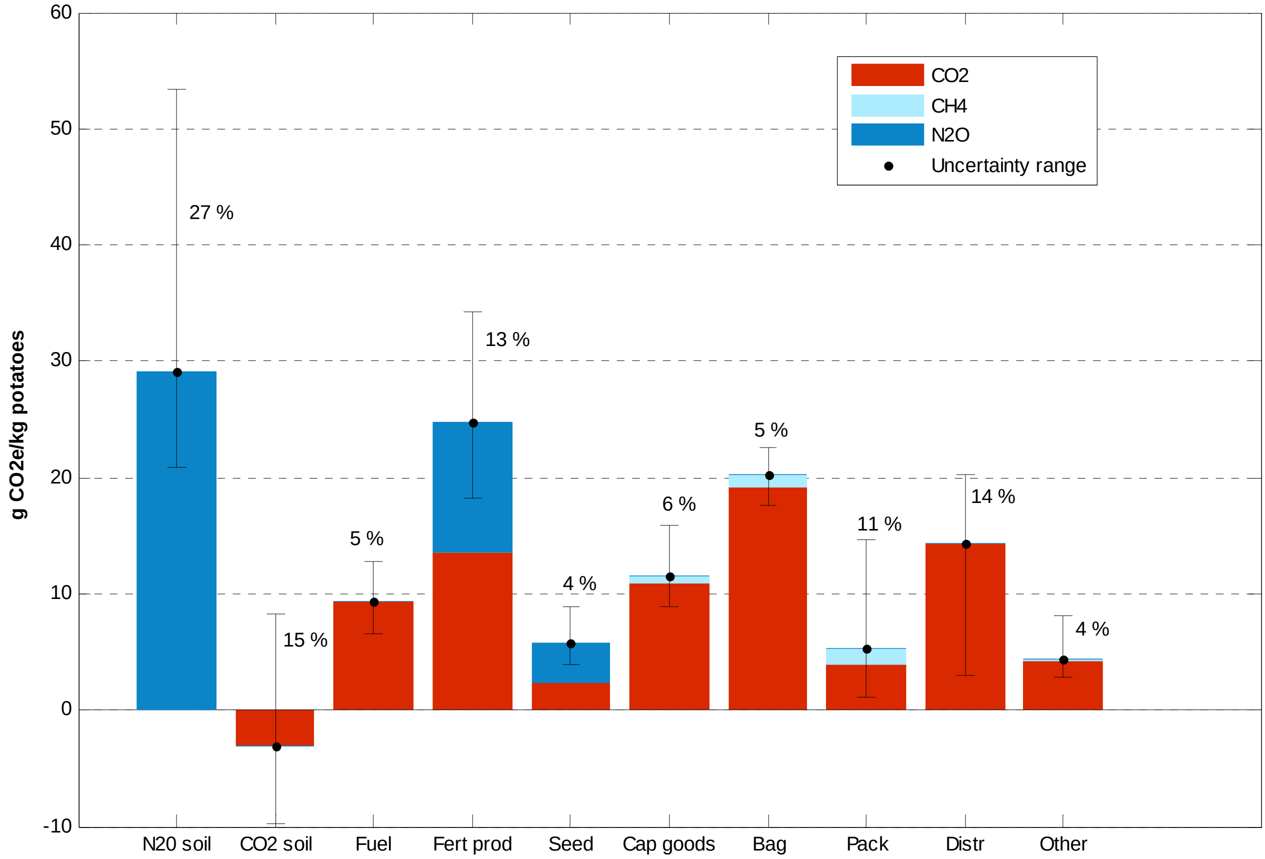



*Figure 5: Contribution to the total potato CF from the main contributing processes, error bars show uncertainty as the range between the 2.5 and 97.5 percentiles. Numbers are the relative contribution to uncertainty from an individual process as the range divided by the total mean CF.*

Monte Carlo simulation results for all scenarios are summarised in Table 27. The 95% uncertainty range for the CF decreased by 19% for a specific year when variations between years in AD such as yield, fertiliser amounts and energy spent (scenario a1 compared with a2) were not included. The uncertainty range was only very slightly affected by calculating the CF for a specific field for which only uncertainty in AD was included, and not variations in clay and humus content and the distance between the field and the farm. The CLfF rules reduced boundaries and marginally reduced the uncertainty range.

*Table 27: Potato CF for different scenarios (kg $CO_2$e per kg potatoes). Boundaries are the 2.5 and 97.5 percentiles and range is the difference between the boundaries. For the arbitrary year, all variations and uncertainties were included, while for the specific year, variations in AD, except transport AD, were excluded. In scenarios a and c variations and uncertainties in field-bound parameters were included, while in scenarios b and d variations in field-bound parameters were excluded. In scenarios c and d, the CLfF rules (CLfF, 2009) were applied*

| Scenario | | Arbitrary year | | Scenario | | Specific year | |
|---|---|---|---|---|---|---|---|
| | | Boundaries | Range | | | Boundaries | Range |
| A1 | Arbitrary field | 0.10-0.16 | 0.060 | a2 | Arbitrary field | 0.11-0.15 | 0.047 |
| B1 | Specific field | 0.10-0.16 | 0.060 | b2 | Specific field | 0.11-0.15 | 0.045 |
| C1 | Arbitrary field CLfF rules | 0.091-0.15 | 0.059 | c2 | Arbitrary field CLfF rules | 0.094-0.14 | 0.045 |
| D1 | Specific field CLfF rules | 0.091-0.15 | 0.059 | d2 | Specific field CLfF rules | 0.094-0.14 | 0.044 |

## 4.4 Comparison of carbon footprints

The distribution of the differences between individual samples from the base scenario a1 and scenario c1 simulations showed that with a probability of 72%, the CF of potatoes produced according to the CLfF rules (c1) was lower for an arbitrary year and field. The probability that the CF was 9% lower (the deterministic average reduction) was 53%. *Figure 6* shows the histogram of the difference in the CF in grams, from which the probability can be read.

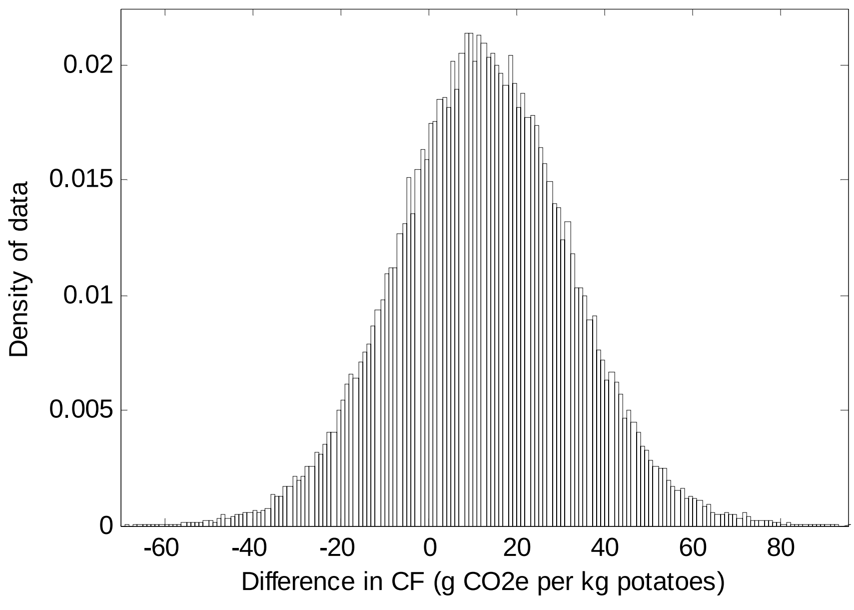



*Figure 6: Histogram of the difference in the CF from potatoes cultivated with and without the application of the CLfF rules for an arbitrary year and field (scenario a1 compared with scenario c1).*

Table 28: Probability that the CF of 1 kg of table potatoes produced according to the CLfF rules was lower than the CF of 1 kg of potatoes without CLfF rules applied for different scenarios

| Reduction | Scenario a1 comp. c1 | Scenario a2 comp. c2 |
|---|---|---|
| < 0 g | 72 | 76 |
| < 10 g | 53 | 53 |
| < 20 g | 33 | 29 |
| < 30 g | 17 | 12 |
| < 40 g | 7 | 4 |
| < 50 g | 3 | 1 |
| < 60 g | 1 | 0.3 |
| < 70 g | 0.3 | 0.09 |

## 5 DISCUSSION

The yield proved to be the most influential parameter for the carbon footprint. This is a common characteristic of agricultural products in general, since the accumulated emissions from a cultivated area are divided across the yield from that area. Hence, maximising yields reduces the CF. Carbon labelling systems with a numerical representation of the CF include this relationship but need to consider the resolution at which yield data (and other data) are collected and how to account for the variations between different years. How this is done depends on the purpose of the CF labelling system. If the aim is to stimulate individual producers to reduce emissions, data have to be collected for each producer individually. The most accurate CF result would be obtained from collecting the data on a per year, per field and per variety basis (scenario b2) and calculating a CF for a specific year. However, such a procedure would hardly be understandable or fair since the crop yield, and as a consequence the CF, from the same farm and under equal cropping systems could vary substantially due to varying weather conditions, pesticide attacks, etc. A correctly designed CF system should not punish a producer for uncontrollable factors, but should promote high yield due to good farming practice, which would lead to higher average yields. Therefore the use of yield data as a temporal average is more reasonable and would take into consideration the influence of yield on the CF, but would not punish a certain product and/or producer in a certain year of misfortunate and uncontrollable conditions. Omitting to take this into consideration when designing a CF system could lead to other products that cause higher overall emissions being favoured during a specific year, leading to an undesired effect of the CF labelling system. A system in which the CF for a specific product from the same producer, using the same production technology, varies considerably between years would also be very confusing for the consumer.

Providing consumer guidance that maximises the reduction in overall GHG emissions from food consumption is another potential goal for a CF system. In such a case the system needs to allow comparisons between different types of products and a CF for potatoes on a regional or national level could be justified. Building on the work initiated in this study, the uncertainty in such a CF for potatoes and other comparable products could be calculated and used in order to determine whether it is possible to have one CF value for all Swedish potatoes with the necessary precision to allow comparison with similar products. However, further methodological complexities are then introduced. Studies are needed on whether a fair comparison is possible without including the use phase in the CF, i.e. the energy requirement for home storage and preparation. The issue of products that can be considered comparable is another area in need of research. Comparable products need to be interchangeable from a functional point of view and must have similar nutrient content, which may require a functional unit based on energy or protein content or similar instead of mass (Schau & Fet, 2008).

Focusing on maximising yield could have serious impacts on other environmental aspects. Crop protection chemicals have little influence on the CF, while excluding pesticides would reduce yield substantially for several crops, giving a great negative influence on the CF. This is especially true for potatoes, a crop that is heavily sprayed, with fungicides in particular. Quantifying how different CF systems would affect ecotoxicity, biodiversity, soil quality and other factors is an area for further investigation.

The amount of N fertiliser is an important parameter since it determines the processes with the largest and the second largest contribution to the CF; the emissions of $N_2O$ from soil and the production of mineral fertilisers. However, the importance of N fertiliser amount might be overestimated, since $N_2O$ emissions depend on several other parameters (Kasimir-

Klemedtsson, 2001) that are not accounted for in the method used to calculate the $N_2O$ emissions. The outcome from the $N_2O$ method only varies with the amount of N applied, giving this parameter too great importance on a per year basis. However, in the long run the amount of N applied is an important parameter, since it contributes to accumulation of N in the soil that will affect $N_2O$ emissions in years to come.

The soil processes involved in the cultivation of agricultural products are often non-linear and difficult to predict and estimate due to their dependency on environmental and climatological factors with large variability in time and space. The large-scale methods for calculating soil emissions used in this study give rise to large uncertainties. More accurate estimates of the soil emissions would be possible using more advanced models, but in a CF system the models need to be practically applicable for CF calculation. For example, by using detailed data such as daily mean air temperature, precipitation and several soil properties, the ICBM model can be used to more precisely calculate the emissions or sequestration of $CO_2$ from soils (Andrén et al., 2004). Measurements of soil properties required by the model, which are associated with considerable variability on a temporal and spatial level, are not realistic during normal crop production today. Future research will have to evaluate whether it is possible to develop methods for assessing soil emissions that take into account controllable factors such as soil type, tillage methods and intensity, crop species, etc. and climate conditions, in order to compare products from different product categories as well as products cultivated in different geographical locations and under different cultivation systems.

Calculating the CF using data from a specific field did not decrease the uncertainty in the CF in this study. However, since the soil humus content is a parameter that can have a considerable impact on GHG emissions (Table 4), this could justify calculation of the CF on a per field basis. Potato cultivation on soils with low humus content could be practically favoured. This would be especially relevant for regions rich in high-humus soils.

The comparison between the CF for production with and without CLfF rules for an arbitrary year and field showed that only approximately half the climate-labelled bags of potatoes led to an emissions reduction of 9% (the deterministic mean reduction) compared with the unlabelled bags. This clearly illustrates the large uncertainty associated with food product CF calculations due to natural variations and uncertainties in models. Obvious reduction measures that do not alter the cultivation system and risk influencing the yield, etc., such as the use of low-emissions fertilisers and electricity as suggested by the CLfF project, should of course be promoted in any case. However, when introducing numerical CF labelling schemes or more complex rule-based systems for comparisons between products, uncertainty analysis cannot be neglected.

The results obtained here were compared with the process of production of potatoes in the ecoinvent database (ecoinvent Centre, 2007). The mean value in ecoinvent is 0.13 kg $CO_2$e per kg table potatoes. Although the ecoinvent process does not include the packaging process, the paper bag or the distribution, the result is still higher than that obtained in this study. The higher value is explained by the lower yield (37.7 ton/ha) used in the ecoinvent process, once again showing the great importance of the yield for the resulting CF. The uncertainty range from running a Monte Carlo simulation on the ecoinvent process gave an uncertainty range of 0.045 kg, which should be compared with the uncertainty range of 0.047 kg for a specific year (a2), since variation in yield is not included in the ecoinvent process. As can be seen, good agreement between the two uncertainty ranges was found, even though the underlying methodology for assessing the uncertainty information was different.

## 6 CONCLUSIONS AND PERSPECTIVES

The CF of table potatoes in this study varied between approximately -17% and +30% of the average value with 95% certainty, showing that uncertainty analysis in the design, calculation and evaluation of food product CF labelling schemes is important to ensure fair and effective comparison. The method outlined in this study, in which the uncertainties were divided into spatial and temporal variations and data/measuring uncertainty, is able to show how CF uncertainty is affected by the parameter resolution in time and space. The results from our study on potatoes showed that the reduction in uncertainty due to fixing the temporal and spatial variation (yield, fertiliser amount, soil properties, energy consumption, etc.) was only 19%.

The probability of reaching different levels of differentiation in the CF from different food production systems can be calculated using Monte Carlo simulation of the two systems and pair-wise comparison. Including this type of uncertainty analysis adds valuable information about the uncertainties in CF, as illustrated in this study by the example with and without the application of CLfF rules.

The natural question is: What is an acceptable level of uncertainty? The question is more political or philosophical than scientific in nature. Depending on the purpose of the labelling system, the uncertainty must be low enough to allow comparisons between potatoes from different producers or between potatoes and other comparable products. This study showed that for an arbitrary year and field, potatoes that were cultivated according to CLfF rules had a lower CF with a probability of 72%, and that the average reduction of 10% occurred with a probability of 53%. These numbers may or may not be regarded as an acceptable level of probability. Results from similar studies comparing the same product and comparable products would allow a rule of thumb to be devised for the acceptable uncertainty for different purposes.

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# Appendix A Detailed results

*Table 29: Deterministic mean emissions for potato cultivation, without and with CLfF rules (CLfF, 2009), calculated using mean values for all parameters. Values that differ between the two are marked in bold*

| | Emissions (g $CO_2$e per kg potatoes) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Without CLfF rules | | | | With CLfF rules | | | |
| Process: | $CO_2$ | $CH_4$ | $N_2O$ | $CO_2$e | $CO_2$ | $CH_4$ | $N_2O$ | $CO_2$e |
| $N_2O$ from soil | 0 | 0 | 29.1 | 29.1 | 0 | 0 | 29.1 | 29.1 |
| $CO_2$ to soil | -3.02 | 0 | 0 | -3.02 | -3.02 | 0 | 0 | -3.02 |
| Diesel fuel at farm | 9.42 | 0 | 0 | 9.42 | 9.42 | 0 | 0 | 9.42 |
| Diesel prod.& tran. | 0.45 | 0.0065 | 0 | 0.46 | 0.45 | 0.0065 | 0 | 0.46 |
| Chemicals prodn. | 0.013 | 0 | 0.0012 | 0.01 | 0.013 | 0 | 0.0012 | 0.01 |
| Chemicals trans. | 0.0006 | 0 | 0 | 0.00 | 0.0006 | 0 | 0 | 0.00 |
| Fertiliser prodn. | **13.5** | **0** | **11.3** | **24.8** | **8.69** | **0** | **4.74** | **13.4** |
| Fertiliser trans. | **1.05** | **0** | **0** | **1.05** | **1.04** | **0** | **0** | **1.04** |
| Seed production | 2.33 | 0.067 | 3.44 | 5.81 | 2.33 | 0.067 | 3.44 | 5.81 |
| On-farm electricity | **0.24** | **0.08** | **0** | **0.32** | **0.054** | **0.0180** | **0** | **0.072** |
| Capital goods | 10.9 | 0.8 | 0 | 11.7 | 10.9 | 0.8 | 0 | 11.7 |
| Transport farm-pack | 2.51 | 0 | 0 | 2.51 | 2.51 | 0 | 0 | 2.51 |
| Paper bag prod. | 19.2 | 0.9 | 0 | 20.1 | 19.2 | 0.9 | 0 | 20.1 |
| Packaging | 3.96 | 1.32 | 0 | 5.32 | 3.96 | 1.32 | 0 | 5.32 |
| Distribution | 14.3 | 0 | 0 | 14.3 | 14.3 | 0 | 0 | 14.3 |

*Table 30: Sensitivity analysis and uncertainty importance analysis of individual parameters, change in the CF in %*

| | Sensitivity analysis | | Uncertainty importance analysis | |
|---|---|---|---|---|
| | + 20% | - 20% | +2 std. | -2 std. |
| **Activity data:** | | | | |
| **Field-bound:** | | | | |
| Clay content | 0 | 0 | + 3 | 0 |
| Humus content | + 1.5 | - 1.5 | **+ 12** | - 4 |
| Distance farm-field | 0 | 0 | 0 | 0 |
| **Cultivation** | | | | |
| Yield | **- 11** | **+ 18** | **- 10** | **+ 15** |
| Quality | **- 10** | **+ 16** | - 3 | + 3 |
| Fuel tillage operations | + 2 | - 2 | **+ 7** | - 3 |
| Amount of N fertiliser | **+ 6** | **- 6** | **+ 7** | - 6 |
| Amount of P fertiliser | + 0.5 | - 0.5 | + 0.5 | - 0.5 |
| Amount of K fertiliser | + 0.5 | - 0.5 | + 0.5 | - 0.5 |
| Amount of seed | + 1 | - 1 | + 1 | - 1 |
| Chemical treatments | 0 | 0 | 0 | 0 |
| Amount of irrigation | 0 | 0 | + 0.5 | - 0.5 |
| Amount of machinery | + 2 | - 2 | + 4 | - 3 |
| Amount of buildings | 0 | 0 | 0 * | 0 * |
| **Processing:** | | | | |
| Energy packaging | + 1 | - 1 | **+ 7** | - 3 |
| Amount packaging mat. | + 3 | - 3 | 0 * | 0 * |
| **Transport:** | | | | |
| Distance farm-process. | + 1 | - 1 | + 2 | - 2 |
| Distribution distance | + 2 | - 2 | + 2 | **- 9** |
| **EF inputs:** | | | | |
| NPK fertiliser | + 3 | - 3 | 0 * | 0 * |
| N fertiliser | + 1 | - 1 | + 1 | - 1 |

| | | | | |
|---|---|---|---|---|
| Chemicals | 0 | 0 | 0 * | 0 * |
| Diesel | 0 | 0 | 0 * | 0 * |
| Seed | + 1 | - 1 | + 2 | - 2 |
| Paper bag | + 3 | - 3 | 0 * | 0 * |
| Electricity | + 1 | - 1 | + 4 | - 3 |
| Machinery | + 2 | - 2 | 0 * | 0 * |
| Buildings | 0 | 0 | 0 * | 0 * |
| **EF transports:** | | | | |
| Road transport tractor | + 0.5 | - 0.5 | +0.5 | -0.5 |
| Road transport truck | + 2 | - 2 | + 2 | - 2 |
| Sea transport | 0 | 0 | 0 | 0 |
| **EF soil:** | | | | |
| EF background | + 1 | - 1 | **+ 10** | - 3 |
| EF synthetic fertiliser | + 2 | - 2 | + 4 | - 3 |
| EF crop residuals | + 1 | - 1 | **+ 11** | - 4 |
| EF leach | + 0.5 | - 0.5 | + 4 | - 2 |
| EF deposition | + 0 | - 0 | + 0.5 | - 0 |
| h | - 4 | + 4 | - 4 | + 4 |
| re | + 1 | - 1 | + 1 | - 1 |

* Variation assumed to be negligible

*Table 31: Contribution to the total potato CF from the main contributing processes, 2.5 and 97.5 percentile values, the range between the 2.5 and 97.5 percentiles and the relative contribution to uncertainty from an individual process as the range divided by the total mean CF*

| | Scenario a1, arbitrary year and field, without CLfF rules | | | | Scenario c1, arbitrary year and field, with CLfF rules | | | |
|---|---|---|---|---|---|---|---|---|
| | Percentiles: | | | | Percentiles: | | | |
| | 2.5 | 97.5 | Range | Relative uncertainty | 2.5 | 97.5 | Range | Relative uncertainty |
| $N_2O$ from soil | 21 | 53 | 32 | 27 | 21 | 53 | 32 | 27 |
| $CO_2$ to soil | -9.7 | 8.3 | 18 | 15 | -9.7 | 8.3 | 18 | 15 |
| Diesel fuel at farm | 6.5 | 13 | 6 | 5 | 6.5 | 13 | 6 | 5 |
| Fertiliser production | 18 | 34 | 16 | 13 | 9.9 | 18 | 9 | 7 |
| Seed production | 3.8 | 8.8 | 5 | 4 | 3.8 | 8.8 | 5 | 4 |
| Capital goods | 9.0 | 16 | 7 | 6 | 9.0 | 16 | 7 | 6 |
| Paper bag production | 18 | 23 | 6 | 5 | 18 | 23 | 6 | 5 |
| Packaging | 1.2 | 15 | 14 | 11 | 1.2 | 15 | 14 | 11 |
| Distribution | 3.0 | 20 | 17 | 14 | 3.0 | 20 | 17 | 14 |
| Other | 2.9 | 8.2 | 5 | 4 | 2.8 | 7.8 | 5 | 4 |

**Tidigare publikationer/ Earlier publications**

**Rapport/Report**

| | | |
|---|---|---|
| 001 | 2008 | Nilsson, D. & Bernesson, S. Pelletering och brikettering av jordbruksvaror – En systemstudie |
| 002 | 2008 | Bernesson, S., Olsson, J., Rodhe, L., Salomonsson, E. & Hansson, P-A. Inblandning av aska från biobränslen i flytande biogasrötrest |
| 003 | 2008 | Gunnarsson, C., Olsson, J., Lundin, G. & de Toro, A.Spannmål till energi – ökad lönsamhet genom anpassning av odlingssystemet |
| 004 | 2008 | Johansson, T. & Lundh, J-E. Försök med upprepad röjning av björk och sälg |
| 005 | 2008 | Cardoso, M. Olsson, J. & de Toro, A. Manual till JTI/SLUs kalkylprogram för maskinkostnader i Excel |
| 006 | 2008 | de Toro, A., Cardoso, M. & Olsson, J.Manual till JTI/SLU:s kalkylator för maskinkostnader i latbruket |
| 007 | 2009 | Amiri, S. On variance estimation and a goodness-of-fit test using the bootstrap method |
| 008 | 2009 | Johansson, T. Avverkningstidpunktens inverkan på rot- och stubbskottutvecklingen hos 15-årig klibbal och 8-årig grail. Biomassaproduktionens variation beroende på avverkningstidpunkten |
| 009 | 2009 | Sundberg, C. Minimisation of odour from composting of food waste through process optimisation – a Nordic collaboration project |
| 010 | 2009 | Cuvilas, C.A. Characterisation of available and potential sources of wood fuels in Mozambique |
| 011 | 2009 | Nilsson, D, & Bernesson, S. Halm som bränsle – Del 1: Tillgångar och skördetidepunkter |
| 012 | 2009 | Olsson, O. European bioenergy markets: integration and price convergence |
| 013 | 2009 | Ladanai, S. & Vinterbäck, J. Global potential of sustainable biomass for energy |
| 014 | 2009 | Johansson, T. Root biomass production and distribution in young birch stands planted at four spacings on two different sites in Sweden |
| 015 | 2009 | Lindgren, M., Arvidsson, H., Wetterberg, C., Johansson, B. & Hansson, P-A. Reglerade emissioner under statiska och transienta belastningar |
| 016 | 2009 | Lindgren, M., Arrhenius, K., Rosell, L., Boss, A., Johansson, L., Wetterberg, C., Johansson, B. & Hansson, P-A. Oreglerade emissioner under statiska och transienta belastningar – Organiska ämnen och partiklar, antalskoncentration och storleksfördelning |

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