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A system approach to quantify greenhouse gas emissions and key parameters from dairy cow production as affected by milk yield and breed

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„For an understanding, not only the elements but their interrelations as well are required”

(Ludwig von Bertalanffy, 1973)

Summary

In view of an increasing global demand for milk and the challenge to mitigate climate change, there is a need to identify dairy cow production systems that produce a kg of milk with lowest greenhouse gas (GHG) emissions. To avoid GHG emission leakage (shift of GHG emissions from one food sector or country to another), the interrelationship of milk production, beef production and land use needs to be considered. The main objective of this thesis was to quantify the effect of increasing milk yield/cow on GHG emissions and on other side effects while considering different methods to account for the close interlink of milk and beef production. A further objective was to classify uncertainty of parameters included in GHG modelling and to explore their impact on variation of GHG emission outcomes. The objectives were addressed in the three parts of this thesis.

In the first part, a deterministic model was developed predicting GHG emissions, land use and economic performance of different dairy and beef production systems using a life cycle assessment approach. Two scenarios were modelled: constant milk production at the farm level and decreasing beef production (beef from culled cows and fattening of surplus calves as co-product of dairy cow systems - Scenario 1) and both milk and beef production kept constant, by compensating for the decline in beef production with beef from suckler cow production (Scenario 2). The modelled dairy cow production systems varied in milk yield/cow/year (6,000 kg, 8,000 kg and 10,000 kg) and breed. Dairy cow ration was assumed to consist of maize silage, grass silage and hay supplied with concentrates (wheat, barley, corn and soybean meal). Scenario 1 resulted in lower GHG emissions with increasing milk yield/cow. However, when milk and beef outputs were kept constant (Scenario 2), GHG emissions remained approximately constant with increasing milk yield from 6,000 to 8,000 kg of milk/cow/year. Further increases in milk yield (10,000 kg of milk/cow/year) ongoing with a change in breed from dual-purpose to milk-oriented breed resulted in higher (8%) total GHG emissions. Accordingly, the use of grassland and arable land increased with increasing milk yield/cow when milk and beef output were kept constant. The study demonstrated that the environmental

(GHG emissions) and land use impact of increasing milk yield/cow in dairy farming differs, depending on the amount and type of meat (beef, pork, poultry) that has to be compensated for.

In the second part of this thesis, the existing deterministic model was further developed. A stochastic model was developed using Monte Carlo simulations to evaluate the effect of uncertainty in input parameters on modelled GHG emissions. The uncertainties were classified according to the nature of uncertainty, i.e. epistemic uncertainty of emission factors due lack of data quality or methodological uncertainty and variability related uncertainty due to inherent variability of production traits (calving interval, replacement rate) and emission factors. This distinction is important, as the different types of uncertainty have fundamentally different causes and need to be addressed in different ways. Two system boundaries were assessed in the stochastic model approach: the system boundary of the "dairy farm gate" (all GHG emissions are allocated between milk and co-products using different allocation rules) and "system expansion" (beef derived from culled cows and fattening of surplus calves was assumed to replace beef from suckler cow production, the avoided GHG emissions from suckler cows were credited to the dairy farm).

The choice of system boundary had the strongest impact on the level and variation of predicted GHG emissions. In the case of the dairy farm gate boundary higher-yielding dairy cow production systems resulted in lower GHG emissions per kg milk with a high probability. In the case of system expansion the order changed. Thus, results of the deterministic model were confirmed.

Variability uncertainty of production traits had the lowest impact on variation of predicted GHG emission levels. Lower-yielding production systems had the highest variation, indicating the highest potential for GHG mitigation of all production systems studied. The variation in predicted GHG emissions increased substantially when both epistemic uncertainty in emission factors and variability uncertainty in production traits were included in the model. If the system boundary was set at the farm gate, the emission factor of direct nitrous oxide (N_2O) emissions from nitrogen input into the soil had the highest impact on variation of predicted GHG emissions. This variation stems from uncertainties predicting N_2O emissions (epistemic uncertainty) but also from inherent variability of N_2O emissions over time and space. The uncertainty of predicted GHG emissions can be reduced by increasing the precision in predicting N_2O emissions. However, this additional information does not reduce GHG emissions itself. Knowing site specific variability of N_2O emissions can help to reduce GHG emissions by specific management (e.g. reduce soil compaction, adopted manure management, choice of suitable crops).

In the case of system expansion the high uncertainty of emission factor for suckler cow beef explained a high percentage of the total variation of GHG emission outcomes and thus dominated uncertainty compared to all other input uncertainties. Uncertainty was based on lack of data as to which suckler beef production system should be chosen to credit dairy beef output. Despite the high degree of uncertainty when using system expansion, its results help in identifying global GHG mitigation options of combined milk and beef production.

If uncertainty of emission factor for soybean meal production was included in the stochastic model, the variation of predicted GHG emissions was dominated by this factor within both investigated system boundaries. This was especially the case in higher-yielding dairy cow production systems. The high range of emission factor for soybean meal production was derived from uncertainty of GHG emissions from land use change. Because there is no common consensus in methodology, the inclusion or exclusion of GHG emissions from land use change need to be reported separately and carefully as they can affect results of GHG emissions per kg of milk substantially.

In the third part of this thesis, commercial dairy farms were analysed. The goal of this study was to firstly compare GHG emissions, land use and beef output/kg milk of dual-purpose and specialized German dairy farms using a life cycle assessment approach and secondly to determine the relative importance of parameters explaining variation of predicted GHG emissions, beef output and land use. Parameters or variables that are high contributors to GHG emissions and show a high degree of variability are defined as “important parameters” as they have a high potential to mitigate GHG emissions. In total, 27 confinement dairy farms from southern Germany with dual-purpose Fleckvieh cows (South-Fleckvieh) and 26 confinement dairy farms from western Germany with Holstein-Friesian cows (West-

Holstein-Friesian) were assessed. Stepwise multiple linear regression and dominance analysis were used to identify parameters that have the highest impact on variation of GHG emissions, beef output and land use. Beef output was calculated as actual (beef from culled cows) and potential beef output (includes not only beef from culled cows but also from fattening of surplus dairy calves outside the farm). The results showed that South-Fleckvieh dairy farms emitted greater GHG emissions per kg of milk than higher-yielding West-Holstein-Friesian dairy farms. A wide range in GHG emissions within the investigated regions and systems was found. Outcomes of variable importance analysis showed that milk yield and replacement rate had the highest impact on variation of GHG emissions in both dairy farm groups. The average potential beef output per kg of milk of West-Holstein-Friesian dairy farms was significantly lower compared to South-Fleckvieh dairy farms. An opposite effect of milk yield and replacement rate on GHG emissions per kg of milk and beef output per tonne of milk was observed, particularly in the case of South-Fleckvieh dairy farms. However, the impact of replacement rate on potential beef output per kg of milk was highly sensitive to assumptions made to estimate potential beef output. No difference between the regions and breeds was found in the case of land use per kg of milk. Trade-offs between GHG emissions, potential beef output and land use per kg of milk, indicate the potential for shift of GHG emissions to other production systems or countries. Therefore, in the search for GHG mitigation options, effective strategies that do not have an undesirable impact on key indicators e.g. feed efficiency, nitrogen use efficiency or calving interval should be prioritised.

The results of this thesis showed that the choice of system boundary in modelling GHG emissions and land use per kg of milk can have an important impact on results and conclusions especially when comparing different dairy cow breeds. The results using the farm-gate boundary provide guidance for dairy farmers to reduce GHG emissions at the farm. The results using system expansion are important to define sound GHG abatement policies, to improve sustainability for milk and beef production and to avoid GHG emissions leakage. When accounting for both milk and beef production it was shown that improvements in GHG emissions due to changes in milk yield are limited. Furthermore, trade-offs between production traits within a farm do exist. Thus, to mitigate GHG emissions of high performing farms the focus

should be on an optimal combination of milk yield and replacement rate rather than solely focusing on increasing milk yield/cow. Future research should continue to focus on the interrelationship between milk and beef production, amount and type of land use and GHG emissions. Land use plays a special role in the discussion of climate change, as it can act both as a carbon source and sink.

Outlook

Results of this study showed that reductions of GHG emissions from changes in animal production systems are limited, especially when looking at net effects. Those measurements should be preferred that have additional positive effects i.e. improved management of manure and mineral fertilizer and increased longevity of dairy cows.

The expansion of suckler cow production in order to keep beef output constant resulted in an increase in GHG emissions. However, these impacts must be judged differently. If suckler cows utilize feed that is not suitable for humans (e.g. grass and hay from permanent grassland), these production systems play an important role in food supply. If suckler cows or cattle are fed with products from arable land that can directly be consumed by humans, they can have negative effects on food security. Furthermore, when comparing animals with high and low outputs per animal per year, it is important to consider further sustainability issues such as animal welfare.

Results of this study also showed that improvements in GHG emissions through production trait changes of dairy cows are marginal compared to a change in consumption patterns.

Generally, in the discussion about climate change, options that address both mitigation and adaptation to climate change should be taken into account.

Zusammenfassung

Klimaschutz stellt weltweit eine zentrale Herausforderung dar. In diesem Zusammenhang besteht angesichts steigender Nachfrage nach Milchprodukten zunehmendes Interesse darin, Milch mit möglichst geringen Treibhausgas (THG)-Emissionen zu erzeugen. Um THG-Leakage-Effekte (Verschiebung von THG-Emissionen von einem Produktionsbereich bzw. einem Land zu einem anderen) zu vermeiden, besteht die Notwendigkeit, die engen Beziehungen zwischen Milch- und Rindfleischproduktion sowie dem Flächenbedarf bei der Bestimmung von THG-Emissionen der Milchproduktion zu berücksichtigen. Ziel dieser Arbeit war es, die Auswirkungen einer Milchleistungssteigerung in der Milchviehhaltung auf THG-Emissionen und weitere Kennzahlen zu quantifizieren. Ein besonderes Augenmerk wurde dabei auf die Methode zur Erfassung der Verknüpfung der Milch- und Rindfleischproduktion gelegt. Ein weiteres Ziel bestand darin, Unsicherheiten, die bei der Modellierung von THG-Emissionen auftreten, zu klassifizieren und diejenigen Parameter zu ermitteln, die den größten Einfluss auf die Variation der THG-Emissionen haben. Die Bearbeitung der Fragestellungen erfolgte in drei Teilbereichen.

Im ersten Teil dieser Arbeit wurde ein deterministisches Modell zur Vorhersage von THG-Emissionen, Flächenbedarf und ökonomischen Kennzahlen unterschiedlicher Milchvieh- und Rindfleischproduktionssysteme erstellt. Dabei wurde der Ansatz einer Lebenszyklusanalyse gewählt. Zwei Szenarien wurden betrachtet: konstante Milch- und abnehmende Rindfleischproduktion (von Schlachtkühen und der Ausmast nicht zur Nachzucht benötigter Kälber - Szenario 1) und Konstanthaltung der Milch- und Rindfleischproduktion (der Rückgang des Rindfleischanfalls wird mit Rindfleisch aus der Mutterkuhhaltung kompensiert - Szenario 2). Die modellierten Milchproduktionssysteme variierten in Bezug auf die Milchleistung (6.000, 8.000 und 10.000 kg Milch/Kuh und Jahr) und Rasse. Als Fütterungssystem wurde eine Ganzjahressilage mit Silomais- und Grassilage ergänzt durch Heu und entsprechende Mengen an Kraftfutter (Weizen, Gerste, Körnermais, Sojaextraktionsschrot) gewählt. Unter der Annahme des ersten Szenarios zeigte sich ein Rückgang der THG-Emissionen mit steigender Milchleistung. Unter der Annahme einer konstanten Milch- und Rindfleischproduktion (Szenario 2) zeigten die Systeme mit 6.000 und 8.000 kg Milch/Kuh und Jahr vergleichbare THG-Emissionen. Ein weiterer Anstieg der Milchleistung (10.000 kg Milch/Kuh und Jahr) einhergehend mit einem Wechsel der Milchviehrasse von einer Zweinutzungs- zu einer spezialisierten Milchrasse führte zu einem Anstieg der THG-Emissionen um 8%. Auch der Bedarf an Grünland und Ackerfläche erhöhte sich mit einem Anstieg der Milchleistung und der Annahme konstanter Milch- und Rindfleischproduktion. Die Untersuchungen haben gezeigt, dass die Umweltwirkungen (THG-Emissionen) und der Flächenbedarf bei einem Anstieg der Michleistung in der Milchviehhaltung vor allem von der Menge und Art des Fleisches (Rindfleisch, Schweinefleisch oder Geflügel) abhängig ist, welches den Rückgang des Rindfleisches aus der Milchviehhaltung kompensiert.

Im zweiten Teil dieser Arbeit wurde das deterministische Modell weiterentwickelt. Ein stochastisches Modell wurde erstellt mit Hilfe von Monte Carlo Simulationen, um den Einfluss der Unsicherheit der Inputparameter auf die modellierten THG-Emissionen zu testen. Dabei wurden die Unsicherheiten zunächst nach der Art der Unsicherheit klassifiziert: epistemische Unsicherheit der Emissionsfaktoren aufgrund mangelnder Daten(-qualität) oder methodischen Unsicherheiten und Unsicherheit aufgrund von Variabilität durch inhärente Variabilität der Emissionsfaktoren und produktionstechnischen Parameter (Zwischenkalbezeit und Remontierungsrate). Diese Differenzierung ist bedeutsam, da diese Arten der Unsicherheit unterschiedliche Ursachen haben und unterschiedlich behandelt werden müssen in Bezug auf die Vermeidung von THG-Emissionen. Weiterhin wurden zwei verschiedene Systemgrenzen im Emissionsmodell berücksichtigt: die Systemgrenze „Milchviehbetrieb“ (alle THG-Emissionen werden zwischen Milch und den Nebenprodukten nach unterschiedlichen Regeln aufgeteilt) und „Systemerweiterung“ (Rindfleisch von Schlachtkühen und aus der Ausmast nicht zur Nachzucht benötigter Kälber ersetzt Rindfleisch aus der Mutterkuhhaltung; dadurch werden THG-Emissionen vermieden; es erfolgt eine THG-Gutschrift für die Milchviehhaltung).

Die Wahl der Systemgrenze zeigte den größten Einfluss auf die Höhe und Variation der modellierten THG-Emissionen. Im Falle der Systemgrenze des Milchviehbetriebs zeigte sich, dass die höher leistenden Milchproduktionssysteme bei hoher Wahrscheinlichkeit niedrigere THG-Emissionen pro kg Milch aufweisen. Im Falle der erweiterten Systembetrachtung kehrte sich die Rangfolge um. Die Ergebnisse des deterministischen Modells wurden weitgehend bestätigt.

Unsicherheit aufgrund von Variabilität bei produktionstechnischen Parametern hatte den geringsten Einfluss auf die Variation der modellierten THG-Emissionen. Die größte Variation der THG-Emissionen war bei niedrig leistenden Milchviehhaltungssystemen zu beobachten. Dies weist darauf hin, dass dort die größten Möglichkeiten einer Reduktion von THG-Emission bestehen. Die Variation der modellierten THG-Emissionen erhöhte sich deutlich im Falle einer gemeinsamen Aufnahme von epistemischer Unsicherheit der Emissionsfaktoren und Unsicherheit aufgrund von Variabilität in produktionstechnischen Parametern. Bei der Systemgrenze „Milchviehbetrieb“ lieferte der Emissionsfaktor zur Vorhersage der Lachgas (N_2O) -Emissionen aus dem Stickstoffeintrag in den Boden den größten Beitrag zur Erklärung der Variation der modellierten THG-Emissionen. Die Unsicherheit des Emissionsfaktors setzt sich zusammen aus der Unsicherheit einer exakten Vorhersage der N_2O-Emissionen (epistemische Unsicherheit) sowie einer inhärenten Variabilität der N_2O-Emissionen in Bezug auf Zeit und Standort. Eine Verbesserung der Vorhersage von N_2O-Emissionen kann zu mehr Sicherheit in Bezug auf die Ergebnisse von modellierten THG-Emissionen führen. Informationen über standortspezifische N_2O Emissionen können dazu genutzt werden, um THG-Vermeidungsstrategien durch standortangepasste Bodenbewirtschaftung anzuwenden (z.B. Verringerung der Bodenverdichtung, angepasstes Güllemanagement, Wahl einer geeigneten Fruchtart).

Im Falle der erweiterten Systembetrachtung erklärte die Unsicherheit des Emissionsfaktors für Mutterkuhrindfleisch den größten Anteil der Variation der modellierten THG-Emissionen. Dies ist vor allem durch die Unsicherheit begründet, welches Mutterkuhsystem gewählt werden soll, um die Gutschrift für die Rindfleischproduktion aus der Milchviehhaltung zu berechnen. Trotz großer Unsicherheit der Ergebnisse im Falle einer erweiterten Systembetrachtung sind diese von großer Bedeutung, wenn es darum geht, THG-Vermeidungsstrategien für Milch- und Rindfleischproduktion zu identifizieren.

Falls die Unsicherheit des Emissionsfaktors für Sojaextraktionsschrot im Modell berücksichtigt wurde, erklärte dieser Faktor den größten Teil der THG-Variation bei beiden Systemgrenzen. Dies war besonders ausgeprägt im Falle höher leistender Milchproduktionssysteme. Die Bandbreite des Emissionsfaktors für Sojaextraktionsschrot ist durch die Unsicherheit begründet, ob bzw. inwieweit der Aspekt Landnutzungsänderung (Abholzung) berücksichtigt wird. Aufgrund fehlender wissenschaftlicher Übereinstimmung in der Wahl der Methode ist es notwendig, den Einfluss einer Berücksichtigung von Landnutzungsänderungen auf die Ergebnisse modellierter THG-Emissionen separat auszuweisen. Die Annahmen im Bereich Landnutzungsänderung können die Ergebnisse entscheidend beeinflussen.

Im dritten, empirischen Teil dieser Arbeit erfolgte eine Untersuchung von Praxisbetrieben. Ziel dieser Studie war es, (1) THG-Emissionen, Landnutzung und Rindfleischanfall pro kg Milch von deutschen Milchviehbetrieben mit unterschiedlicher Rasse anhand einer Lebenszyklusanalyse zu vergleichen und (2) die relative Wichtigkeit von Parametern bei der Erklärung der Variation von THG-Emissionen, Landnutzung und Rindfleischanfall zu bestimmen. Parameter oder Variablen, die einen großen Beitrag zu den Emissionen liefern und eine hohe Unsicherheit aufgrund von Variabilität aufweisen, werden als „wichtige Parameter“ bezeichnet, da sie ein hohes Potential für die Vermeidung von THG-Emissionen aufweisen. 27 Betriebe aus Süddeutschland mit Milchkühen der Zweinutzungsrasse Fleckvieh (Süd-Fleckvieh) sowie 26 Betriebe aus Westdeutschland mit Milchkühen der Milchspezialrasse Holstein-Friesian (West-Holstein-Friesian) wurden untersucht. Schrittweise multiple Regressionen und Dominanzanalysen wurden durchgeführt, um diejenigen Parameter zu bestimmen, welche den größten Beitrag zur Erklärung der Variation der THG-Emissionen, der Landnutzung und des Rindfleischanfalls liefern. Bei der Berechnung des Rindfleischanfalls erfolgte eine Differenzierung zwischen aktuellem (Schlachtkuhfleisch) und potentiellem Rindfleisch (zusätzlich Rindfleisch aus der Ausmast von nicht zur Nachzucht benötigten Kälbern außerhalb des Milchviehbetriebs).

Die Modellierung der THG-Emissionen pro kg Milch ergab signifikant höhere Werte für die Süd-Fleckvieh-Betriebe im Vergleich zu den West-Holstein-Friesian-Betrieben. Die untersuchten Regionen und Systeme wiesen eine hohe Bandbreite an Emissionen pro kg Milch auf. Die Bestimmung wichtiger Parameter ergab, dass Milchleistung und Remontierungsrate den größten Beitrag zur Erklärung der Variation der THG-Emissionen lieferten. Der durchschnittliche potentielle Rindfleischanfall pro kg Milch war signifikant höher bei den Süd-Fleckvieh-Betrieben im Vergleich zu den West-Holstein-Friesian-Betrieben. Der Einfluss von Milchleistung und Remontierungsrate auf THG-Emissionen pro kg Milch und Rindfleischanfall pro kg Milch verhielt sich gegensätzlich. Dabei ist zu berücksichtigen, dass die Bedeutung der Remontierungsrate auf den Rindfleischanfall entscheidend durch die Annahmen zur Berechnung des potentiellen Rindfleischanfalls beeinflusst wird. Es konnte kein signifikanter Unterschied zwischen den untersuchten Regionen und Produktionssystemen in Bezug auf Landnutzung pro kg Milch festgestellt werden. Die aufgezeigten Trade-offs zwischen THG-Emissionen, potenziellem Rindfleischanfall und Landnutzung geben einen Hinweis auf eine potentielle Verschiebung von THG-Emissionen in andere Produktionssysteme bzw. Länder. Daher sollten bei der Suche nach THG-Vermeidungsoptionen solche Strategien fokussiert werden, welche andere Impakt-Kategorien nicht negativ beeinflussen. In der vorliegenden Studie waren dies beispielsweise Futtereffizienz, effizienter Stickstoff-Einsatz und Zwischenkalbezeit.

Anhand der einzelnen Studien konnte aufgezeigt werden, dass die Wahl der Systemgrenze einen entscheidenden Einfluss auf die Ergebnisse von THG-Emissionen pro kg Milch und des Bedarfs an Fläche pro kg Milch haben. Dies zeigte sich insbesondere beim Vergleich unterschiedlicher Milchviehrassen. Die Ergebnisse im Falle der Systemgrenze „Milchviehbetrieb“ liefern Hinweise für Landwirte zur Vermeidung von THG-Emissionen auf Milchviehbetrieben. Die Ergebnisse im Falle einer erweiterten Systembetrachtung sind von Bedeutung bei der Formulierung von politischen Maßnahmen zur Reduktion von THG-Emissionen, bei einer Verbesserung der Nachhaltigkeit der Milch- und der Rindfleischproduktion sowie um Verschiebungen von THG-Emissionen zu vermeiden. Bei einer Berücksichtigung der Milch- und Rindfleischproduktion zeigte sich, dass eine Reduktion der THG-

Emissionen durch eine Verbesserung der Milchleistung nur in begrenztem Umfang möglich ist. Zudem existieren Trade-offs zwischen produktionstechnischen Parametern innerhalb von Milchviehbetrieben. Daher sollte bei Systemen mit bereits sehr hohen Milchleistungen der Fokus auf einer Optimierung von Milchleistung und Remontierungsrate liegen anstelle einer einseitigen Fokussierung auf weitere Milchleistungssteigerungen. In zukünftigen Studien sollte die Wechselwirkung zwischen Milch- und Rindfleischproduktion, Art und Umfang der Flächennutzung und den Emissionen klimarelevanter Gase vertieft untersucht werden. Flächenbedarf spielt im Klimaschutz eine bedeutende Rolle aufgrund der Eigenschaft von Böden, als Kohlenstoffquelle und -senke zu fungieren.

Ausblick

Die Ergebnisse dieser Arbeit haben gezeigt, dass die Vermeidung von THG-Emissionen im engeren Bereich der tierischen Produktion nur in begrenztem Umfang möglich ist, vor allem, wenn die Nettoeffekte betrachtet werden. Im Hinblick auf die THG-Emissionsminderung sollten diejenigen Maßnahmen präferiert werden, welche mit positiven Nebenwirkungen verbunden sind. Dazu zählen unter anderem Verbesserungen im Management des organischen und mineralischen Düngers sowie eine Erhöhung der Nutzungsdauer von Milchkühen.

Unter der Annahme einer steigenden Milchleistung und konstantem Rindfleischbedarf führt die damit verbundene Ausweitung der Mutterkuhhaltung tendenziell zu steigenden THG-Emissionen. Diese Konsequenzen sind aber unterschiedlich zu beurteilen. Sofern Mutterkühe mit Futtermittel versorgt werden, die für den Menschen nicht unmittelbar verwertet werden können (z.B. Gras und Heu von absolutem Grünland), leisten diese Produktionsverfahren einen wichtigen Beitrag zur Erweiterung der Nahrungsbasis. Sofern Mutterkühe bzw. Wiederkäuer mit auch vom Menschen nutzbarem Protein gefüttert werden, schmälert dies die Nahrungsversorgung. Darüber hinaus müssen beim Vergleich von Nutztieren mit unterschiedlich hohem Output an Nahrungsmitteln pro Tier und Zeiteinheit auch weitere Aspekte wie z.B. im Bereich Tierwohl berücksichtigt werden.

Im Rahmen dieser Arbeit zeigte sich zudem, dass Vermeidungspotentiale von THG-Emissionen im Tierproduktionsbereich relativ begrenzt sind im Vergleich zu den Einsparmöglichkeiten durch veränderte Konsumgewohnheiten.

Generell sind im Zusammenhang mit der Diskussion um den Klimawandel solche Maßnahmen zu berücksichtigen, die sowohl einen Beitrag zur Verminderung von THG-Emissionen als auch zur Anpassung an den Klimawandel liefern.

Contents

List of Publications

The following research papers are the basis of this cumulative dissertation. Within the text the Roman numbers introduced below are used to refer to the different papers.

I Zehetmeier, M., Baudracco, J., Hoffmann, H., Heissenhuber, A., 2012. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. *Animal*. 6 (1), 154–166.

II Zehetmeier M., Gandorfer, M., de Boer, I.J.M., Heißenhuber A. Economic allocation and system expansion modelling GHG emissions in dairy farming. The impact of uncertainty. *Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaus e.V.* (GEWISOLA) 48, 397-406.

III Zehetmeier M., Gandorfer, M., Hoffmann, H., Müller, U.K, de Boer, I.J.M., Heißenhuber A. The impact of uncertainties on predicted GHG emissions of dairy cow production systems. *Journal of Cleaner production* (in Press).

IV Zehetmeier M., O’Brien, D., Hofmann, G., Dorfner, G., Heißenhuber A., Hoffmann, H. An assessment of variable importance when predicting greenhouse gas emissions, beef output and land use of dual-purpose and specialized German dairy farms. (under Review).

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List of Abbreviations

ADR	Arbeitsgemeinschaft Deutscher Rinderzüchter e.V.
ALCA	Attributional Life Cycle Assessment
AMI	Agrarmarkt und Informations-Gesellschaft
BZA	Betriebszweigauswertung
CaO_3	Calcium carbonate
CF	Crude fibre
CH_4	Methane
CLCA	Consequential Life Cycle Assessment
CO_2	Carbon dioxide
CP	Crude protein
DLG	Deutsche Landwirtschafts-Gesellschaft
EA	Economic allocation
EE	Ether extract
EU	European Union
FAO	Food and Agriculture Organization
$F_{commercial}$	Commercial Farm
FPCM	Fat and protein corrected milk
FV	Fleckvieh
GHG	Greenhouse gas
GWP	Global warming potential
IPAT	Impact, population, affluence, technology
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

K	Potassium
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
LCA	Life Cycle Assessment
LfL	Landesanstalt für Landwirtschat
LKV	Landeskuratorium der Erzeugerringe für tierische Veredelung in Bayern e.V.
LUC	Land use change
MCF	Methane conversion factor
M_{det}	Deterministic model
MLR	Multiple linear regression
MS	Microsoft
M_{stoch}	Stochastic model
N	Nitrogen
NfE	Nitrogen free extract
N_2O	Nitrous oxide
NPP	Net prime productivity
OECD	Organization for Economic Co-operation and Development
P	Phosphorus
PAS	Publicly available specification
SD	Standard deviation
SE	System expansion
SOC	Soil organic carbon
THG	Treibhausgas
VS	Volatile solids
ZMP	Zentrale Markt – und Preisberichtstelle

1. General Introduction

Research Background

Livestock production is involved in three main future challenges faced by humanity: (1) the need to increase food supply due to an increase in food demand caused by changing consumption patterns and a growing global population, (2) the competition for the scarce resource of land, and (3) the prevention of dangerous climate change (Smith et al., 2013).

(1) It is forecasted that there will be a considerable increase especially in protein sources from animal production in the developing world. OECD (2013) forecast an increase in meat demand per capita from 2013 until 2022 by 5.4% in the developed world and by 8% in the developing world. Whereas poultry meat is predicted to constitute the highest to the increase in total meat demand (63% developed world, 52% developing world), followed by pig meat (23% both developed and developing world) also beef and veal demand per capita is predicted to increase (14% developed world, 19% developing world). Furthermore, it is assumed that per capita increase in demand for fresh dairy products and cheese is 4% in the developed world and 14% in the developing world (OECD, 2013).

(2) Production of food from animal origin is strongly linked with land through the demand for feed. The efficiency of feed use differs depending on the type of animal and feed. Total feed conversion ratio (kg of feed dry matter input/kg of product output) generally decreases from beef meat to pig meat, to egg and poultry meat and milk production. Furthermore, it can be distinguished between different feed types e.g. in the case of beef production i.e. feed from arable land as cereals or forage from grassland. Feed conversion efficiency generally increases with a higher amount of feed from arable land in the diet due to higher energy contents (Wilkinson et al., 2011; deVries and de Boer, 2010). Whereas pork and poultry production is mainly based on crops from arable land and residues from food processing, cattle production has a special role as it is able to convert outputs from non-human edible grassland into high value protein, making this type of land available for food production. Grassland makes up approximately 75% of total agricultural land

worldwide (Smith et al., 2013). In Germany approximately 30% of agricultural land is defined as permanent grassland (Nitsch et al., 2010).

(3) Since the 2006 Food and Agriculture Organization of the United Nations (FAO) report called Livestock Long Shadow (Steinfeld et al., 2006), increasing attention is being given to the environmental impact of livestock production. It is stated that the expansion of livestock production can be considered as a key factor in deforestation (e.g. approximately 70% of previous forested land in the Amazon is now occupied by pastures and a certain amount of the remainder by feed crops) and land degradation (Steinfeld et al., 2006). Steinfeld et al. (2006) also pointed out the contribution of livestock production to climate change due to emissions of greenhouse gases (GHGs). Confidence has increased that the increase in global mean temperature needs to be limited to not exceeding 2° above 1990 levels to prevent climate change risks, impacts and damages (IPCC, 2007b; Meinshausen et al., 2009). To achieve this demanding target, limitation of increases and even reduction of the CO_2 concentration in the atmosphere are needed. This means significant cuts of over 80% in GHG emissions over the coming decades (Meinshausen et al., 2009; Smith et al., 2013). The contribution of agriculture to global anthropogenic GHG emissions is estimated to be approximately 17 to 32% (Bellarby et al., 2008). Of these, 6-17% is assumed to be contributed by land conversion to agriculture and 10-12% by direct methane (CH_4) and nitrous oxide (N_2O) emissions. Direct CH_4 emissions are mainly derived from enteric fermentation of cattle. Lesschen et al. (2011) estimated contribution of the livestock sector in the European Union (EU) to total anthropogenic GHG emissions to be 10%, while emissions from land use change were not included. More than 70% of these emissions could be attributed to dairy and beef production (Lesschen et al., 2011). The EU has made a unilateral commitment to reduce overall GHG emissions from its 27 Member States by 20% in 2020 compared to 1990 levels (EC, 2013). Thus, certain focus lies on dairy and beef production in the search for GHG mitigation options in the EU and worldwide.

The increase in productivity in dairy (measured in kg of milk/cow/year) and beef production is mentioned in many studies as an option to both reduce GHG emissions per kg of milk and beef and also to increase land use efficiency (Capper et al., 2009; Monteny et al., 2006; Smith et al., 2008; Steinfeld and Wassenaar, 2007). As technical efficiency of these systems is often higher compared to lower productive systems (Shortall and Barnes, 2013), an ongoing increase in milk yield/cow/year towards specialized dairy breeds can be observed in many countries in recent years. Milk-oriented Holstein-Friesian dairy cows are the dominant breed in many countries around the world (e.g. 93% of total dairy cows are estimated to be Holstein-Friesian in Canada, USA and UK; WHFF, 2011). However, in some European countries dual-purpose Fleckvieh dairy cows still play an important role. The contribution of dual-purpose Fleckvieh dairy cows on total dairy cows is 80% in Austria and Serbia, 50% in Slovenia and Czech-Republic, 16% in France and Switzerland (ESF, 2013). In Germany approximately 30% of total dairy cows are dual-purpose Fleckvieh breed mainly located in the south of Germany. The Fleckvieh breed is characterised by a lower milk yield/cow, a higher live weight of dairy cows and better fattening characteristics of bulls and heifers (Haiger and Knaus, 2010). However, high-yielding dairy cow production systems with pure milk-oriented breeds produce relatively less beef than less intensified (lower milk yield) and less specialised (dual-purpose breed) dairy cow systems (Zehetmeier et al., 2012). If less beef is provided from dairy cow production systems, this decrease would have to be compensated by increases in suckler cow production systems to maintain the same level of beef production. It is assumed that approximately 60% of European beef output and about 70% of German beef output is derived from dairy cow production (fattening of surplus calves not needed for replacement or culled cows) (Leip et al., 2010; AMI, 2010).

Only a few studies in literature take account of the close interlink between milk and beef production when modelling GHG emissions or land use from different dairy cow production systems with different milk yields (Weidema et al., 2008; Wirsenius et al., 2010; Flysjö et al., 2011a, 2012) and none of them considered different breeds. However, the interlink of milk and beef production and land use plays an important role when comparing GHG emissions of different dairy cow production systems. Figure 1 shows the interrelationship of GHG emissions, land use and food supply within the chain of milk and beef production. Land is the first part of the chain and can in the case of arable land be a direct source of food consumption or be used as food for milk and beef producing livestock. Land has a special role, since it can be a source of GHG emissions, e.g. through carbon dioxide (CO_2) emissions from land use change (deforestation, ploughing of peat land) but also as a help to mitigate GHG emissions through carbon storage in soil and biomass or production of bioenergy crops that replace fossil fuel (Smith et al., 2013). Milk and beef production are linked through fattening of surplus calves from dairy farming in beef fattening systems. Beef can also be produced by pure beef production systems.

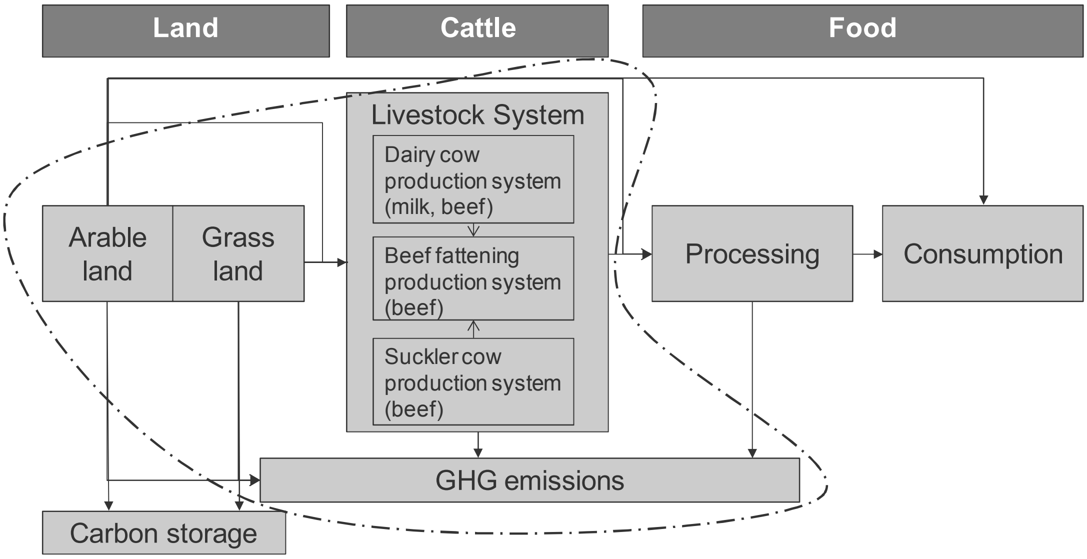

Figure 1: Interrelationship between different parts of the milk and beef supply chain and greenhouse gas (GHG) emissions (modified from Smith et al., 2013), dotted line: considered system boundaries and interrelationships in this thesis

When identifying and comparing GHG mitigation options, it has to be considered that changes in one part of the chain can cause changes in other parts and thus result in GHG emission leakage (shift of GHG emissions from one sector or country to another). Thus, when investigating GHG mitigation options, the interrelationship between land use, milk and beef production and GHG emissions in dairy cow production systems need to be considered.

Furthermore, it needs to be considered that models predicting GHG emissions from dairy and beef production systems have a high degree of uncertainty (Flysjö et al., 2011b). According to Walker et al. (2003) uncertainty can be discriminated based on the nature of uncertainty: epistemic uncertainty due to data quality or methodological choices, and variability-related uncertainty (variability uncertainty) due to inherent variability (e.g. of production traits among dairy farms) in the systems or processes under consideration. Considering both types of uncertainties is important for developing GHG abatement options because they have fundamentally different causes and need to be addressed in different ways (Morgan and Henrion, 2006). Epistemic uncertainty is due to "imperfection of our knowledge, which may be reduced by more research and empirical efforts" (Walker et al., 2003). Variability uncertainty is due to the inherent variability of natural and human systems and thus natural heterogeneity of values (Walker et al., 2003); it may be reduced by disaggregation and points at possibilities for improving the system (Basset-Mens et al., 2009). Consideration of uncertainties provides information for policy makers and farmers on robustness (sensitivity to changes in parameters) (Mußhoff and Hirschauer, 2011) and helps identify "variables with the most influence on predictions" (Pannell, 1997).

Research Objectives and Structure of the Work

The main objective of this thesis was to assess the effect of dairy cow production systems with varying milk yield and breed on GHG emissions and land use. A special focus was given to the close interlink between milk and beef production.

Specific objectives of the different parts of this thesis were:

- to determine the effect of increasing milk yield/cow on total GHG emissions, land use and economic performance in German dairy systems under two different scenarios: constant milk output but decreasing beef output and constant milk and beef output (Paper I)
- to classify the nature of uncertainty of main model parameters predicting GHG emissions (Paper III): epistemic uncertainty due to data quality or methodological choices, and variability-related uncertainty (variability uncertainty) due to inherent variability
- to include uncertainty of main model parameters in GHG modelling to identify those with the largest effect on variation of predicted GHG emissions in dairy cow production systems (Paper II and Paper III)
- to quantify the robustness of model predictions in response to varying system boundaries of dairy cow production systems (Paper II and Paper III)

- to investigate GHG emissions, beef output and land use per kg of milk of commercial dairy farms from two regions in Germany as affected by breed and production traits (Paper IV)
- to identify the relative importance of these parameters explaining variation of investigated farm outputs (Paper IV)

To achieve these objectives, different methods and approaches were applied in each part of this thesis (Figure 2). Initially, a deterministic model was built to predict GHG emissions, land use and economic performance of dairy cow production systems with different milk yield and breed. A whole life cycle “cradle to farm gate” approach was applied to predict GHG emissions and land use based on life cycle assessment (LCA) guidelines (ISO, 2006a, b). Results were referred to a constant amount of milk[1] and varying amounts of beef. In a second step, a stochastic model was developed to estimate the robustness of predicted GHG emissions based on input parameters and their uncertainties. Model inputs were classified according to the nature and type of uncertainty and included in the model approach using Monte Carlos simulation. In the third part of this thesis GHG emissions, land use and beef output were calculated for commercial dairy farms using data from BZA-Milk (economic performance of milk production branch within a farm) network (Dorfner and Hofmann, 2012). Dominance analysis (Azen and Budescu, 2003) was used to identify most important variables that have the highest impact on variation of predicted GHG emissions, beef output and land use.

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[1] milk means fat and protein corrected milk according to DLG (2011) throughout the text

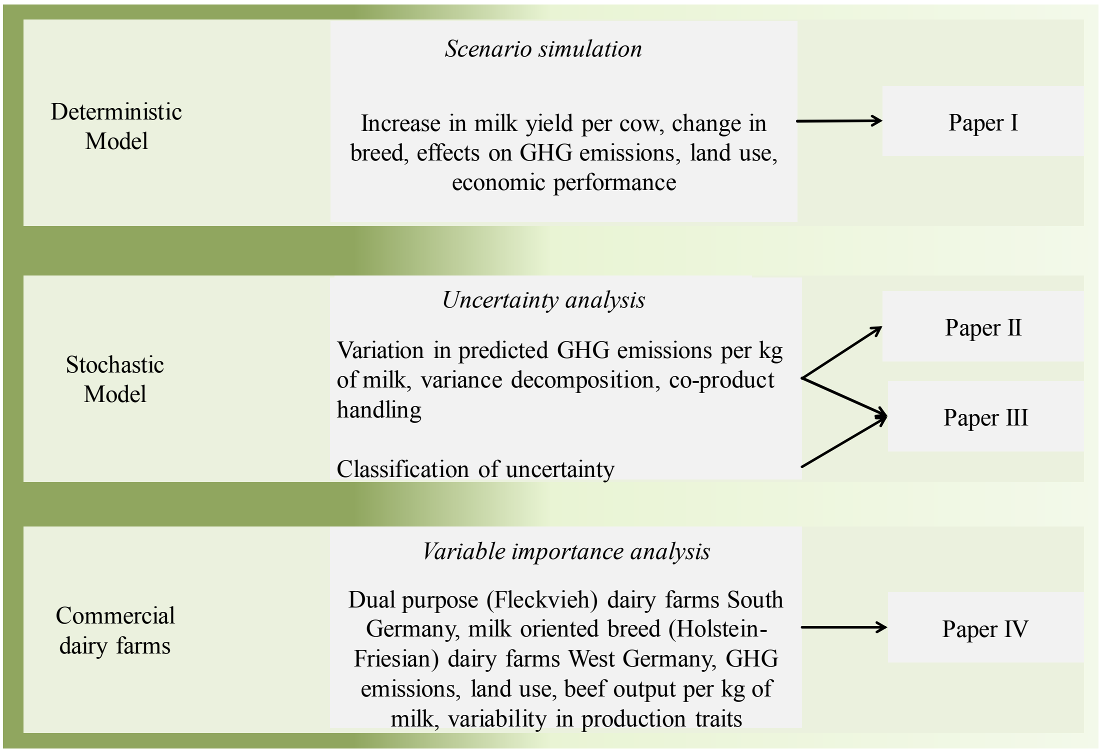

Figure 2: Overview of thesis structure and papers included in the thesis, GHG=greenhouse gas

2. Material and Methods

The first part of this section contains an overview of general modelling assumptions and data sources for all study approaches (deterministic model approach, stochastic model approach, study of commercial dairy farms). In the second part, a description of main methods to model GHG emissions, land use, economic performance and beef output of investigated dairy cow and beef production systems is given. In the third part, methods applied in the different studies to conduct sensitivity and uncertainty analysis are described.

General Modelling Overview

A simulation modelling approach using MSExcel was undertaken to explore the effect of dairy cow production systems with varying milk yield/cow and breed on defined impact categories (i.e. global warming potential (GWP), land use, milk and beef production and economic performance). Global warming potential is the impact GHG emissions have on heat radiation absorption of the atmosphere (IPCC, 2007b). Each study (deterministic model, stochastic model, commercial dairy farms) of this thesis was based on a system modelling approach where interaction within and between dairy cow and beef production systems were considered (Figure 3). The system boundary of a dairy cow production system at the farm gate represents a typical dairy cow farm with milk, beef from culled cows and calves not needed for replacement as output. Dairy cow, suckler cow and beef fattening production systems were modelled both individually (representing typical farms) and as one combined system, i.e. expanded system boundary of dairy cow production system. Outputs of the expanded system boundary are milk and beef from culled cows and fattening of surplus calves (potential beef output). The suckler cow production system and corresponding beef fattening systems of suckler cow calves included in the modelling represent a pure beef production system. Production of milk, beef and calves was referred to a time period of one year.

Material and mass flows between model components were connected using mechanistic or empirical equations. On-farm activities (occurring within the system boundary of a typical farm gate) were distinguished from off-farm activities (production and transport of farm inputs).

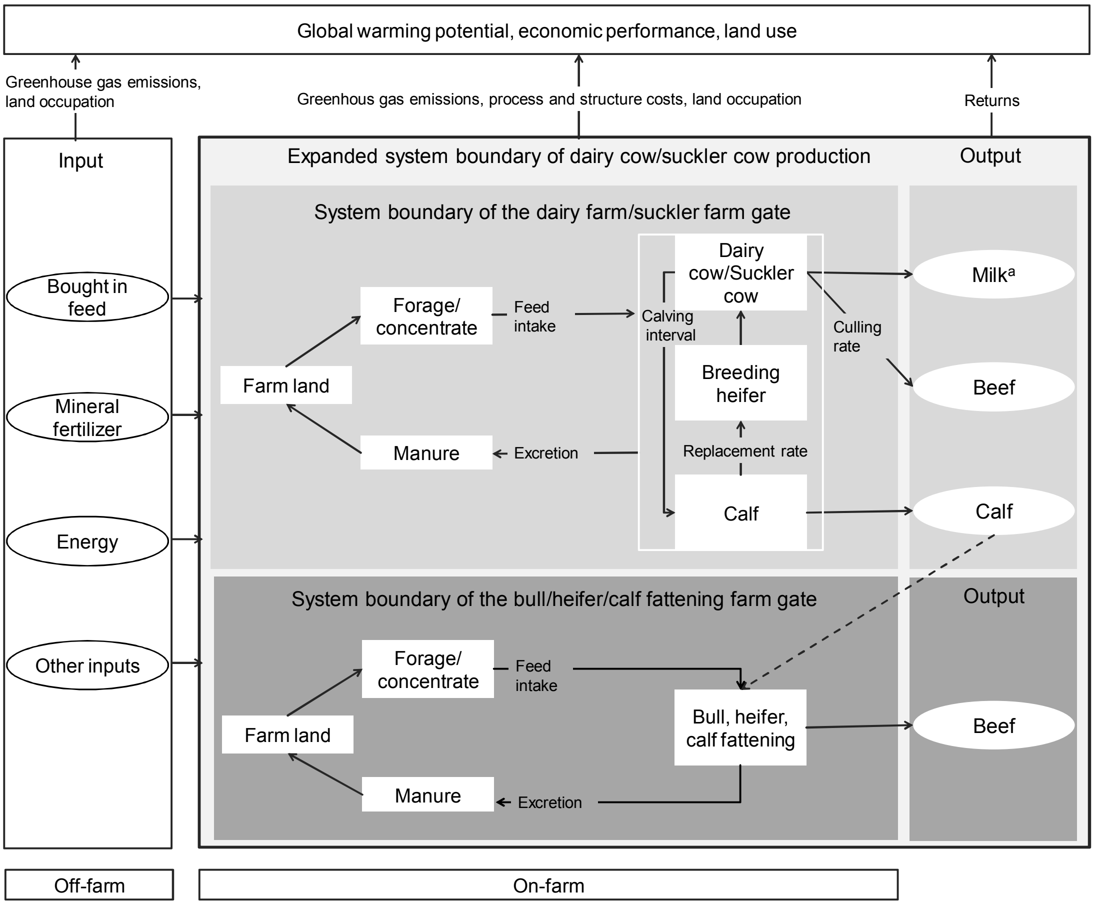

Figure 3: A flow chart of dairy cow and beef fattening production systems considering different system boundaries; main model components are represented as blocks, relationships between components (material and mass flows) (model parameters) as lines; [a]only for dairy cow production systems

Considered production systems – deterministic and stochastic model approach

Three types of dairy cow production systems were simulated in the deterministic and stochastic model approach by changing the breed and the level of milk yield as follows:

- Milk yield of 6,000 kg/cow/year using dual-purpose Fleckvieh dairy cows – 6,000 kg Fleckvieh-system
- Milk yield of 8,000 kg/cow/year using dual-purpose Fleckvieh dairy cows – 8,000 kg Fleckvieh-system
- Milk yield of 10,000 kg/cow/year using Holstein-Friesian dairy cows –10,000 kg Holstein-Friesian-system

It was assumed that surplus calves occurring at the dairy farm gate system boundary are fattened in bull and heifer fattening systems in the case of Fleckvieh dairy cows. In the case of Holstein-Friesian dairy cows 50% of bull calves were assumed to be fattened in calf fattening systems. A confinement system was defined for dairy cows and replacement heifers as well as bull, heifer and calf fattening production systems with livestock indoors all year round. Feed components consisted of grass silage, maize silage, hay, wheat, barley and soybean meal. Suckler cows, replacement heifers and rearing calves of the modelled suckler cow production system were considered to be on pasture for 185 days during summer time.

Considered production system - commercial dairy farm approach

The study of commercial dairy farms covered a total of 27 dairy farms breeding dual-purpose Fleckvieh dairy cows from the state of Bavaria in the south of Germany (South-Fleckvieh) and 26 dairy farms breeding Holstein-Friesian dairy cows from the state of Nordrhein-Westfalen in the west of Germany (West-Holstein-Friesian). Data from BZA (economic performance of milk production branch within a farm)-Milk network (Dorfner and Hofmann, 2012) were taken to model GHG emissions, land use and potential beef output of each farm. BZA-Milk is a farm accounting tool established to calculate economic, physical and management parameters of German dairy farms on a yearly basis. To stress the effects of breed and to ensure that results of our study are not influenced by differences in management ability of the farmer ”high-performing-farms” were chosen. These farms have a higher economic performance, and higher production trait performance compared to the average of the farms reported in BZA-Milk (Dorfner, 2013). Furthermore, only those farms were included in the study that are characterised by a confinement system (animals indoors all year round, maize silage, grass silage as main forage components).

Mean and standard deviation (SD) of main South-Fleckvieh and West-Holstein-Friesian dairy farm characteristics are described in Paper IV. Average milk yield/cow was 8,560 kg for South-Fleckvieh dairy farms which is higher compared to the 8,000 kg yielding Fleckvieh dairy cow production system considered in the deterministic and stochastic model approaches. Average West-Holstein-Friesian dairy farms showed a milk yield of 9,600 kg/cow which is 400 kg lower compared to the Holstein-Friesian production system of the model approaches.

General overview of input data

Several impact categories and food output of the investigated dairy and beef production systems were studied in this thesis based on the conceptual framework of LCA approach (ISO, 2006a, b): GWP, land use, economic performance and milk and beef output. Thus, all model components, mass and material flows were connected with factors and equations to estimate GHG emissions, land requirement, costs and prices or amount of milk and beef output. All data included in the three main study approaches (deterministic model, stochastic model, commercial dairy farms) to define the components and parameters of the modelled systems and their environmental or economic impact were directly obtained from relevant sources (default values), derived from calculations based on these data (submodels) or reported from commercial farms (Table 1).

Table 1: Overview of main model parameter included in the deterministic, stochastic and commercial dairy farm study approach and their data sources

Model parameter	Deterministic model (Paper I)	Stochastic model (Paper II, III)	Commercial dairy farms (Paper IV)
Production traits			
Calving interval	Submodel[a]	Probabilistic distribution[b]	Reported[c]
Replacement rate	Default value[d]	Probabilistic distribution[b]	Reported[c]
Milk yield	Default value[d]	Probabilistic distribution[b]	Reported[c]
Milk components	Default value[d]	Default value[d]	Reported[c]
Live weight, live weight gain, carcass characteristics	Default value[d]	Default value[d]	Default value[d]
Age of first calving	Default value[d]	Default value[d]	Reported[c]
Animal losses	Default value[d]	Default value[d]	Reported[c]
Nutrient flows			
Feed intake	Submodel[e]	Submodel[e]	Reported[c]
Excreta	Submodel[f]	Submodel[f]	Submodel[f]
Electricity	Default value[d], Submodel[g]	Default value[d]	Default value[d]
Feed production on-farm			
Mineral fertilizer	Submodel[h]	Submodel[h]	Reported[c]
Lime, diesel, pesticides	Default value[d]	Default value[d]	Submodel[i]
Yield/losses feed production	Default value[d]	Default value[d]	Reported[c]
Feeding value	Default value[d]	Default value[d]	Default value[d]/ Reported[c]
Characteristics of bought in feed (production inputs, feeding value)	Default value[d]	Default value[d]	Submodel[i]

[a] equation with calving interval as dependent and milk yield as independent variable (Heanel, 2010); [b] data from milk recording LKV (Landeskontrollverband) Bayern (unpublished data) and LKV Weser Ems (unpublished data); [c] data from BZA-Milk database evaluated on farms LfL (Bayerische Landesanstalt für Landwirtschaft) (unpublished data) [d] most important sources for default values: ADR (2010), AMI (2011), DLG (1997), Haiger and Knaus (2010), KTBL (2008), LfL (2006), LfL (unpublished data), ZMP, different years; [e] modelling of feed intake for dairy cows based on equation from Gruber et al. (2006) (Software Super-RATION, 2012), feed intake of other animals calculated in order to satisfy requirements for metabolizable energy and crude protein (GfE, 1995, 2001); [f] excreta-nitrogen (N), phosphorus (P), potassium (K) was calculated as the difference between N, P, K intake from forage and concentrates and N, P, K retained as animal products (i.e. milk and live weight gain); [g] equation with electricity demand from dairy cows as dependent and milk yield as independent variable (Kraatz, 2009); [h] soil N, P, K balance: difference between N, P, K inputs (manure application, deposition and fixation) and N, P, K output (N in the crop harvested, losses through nitrate leaching and ammonia volatilization); [i] data derived from FeedPrint model (Vellinga et al., 2012)

Input Data and Modelling Approaches to Calculate Global Warming Potential, Land use, Economic Performance and Beef Output

Main methodological considerations, equations and emission factors to model considered impact categories (GWP, economic performance, land use) and milk and beef output are described in the following section.

Global warming potential

The GWP is a metric comparing the potential climate impact of the emissions of different GHGs investigated in our study, i.e. CH_4, N_2O and CO_2. A GWP of 1, 25, and 298 was used to convert CO_2, CH_4 and N_2O emissions into CO_2 equivalents (CO_2-eq) (IPCC, 2007a). Greenhouse gas emissions (in GWP) were calculated using a “cradle to farm gate” approach based on LCA guidelines (ISO, 2006a, b). Sources of GHG emissions for the modelled production system were distinguished between on-farm (or primary source) GHG emissions and off-farm (or secondary) source GHG emissions. On-farm GHG emissions are those occurring within the system boundary of a typical farm during feed production, maintenance of animals and manure management. Off-farm sources of GHG emissions include emissions occurring from activities outside the system boundary of a typical farm, for instance, those emissions generated during production of fertilizer, pesticides or diesel (Rotz et al., 2010). The majority of emission factors and equations used in this thesis are based either on IPCC (2006) guidelines or the German application of the guidelines in the national emission inventory report from 2010 (Haenel, 2010) (Table 2). An advanced equation from Kirchgeßner et al. (1995) was used to model CH_4 emissions from enteric fermentation of dairy cows as this is reported in literature to be the major source of GHG emissions in dairy farms (Kristensen et al., 2011; O’Brien et al., 2012a). In the study of the stochastic model approach, a range of equations or emission factors was included for those emission sources having a high impact on predicted GHG emissions (e.g. CH_4 from enteric fermentation of dairy cows, N_2O emissions from nitrogen input into the soil) and/or are known to have a high uncertainty (e.g. N_2O emissions from nitrogen input into the soil, emission factor for soybean meal production) (Table 2).

Table 2: Summary of emission factors and equations to quantify on-farm greenhouse gas (GHG) emissions applied in the deterministic model (M_{det}), stochastic model (M_{stoch}) and commercial farm ($F_{commercial}$) study approach

GHG	Emission source	Emission factor/equation	Unit	Reference	Study approach
	Direct on farm				
CH_4	Enteric fermentation				
	Dairy cow	(63+79*CF[a]+10*NfE[b]+26*CP[c]-212*EE[d])	g CH_4/d	Kirchgeßner et al. (1995)	$M_{det}/M_{stoch}/F_{commercial}$
		3.23+0.809*dry matter intake	MJ CH_4	Dämmgen et al. (2009)	M_{stoch}
		32.76-0.384*dry matter intake/body weight	g CH_4/kg of dry matter intake	Jentsch et al. (2009)	M_{stoch}
	Calves up to 125 kg	0.02*gross energy intake	MJ CH_4/MJ	Haenel (2010)	$M_{det}/M_{stoch}/F_{commercial}$
	Other cattle	0.065* gross energy intake	MJ CH_4/MJ	Haenel (2010)	$M_{det}/M_{stoch}/F_{commercial}$
	Manure storage				
	Dairy cow	0.24*(VS[e]*MCF[f])	m³ CH_4/kg	Haenel (2010)	$M_{det}/M_{stoch}/F_{commercial}$
	Other cattle	0.18*(VS[e]*MCF[f])	m³ CH_4/kg	Haenel (2010)	$M_{det}/M_{stoch}/F_{commercial}$
N_2O	Manure storage	0.005*(N excreted+N in straw)	kg N_2O-N/kg	Haenel (2010)	$M_{det}/M_{stoch}/F_{commercial}$
	Nitrogen input into the soil				$M_{det}/M_{stoch}/F_{commercial}$
	Manure/mineral fertilizer application	0.01*N in manure/mineral fertilizer	kg N_2O-N/kg	IPCC (2006)	$M_{det}/M_{stoch}/F_{commercial}$
	(min-max)[g]	(0.003-0.03)*N in manure/mineral fertilizer	kg N_2O-N/kg	IPCC (2006)	M_{stoch}
	Grazing	0.02*N excreted	kg N_2O-N/kg	IPCC (2006)	$M_{det}/M_{stoch}/F_{commercial}$
	Crop residues	0.01*N in crop residues	kg N_2O-N/kg	IPCC (2006)	$M_{det}/M_{stoch}/F_{commercial}$
CO_2	Lime application	0.44 $CaCO_3$	kg CO_2/kg $CaCO_3$	Patyk and Reinhardt (1997)	M_{det}/M_{stoch}
	Diesel consumption	2.637*diesel	kg CO_2/kg of diesel	Rotz et al. (2010)	M_{det}/M_{stoch}
	Machinery[h]	30-80g	kg CO_2/hour	FeedPrint model (Vellinga et al., 2012)	$F_{commercial}$
	Indirect on-farm				
N_2O	Leaching	0.0075*N input into the soil*N fraction lost	kg N_2O-N/kg N	IPCC (2006)	$M_{det}/M_{stoch}/F_{commercial}$
	Volatilisation	0.01*NH_3-N volatilised	kg N_2O-N/kg NH_3-N	IPCC (2006)	$F_{commercial}$

[a] CF = crude fibre; [b] NfE = N-free extract; [c] CP = crude protein; [d] EE' = ether extract; [e] VS = volatile solids; [f] MCF = CH_4 conversion factor, 0.1 kg/kg carbon for slurry, 0.02 kg/kg carbon for farm yard manure; [g] minimum and maximum value for probabilistic distribution within the stochastic model approach; [h] includes direct fuel use and indirect emissions related to the production and maintenance of machinery, value differs among feed due to differences in type of machinery, machinery work and diesel use

Off-farm GHG emissions are not assigned to the agricultural sector within the IPCC guidelines (IPCC, 2006). Instead they contribute to the industrial sector where the emissions occur (e.g. energy sector for energy production). Thus, emission factors for off-farm GHG emission sources are not reported within the IPCC guidelines and need to be taken from different studies in literature (Table 3). Within the deterministic and stochastic model approaches, soybean meal and concentrates for calves are the only feed components which were assumed to be bought in and thus contributing to off-farm GHG emissions. All other feed components were assumed to be produced within the system boundary of a typical farm. In the commercial farm study, data on feed intake from on and off-farm (bought in) feed were available for each farm. Calculation of GHG emissions from bought in feed was taken from one database, i.e. FeedPrint model (Vellinga et al., 2012). The emission factors for e.g. mineral fertilizer or pesticide production used in the FeedPrint model were also taken for the calculation of GHG emission from on-farm feed production to ensure methodological homogeneity within the commercial farm study approach. Emissions from the production of capital goods, such as buildings and machinery, were not accounted for in the deterministic and stochastic model approach following recommendations from the British Standards Institution (BSI, 2008). In the commercial farm study approach emission from production of machinery was included according to FeedPrint model (Vellinga et al., 2012) (Table 2).

Table 3: Summary of emission factors to quantify off-farm greenhouse gas (GHG) emissions applied in the deterministic model (M_{det}), stochastic model (M_{stoch}) and commercial farm ($F_{commercial}$) study approach

Off-farm GHG emission sources	Emission factor	kg CO_2-eq/ unit	Reference	Study approach
Electricity production	0.605	MJ	Umweltbundesamt (2010)	M_{det}/M_{stoch}/ $F_{commercial}$
Diesel production	0.374	MJ	Rotz et al. (2010)	M_{det}/M_{stoch}
Mineral fertilizer				
N	7.51	kg	Patyk and Reinhardt (1997)	M_{det}/M_{stoch}
	5.85	kg	FeedPrint model (Vellinga et al., 2012)	$F_{commercial}$
P_2O_5	1.18	kg	Patyk and Reinhardt (1997)	M_{det}/M_{stoch}
	1.91	kg	FeedPrint model (Vellinga et al., 2012)	$F_{commercial}$
K_2O	0.67	kg	Patyk and Reinhardt (1997)	M_{det}/M_{stoch}
	0.36	kg	FeedPrint model (Vellinga et al., 2012)	$F_{commercial}$
$CaCO_3$ production	0.12	kg	Patyk and Reinhardt (1997)	M_{det}/M_{stoch}
$CaCO_3$ production	0.12	kg	FeedPrint model (Vellinga et al., 2012)	$F_{commercial}$
Seed production (grass/maize/winter wheat/barley)	1.94/2.05/ 0.64/0.47	kg	Ecoinvent (2007)	M_{det}/M_{stoch}
Pesticides	5.37	kg	Biskupek et al. (1997)	M_{det}/M_{stoch}
	7.34	kg	FeedPrint model (Vellinga et al., 2012)	$F_{commercial}$
Milk replacer	2.1	kg	Neufeldt and Schäfer (2008)	M_{det}/M_{stoch}
Soybean meal production	0.34	kg	Dalgaard et al. (2008)	M_{det}/Ms$_{toch}$
(min-max)^g	0.34-10	kg	Flysjö et al. (2012b)	M_{stoch}
Bought in feed			FeedPrint model (Vellinga et al., 2012)	$F_{commercial}$

^{g}minimum and maximum value for probabilistic distribution within the stochastic model approach

System boundaries and methods to handle co-products in GHG modelling

In order to make different dairy and beef production systems comparable, the results of environmental and economic impact modelling were presented on a functional unit basis. The choice of functional unit mainly depends on the type of environmental and economic impacts studied and the goal and scope of the study.

Greenhouse gas emissions constitute global impacts. Thus, GHG emissions "must be presented with respect to some unit of output" e.g. kg of milk or beef "rather than as emission from an individual farm businesses or as GHG/ha" (Franks and Hadingham, 2012). This is to avoid shift of GHG emissions from one sector or country to another (GHG emission leakage) and to identify systems that produce milk and beef with the lowest GHG emissions. Different outputs from dairy and beef production systems and system boundaries investigated in our study are summarized in Table 4.

Table 4: Main (bold X) and co-products (standard X) of dairy and beef production systems included in the study approaches

Products System boundary	Milk	Beef from culled cows	Surplus calves	Beef from bull, heifer and calf fattening
Dairy farm gate	**X**	X	X	
Suckler cow farm gate		X	**X**	
Bull/heifer/calf fattening farm gate				**X**
Expanded system boundary of dairy cow production[a]	**X**	X		X
Expanded system boundary of suckler cow production[a]		**X**		**X**

[a] includes dairy/suckler cow production at the farm gate and fattening of surplus calves not needed for replacement

For the system boundary of the dairy farm gate, GHG emissions are generally referred to the main output (i.e. milk), while different methods to handle co-products are discussed in literature (Flysjö et al., 2011a; ISO, 2006a, b). Allocation of GHG emissions between main and co-products can be undertaken according to several principles (e.g. 100% to milk, economic allocation, physical causality allocation, protein allocation, etc.). The system boundary of the dairy farm gate is most important for dairy farmers to reduce GHG emissions at the farm level.

The system boundary can be expanded to account for milk and potential beef production (beef from culled cows and fattening of surplus calves in bull, heifer and calf fattening systems). This system boundary is important for policy makers to identify possible GHG emission leakage effects in beef production and to identify GHG mitigation options of combined milk and beef production. Two methods for each system boundary were included in the different studies of this thesis to account for differences in milk and beef output and to identify the sensitivity of model results to the different methods:

(1) System boundary is the dairy farm gate (functional unit: 1 kg of milk)

- 100% to milk (Paper I, Paper II, Paper IV) - all GHG emissions are allocated to milk, no emissions are allocated to co-products (surplus calves, beef from culled cows)
- Economic allocation (Paper I, Paper II) - all GHG emissions are allocated between milk and co-products according to their economic value

Expanded system boundary of dairy cow production to account for GHG emissions of milk and beef production:

- Constant amount of milk and beef output (Paper I): the products of the reference scenario were 6,000 kg of milk and 322 kg of beef (from culled cows and fattening of surplus calves) according to an expanded dairy cow production system with 6,000 kg of milk/cow/year. With an increase in milk yield/cow, less dairy cows were needed to produce the constant amount of milk as in the basis scenario. This resulted in a decrease in beef output because of two main reasons: First, the number of surplus calves available for fattening is decreasing. Second, the change in breed towards milk-oriented breed Holstein-Friesian is ongoing with a deterioration of fattening characteristics. The decline in beef output is assumed to be compensated for by beef from suckler cow production to keep beef output constant.
- System expansion (Paper II and Paper III): for system expansion a GHG emission credit is given to the dairy cow production systems. In a first step, GHG emissions and beef output from dairy cow production at the farm gate and fattening of surplus calves were calculated. Secondly, GHG emissions from suckler cow production for an equal amount of beef was calculated and subtracted from GHG emissions of the dairy cow production unit. The GHG emission outcomes were expressed in CO_2-eq/kg of milk. This can also be considered as a credit to dairy cow production systems due to its beef output.

Economic performance

Within the deterministic and stochastic model approach, monetary value (costs, returns) of main model components was determined to identify economic performance of different dairy and beef production systems. Total costs included all costs from profit and loss accounting as reported by DLG (2004) (e.g. water, electricity, health, insemination, depreciation and maintenance of buildings, etc.) and opportunity costs i.e. own production factor costs (imputed interest for e.g. buildings, machines and inventory, rate of interest: 4%), unpaid manual labour (12.5 €/commercial hour) and imputed rental value of owner-occupied land (180 €/ha grassland, 290 €/ha arable land) (Dorfner and Hofmann, 2012). It was assumed that forage production occurred on-farm with own land. All labour on-farm was assumed to be own labour. A farm size of 60 cows and corresponding sizes of buildings and machines was assumed to calculate depreciation values. Values for profit and loss accounting referring to animal husbandry and forage production were taken from KTBL (2008) and LfL (2006). Costs for concentrates and returns for milk, beef and calves were based on a 10 year average (2000-2010) reported in AMI (2011) and ZMP (various years). A probabilistic distribution of those costs and prices of model components which change depending on milk yield (concentrates) or breed (milk, calf and beef output) of animals was included in the stochastic model approach (AMI, 2011; ZMP, various years). Total costs were expressed in €/kg of milk. Returns of outputs other than milk, such as beef and surplus calves were subtracted from the total costs, which yields value-adjusted total costs (equation 1) to ensure comparability of milk production costs of different dairy cow systems.

$$TC_{VA} = \frac{TC_{DCFG} - (p_{cf\,HF\,|BF\,|CF} * Cf_{HF\,|BF\,|CF} + p_{culled\,cow} * b_{culled\,cow})}{milk\ delivered} \quad \text{(equation 1)}$$

where TC_{VA} are value-adjusted total costs expressed in €/kg of milk; TC_{DCFG} are total costs for dairy cow production at the dairy farm gate expressed in €; $p_{CfHF/BF/CF}$ is the price of calves entering heifer/bull/calf fattening expressed in €/calf; $Cf_{HF/BF/CF}$ is the number of calves entering heifer/bull/calf fattening; $p_{culled\ cow}$ price of beef from culled cows expressed in €/kg; $b_{culled\ cow}$ is the amount of beef from culled cows expressed in kg; milk delivered is expressed in kg.

Land use

Land use was chosen as an impact parameter for three main reasons: (1) after the abolishment of milk quotas land is expected to be one of the most important limiting factors of milk production (Lassen, 2011); (2) “land use refers to the loss of land as a resource, in the sense of being temporarily unavailable for other purposes” (O’Brien et al., 2012a); (3) land use plays a special role in climate change as it can be a carbon source and sink (Smith et al., 2013). Land use can be distinguished between type of land (grassland, arable land) and according to its origin of production: on-farm versus off-farm. Land use is calculated based on feed demand of animals and yield of feed production (including losses during harvest, transport to the farm, storage and feeding to animals). In the deterministic and stochastic model approach input data were mainly derived from KTBL (2008) and LfL (2006). In the commercial farm study, data of on-farm forage and crop yield were reported from investigated farms. Forage and crop yield of bought-in feed was taken from FeedPrint model (Vellinga et al., 2012).

In the deterministic model approach, land use of different dairy cow production systems was compared assuming a constant amount of milk and beef similar to GHG modelling. Land use was not studied in the stochastic model approach. In the commercial farm study approach, land use was referred to 1 kg of milk at the system boundary of the dairy farm gate. In that study total amount of land use was allocated to milk.

Beef output

In the commercial farm study approach, all on and off-farm GHG emissions from dairy farms were allocated to 1 kg of milk to ensure full traceability of GHG emissions from milk production at the system boundary of the dairy farm gate. Beef output per kg of milk was defined as an additional indicator to account for differences in co-products of the farms. Two different types of beef output were distinguished: beef output at the dairy farm gate (only beef from culled cows) and potential beef output (beef from culled cows and fattening of surplus calves in bull, heifer and calf fattening systems).

Sensitivity Analysis and Uncertainty Modelling

Different methods were applied in this thesis to account for uncertainty in model parameters:

- Sensitivity analysis gives insight into sensitivity of model outcomes to a change in input parameters.
- Probabilistic simulation gives insight into distribution and probability of model outcomes.
- Variance decomposition provides information on those parameters that have the highest contribution to variance of model or commercial farm outcomes.

One-way sensitivity analysis

One-way sensitivity analysis investigates the change in value of output parameter from a change in input parameter value. A constant percentage of change in input value was assumed to make sensitivity of model outcomes to input parameters comparable. A sensitivity index was defined as the percentage change in predicted GHG emissions to a 10% change in the given input parameter (Björklund, 2002).

Probabilistic simulation using Monte Carlo simulation

To analyse distribution and probability of predicted GHG emissions from various dairy cow production systems, Monte Carlo simulations were performed using @RISK (Palisade Corporation software, Ithaca NY USA). Probabilistic distribution of several model parameters were specified in two different study approaches (Paper II, Paper III) (Table 5). The uncertainty of emission factor for soybean meal production derives from a lack of knowledge as to whether direct land use change (e.g. from forest to arable land) and corresponding release of GHG emissions occurred to produce soybeans. Probabilistic distribution of the emission factor for soybean meal production was included in one study of the stochastic model approach (Paper II).

Table 5: Summary of model parameters with probabilistic distribution included in the stochastic model

Stochastic model Paper II and Paper III	Stochastic model only Paper II
Greenhouse gas modelling	
EF for CH_4 emissions from enteric fermentation EF for N_2O emissions from nitrogen input into the soil	EF for soybean meal production
Production traits	
Calving interval Replacement rate	Milk yield/cow
Economic parameter	
	Returns for beef from culled cows, surplus calves and milk

EF= emission factor

Triangle distribution function was used to describe probability distribution of GHG emission factors (Table 2). Normal distribution was assumed for all production traits and an empirical cumulative probability function was implemented in the stochastic model to describe probability distribution of emission factor for beef from suckler cow production and economic parameters (Paper II, Paper III). Statistically significant correlations between economic parameters and between production traits were calculated and accounted for. Greenhouse gas emission factors were assumed to be independently distributed.

Identification of most important input parameters - decomposition of outcome variation

Variation in outcomes can be analysed with statistical techniques to identify "important parameters". Variable importance combines the leverage an input parameter has on the criterion variable (the information derived from sensitivity analysis) and the degree of uncertainty of those input parameters (Makinson et al., 2012). This is important to identify those parameters that have the highest potential to influence predicted GHG emissions. An outcome parameter can be very sensitive to a change in input parameter. However, if this parameter has a low variability there is little room for improvement. The other way round, a parameter that contributes highly to the sensitivity of a parameter outcome and also shows a large variability, has a high potential to influence parameter outcome (Heijungs, 1996; Makinson et al., 2012).

Standardized ß-coefficient. In the stochastic study approaches, standardized regression coefficients were used to compare the importance of each uncertainty parameter on variation of GHG emission outcomes of each dairy cow production system. Multivariate linear regression implemented in @Risk was used to calculate standardized regression coefficients. The coefficients predict "the standard deviation change in the dependent variable when the independent variable is changed by one standard deviation, holding all other variables constant" (Murray and Conner, 2009). When interpreting regression coefficients it is important to keep in mind that coefficients reflect both the uncertainty of the model parameters and the sensitivity of the model to this particular parameter (Basset-Mens et al., 2009). In the case of uncorrelated input parameters the quadrate of standardized regression coefficient adds up to R^2 of linear regression model. Thus, a complete decomposition of R^2 can be given.

Dominance analysis. Multiple linear regression and dominance analysis was undertaken to identify "important input parameters" in the study of commercial dairy farms. To identify the nature and degree of relationship of farm input parameters (predictor variables) on output parameters (criterion variable) (GHG emissions, potential beef output, land use) multiple linear regression (MLR) models were defined using the statistical programme R (R Development Core Team, 2006). The number of variables within the multiple linear regression models was set at a maximum of four predictor variables to avoid over-fitting owing to the low number of observations (number of farms within investigated farm groups).

Four predicator variables were chosen that were expected to explain the majority of the variation in emissions (or land use or beef output). The choices were guided by theory - the chosen variables were those input variables to the GHG (land use or beef) model that are predicted by theory to have the strongest effect on model outputs (Azen and Budescu, 2003; Bortz and Weber, 2005). The choice was assessed by calculating the overall R^2 of the MLR model and testing goodness of model fit (Crawley, 2013). Estimated effects (beta coefficients) depend on the unit of the predictor variable and the unit of the outcome variable. Thus, coefficients belonging to different predictors cannot be compared but corresponding coefficients from the different MLR, as they have matching units of predictor- and outcome variable. Another focus was to infer how much each of the predictor variables contributes to the variation of model outcomes. Thus, relative importance of predictor variables included in the MLR model was identified using the approach of Budescu (1993) called "dominance analysis". In the case of "dominance analysis" "one predictor is more important than another if it would be chosen over its competitor in all possible subset models where only one predictor of the pair is to be entered" (Azen and Budescu, 2003). Dominance weights sum to the MLR model R^2, thus it is "possible to provide a truly meaningful decomposition of the total predicted variance in the criterion" (LeBreton et al., 2004) variable. This is also true in the case of multicollinearity of predictor variables. The results of dominance analysis depend on the set of predictor variables and their variance within the investigated group of farms (Azen and Budescu, 2003). Dominance analysis was assessed using "relaimpo – lmg metrics" package of the statistical programme R (equation 2).

$$\boldsymbol{LMG(x_k) = \frac{1}{p} * \sum_{i=0}^{p-1} \left(\sum_{\substack{S \subseteq \{x_1,\ldots,x_p\} \backslash \{x_k\} \\ n(S)=i}} \frac{seqR^2(\{x_k\} \intercal S)}{\binom{p-1}{i}} \right)} \quad \text{(equation 2)}$$

where LMG (xk) is the average over model sizes i of average improvements in R^2 when adding regressor x_k to a model of size i without x_k, seqR^2 ($\{x_k\}$IS) is the additional R^2 when adding x_k to a model with the regressors in set S. A detailed description of the method and the package "relaimpo" is given by Groemping (2006) and Christensen (1992).

3. Synthesis of Study Results

In the first part of this section, average values and variation of model and commercial farm outcomes are described. A comparison between model approach studies and the study of commercial farms is undertaken. It has to be considered that not all impact categories were investigated in each study approach. Thus, the studies included in the comparison of outcomes differ by impact category. In the second part, an overview on robustness of predicted GHG emissions in various dairy cow production systems is given. These results refer to the studies of the stochastic model approach. In the third part, results from sensitivity analysis and identification of most important input parameters within the stochastic model and the commercial farm approach are described.

Comparison of Average Values and Variation of Study Outcomes

The objective of this section is to compare average values and variation of impact category outcomes and food output i.e. GWP, land use, economic performance and potential beef output of the different studies undertaken in this thesis.

Global warming potential

Dual-purpose Fleckvieh and milk-oriented Holstein-Friesian dairy cow production systems with different milk yield/cow/year were compared in this thesis using various model approaches. Within all study approaches lower-yielding dairy cow production systems resulted in higher GHG emissions per kg of milk compared to higher-yielding dairy cow production systems if the system boundary was set at the dairy farm gate and all GHG emissions were allocated to milk (Table 6). The level of average predicted GHG emissions was considerably higher in the first study with the stochastic model approach (Paper II) compared to the deterministic model approach (Paper I). This was due to the consideration of land use change and assumptions for its uncertainty in the emission factor for soybean meal production.

Greenhouse gas emissions from land use change of soybean meal production were not included in the second study of the stochastic model (Paper III). Thus, predicted GHG emissions of the 8,000 and 10,000 kg yielding dairy cow production systems were higher in the first study (Paper I) even though economic allocation was applied to allocate GHG emissions between milk and co-products.

Similar values for GHG emissions per kg of milk were observed in the deterministic approach and in the second study using the stochastic model approach (Paper III) if only variability uncertainty of production traits (calving interval and replacement rate) was included in the uncertainty modelling. The 6% lower GHG emissions per kg of milk observed for the 10,000 kg Holstein-Friesian-system can be explained by lower values of replacement rate within the stochastic model approach (Paper I, Paper III). The differences in predicted GHG emissions between models that consider only production traits and models that consider the full range of variability and epistemic uncertainties can be attributed to the skewed triangle distributions of the additional uncertainties (Paper III).

In the study of commercial farms dual-purpose South-Fleckvieh dairy farms resulted on average in higher GHG emissions per kg of milk compared to higher-yielding West-Holstein-Friesian dairy farms. The difference in average milk yield/cow/year between average South-Fleckvieh and West-Holstein-Friesian dairy cows was 1,000 kg lower compared to the model approaches. Thus, difference of average predicted GHG emissions between the two dairy cow production systems were lower within the commercial farm study approach compared to model approaches.

Table 6: Comparison of greenhouse gas emissions (GHG) per kg of milk of various dairy cow production systems (system boundary at the dairy farm gate) calculated in the deterministic (M_{det}), stochastic (M_{stoch}) and commercial farm study approaches ($F_{commercial}$); values are shown in average, standard deviation in parenthesis

Co-product handling	Production system			Study approach	Paper
	Fleckvieh 6,000[a]	Fleckvieh 8,000[b]	Holstein-Friesian 10,000[c]		
	GHG emissions [kg CO_2-eq/kg of milk]				
100% to milk[d]	1.35	1.13	0.98	M_{det}	Paper I
EA[e]	1.06	0.93	0.89		Paper I
100% to milk[d]	1.37 (0.07)	1.14 (0.05)	0.92 (0.04)	M_{stoch2}[f]	Paper III
100% to milk[d]	1.43 (0.13)	1.20 (0.11)	0.99 (0.09)	M_{stoch2}[g]	Paper III
EA[e]	1.32 (0.13)	1.23 (0.14)	1.22 (0.17)	M_{stoch1}[h]	Paper II
	South-Fleckvieh 8,560[i]		West-Holstein-Friesian 9,600[i]		
100% to milk[d]	1.06 (0.10)		0.98 (0.12)	$F_{commercial}$	Paper IV

[abc] milk yield (in kg of milk/cow per year) and breed of dairy cow production systems; [d]100% to milk = all GHG emission are allocated to milk; [e]EA = economic allocation = all GHG emissions are allocated between milk and co-products according to their economic value; [f]M_{stoch2} = stochastic model approach considering only variability of production traits; [g]M_{stoch2} stochastic model approach considering both epistemic uncertainty of GHG modelling and variability of production traits; [h]M_{stoch1} stochastic model approach considering also uncertainty of GHG emission factor from soybean meal; [i]milk yield (in kg of milk/cow per year) and breed of investigated commercial farms from southern and western Germany

Differences in SD of predicted GHG emissions between the studies of the stochastic model approach can mainly be explained by changing assumptions of parameter uncertainties included in the modelling:

- Relatively low SD was observed if only variability uncertainty of production traits (replacement rate and calving interval) was included in Monte Carlo simulations (Paper III). The fact that higher-yielding dairy cow production systems have a lower variability in their GHG emissions can be attributed largely to the higher homogeneity in investigated production traits in high-yielding production systems.
- SD in predicted GHG emissions increased substantially when both epistemic and variability uncertainty in emission factors and variability uncertainty in production traits were included in the model (cf. Paper III).

- Taking into account uncertainty in land use change in emission factor for soybean meal production resulted in a considerable increase in SD, especially in the case of higher-yielding dairy cow production systems (cf. Paper II).

The allocation of GHG emissions between milk and co-products in both ways (100% to milk or economic allocation) does not account for the strong link between milk and beef production. A change in beef output derived from dairy cow production (beef from culled cows and fattening of surplus calves) could result in an increase of beef production from the alternative beef production system i.e. suckler cow production (Flysjö, 2012a). Thus, the system boundary of the dairy farm gate was expanded using different methods to evaluate the impact on GHG emissions of such a change in origin of beef production (Table 7). In the deterministic model approach, beef output per kg of milk was kept at a constant level based on milk and beef output of a 6,000 kg yielding dairy cow production system (6,000 kg of milk and 320 kg of beef/cow/year). Beef output per kg of milk decreased with increasing milk yield/cow and a change in breed towards Holstein-Friesian. Reduction in beef output was compensated for with beef derived from suckler cow production. Results showed that GHG emissions remained equal when milk yield increased from 6,000 to 8,000 kg of milk/cow/year. However, GHG emissions increased up to 8% when milk yield increased from 8,000 to 10,000 kg of milk/cow/year ongoing with a change in breed. This can mainly be explained by a higher reduction in beef output when the increase in milk yield is ongoing together with a change in breed. It was assumed that 50% of bull calves from the Holstein-Friesian dairy cow are fattened in calf fattening systems with lower beef output. Furthermore, fattening characteristics as daily gain and carcass percentage were assumed to be lower in Holstein-Friesian bull and heifer fattening systems compared to Fleckvieh-systems.

To avoid dependency from a basis scenario and to express GHG emissions per kg of milk, the method called system expansion was applied (Table 7) to account for the close interlink of milk and beef production. For system expansion, beef derived from culled cows and fattening of surplus calves was assumed to replace beef from suckler cow production. The avoided GHG emissions from suckler cow beef production were credited to the dairy farm. Results showed that the credit given to dairy farms reduced GHG emissions per kg of milk especially within lower-yielding dairy cow production systems if compared to GHG emissions per kg of milk using allocation methods (Table 6). The predicted GHG emissions per kg of milk from dual-purpose 6,000 and 8,000 kg yielding dairy cow production systems were equal. However, GHG emissions increased 30% (deterministic model), 22% (stochastic model, Paper II) and 65% (stochastic model, Paper III) with increasing milk yield and a change in breed from the 8,000 kg Fleckvieh-system towards the 10,000 kg Holstein-Friesian-system. The higher increase in GHG emissions in the second study of the stochastic model approach (Paper III) can be explained by the lower level of GHG emissions per kg of milk when compared to the first study (Paper II). The consideration of land use change within the emission factor of soybean meal resulted in a higher level of GHG emissions per kg of milk in the first study of the stochastic model approach (Paper II). The differences in mean values between the results of the deterministic model and the second study of the stochastic model (Paper III) can be explained by different assumptions on GHG emissions per kg of beef from suckler cow production. The 6,000 kg Fleckvieh-system showed highest variation in GHG emission outcomes in both studies of the stochastic model approach. This can be explained by a high uncertainty in the credit for beef output evaluated with the emission factor from suckler cow production and the relatively high beef output of the lower-yielding dairy cow production systems (approximately 55 kg of beef/tonne of milk for the 6,000 kg Fleckvieh-system; approximately 22 kg of beef/tonne of milk for the 10,000 kg Holstein-Friesian-system).

Table 7: Greenhouse gas (GHG) emissions of dairy cow production systems in the deterministic (M_{det}) and stochastic model approaches (M_{stoch}) accounting for differences in beef output of the expanded system boundary, values are shown in average, standard deviation in parenthesis

	Production system			Study approach	Paper
	Fleckvieh 6,000^a	Fleckvieh 8,000^b	Holstein-Friesian 10,000^c		
	Constant milk (6,000 kg) and constant beef production (322 kg)				
	Basis scenario	+ suckler cow^d	+ suckler cow^d		
	GHG emissions [kg CO_2-eq/**unit**]				
	9,578	9,594	10,365	M_{det}	Paper I
	GHG emissions [kg CO_2-eq/**kg of milk**]				
SE^e	0.43	0.43	0.56	M_{det}	
SE^e	0.73 (0.35)	0.75 (0.31)	0.92 (0.23)	M_{stoch1}	Paper II
SE^e	0.32 (0.30)	0.32 (0.23)	0.53 (0.14)	M_{stoch2}	Paper III

^{abc}milk yield (in kg of/cow per year) and breed of dairy cow production systems, ^{d}the reduction in beef output is compensated for with beef from suckler cow production (22 kg CO_2-eq/kg of beef), ^{e}SE = system expansion = a GHG credit was given to the dairy cow system (beef output from dairy cow production was assumed to avoid GHG emissions from suckler cow production)

The results for system expansion were highly dependent on beef output per kg of milk. Thus, a sensitivity analysis on assumptions on fattening characteristics for bull fattening systems was undertaken (Table 8). Different scenarios were investigated for the 10,000 kg yielding dairy cow production system using the deterministic model approach. If it was assumed that bull calves from the Holstein-Friesian dairy cow production system show the same fattening characteristics as Fleckvieh bull calves, GHG emissions in the case of system expansion were comparable to the 8,000 kg yielding dairy cow production system. Improvement in fattening characteristics in Holstein-Friesian systems might be possible using sexed semen of beef cattle on Holstein-Friesian dairy cows. In the scenario where it was assumed that the Holstein-Friesian bull calves are not used for bull fattening GHG emissions increased 23% compared to the basis scenario.

Table 8: Effect of variation in bull fattening systems on greenhouse gas (GHG) emissions of the 10,000 kg Holstein-Friesian-system, method used to account for beef output: system expansion (compare material and methods)

Variation of assumptions for fattening of surplus calves	Beef output[a] [kg/cow/year]	GHG emissions [kg CO_2-eq/kg of milk]
Basis scenario[b]: 50% of bull calves are fattened in calf fattening systems	218	0.56
All bull calves are fattened in bull fattening systems	266	0.51
All bull calves fattened in bull fattening systems, improved fattening characteristics of bull calves[c]	294	0.45
Surplus calves are not fattened[d]	132	0.69

[a]including beef from culled cow and fattening of surplus calves; [b]daily gain fattening period: 1,100g, final weight (carcass in %): bull fattening 600 kg (56%), calf fattening: 180 kg (54%), [c]daily gain fattening period: 1300g, final weight (carcass in %): bull fattening 700 kg (58%), calf fattening: 180 kg (54%), [d]only beef from culled cow

Land use

The amount and type of land use needed to produce milk and beef was calculated in the study of the deterministic model approach and commercial farms. Assuming the system boundary of the dairy farm gate, results from the deterministic model approach showed that land use per kg of milk decreased with increasing milk yield (Table 9). This is mainly caused by a decrease in use of grassland while arable land use per kg of milk increased. The increase in arable land can be explained by an increase in demand for feed with high energy content of the higher-yielding dairy cows. Comparable to modelling of GHG emissions, the system boundary was expanded and land use was calculated for a constant amount of milk and beef. An output of a 6,000 kg yielding dairy cow production unit of milk (6,000 kg) and beef (322 kg) was chosen as basis scenario. The decrease in beef output with increasing milk yield was compensated for with beef from sucker cow production. In total, land use increased with increasing milk yield due to an increase in proportion of beef derived from suckler cow production (Table 9). As suckler cow production was assumed to mainly take place on grassland, the proportion of grassland on total land use per kg of beef increased. Again it has to be considered that these results of the deterministic model approach depend on assumptions of beef output per kg of milk of the basis scenario. Furthermore, it needs to be pointed out that the quality of grassland can differ between production systems, e.g. suckler cow production systems are able to utilize grassland of lower quality.

Table 9: Accounting for differences in beef output modelling land use from dairy cow production systems within the deterministic model approach (Paper I)

Type of land	Production system		
	Fleckvieh 6,000^{a}	Fleckvieh 8,000^{b}	Holstein-Friesian 10,000^{c}
	Land use [m^2/kg of **milk**] (system boundary of the dairy farm gate)		
Grassland	0.92	0.70	0.55
Arable land	0.67	0.80	0.86
Total	1.59	1.50	1.41
	Constant milk (6,000 kg) and constant beef production (322 kg)		
	Basis scenario	+ suckler cow^{d}	+ suckler cow^{d}
	Land use [ha/**unit**]		
Grassland	0.58	0.67	0.85
Arable land	0.66	0.74	0.75
Total	1.24	1.41	1.60

^{abc} milk yield (in kg of milk/cow/year) and breed of dairy cow production systems, ^{d}the reduction in beef output is compensated with beef from suckler cow production (2.7 m^2 of grassland/tonne of beef, 0.89 m^2 of arable land/tonne of beef)

In the commercial farm study approach, land use per kg of milk of South-Fleckvieh and West-Holstein-Friesian dairy farms was calculated. Despite a higher average milk yield of West-Holstein-Friesian dairy farms, land use per kg of milk differed only marginally between the two different dairy cow production systems (Table 10). It has to be considered that average yield of grassland was reported to be about 20% lower for West-Holstein-Friesian dairy farms compared to South-Fleckvieh dairy farms, resulting in a higher demand for of land to produce grass silage (Paper IV). The lower difference between production systems for land use in the study of commercial dairy farms compared to the deterministic model approach can also be explained by a lower difference in average milk yield/cow between South-Fleckvieh and West-Holstein-Friesian dairy farms compared to the 8,000 kg Fleckvieh-system and the 10,000 kg Holstein-Friesian-system of the model approach. A lower amount of grassland and a higher amount of arable land per kg of milk was observed within South-Fleckvieh dairy farms. This can be explained by low proportion of grassland on total farmland for South-Fleckvieh dairy farms (on average 15%) compared to West-Holstein-Friesian dairy farms (on average 60%) and thus a higher amount of feed produced on arable land. Besides the type of land, on-farm (produced inside the system boundary of the farm gate) and off-farm (feed imported to the farm) land use was distinguished in the commercial farm study approach. It was shown that approximately 70% of land use occurred on-farm indicating a mainly land based milk production. As some farms in the group of West-Holstein-Friesian dairy farms bought in forage as grass and maize silage, SD of off-farm land use was high compared to South-Fleckvieh farms.

Table 10: Average land use of dairy farms from the commercial farm study approach (Paper IV), values are shown in average, standard deviation in parenthesis

Type of land	Production system	
	South-Fleckvieh 8,560 kg[a]	West-Holstein-Friesian 9,600 kg[a]
	Land use [m²/kg of milk]	
Grassland	0.41 (0.17)	0.47 (0.20)
Arable land	0.67 (0.12)	0.58 (0.16)
On-farm	0.80 (0.17)	0.68 (0.21)
Off-farm	0.28 (0.08)	0.37 (0.16)
Total	1.08 (0.16)	1.05 (0.15)

[a]average milk yield and breed of investigated commercial farms from southern and western Germany

Potential beef output

Several methods were applied in the studies of the deterministic and stochastic model approaches to account for differences in potential beef output in GHG modelling. In the commercial farm study approach, differences in potential beef output were not weighted in terms of GHG emissions to insure full traceability of GHG emissions per kg of milk for each individual farm. Potential beef output was calculated for each investigated farm and reported as an additional farm indicator to identify a possible trade-off between GHG emissions per kg of milk and beef output per kg of milk. Potential beef output was significantly lower for West-Holstein-Friesian dairy farms (23 kg beef/kg of milk) compared to South-Fleckvieh dairy farms (44 kg beef/kg of milk). The difference can be explained by a higher amount of beef output from the fattening of surplus dual-purpose calves divided by a lower amount of milk. It was determined that 25% (South-Fleckvieh) and 30% (West-Holstein-Friesian) of total potential beef output was made up by beef from culled cows. The remaining beef was assumed to be derived from fattening of surplus calves in beef fattening systems. A trade-off between GHG emissions per kg of milk and beef output per kg of milk was observed in the study of commercial farms (Paper IV).

Economic performance

In the deterministic model approach, average value adjusted total costs for the three dairy cow production systems were investigated (6,000 kg Fleckvieh-system; 8,000 kg Fleckvieh-system; 10,000 kg Holstein-Friesian-system). Due to economies of scale the total value adjusted costs decreased with increasing milk yield (Figure 4). However, only little difference was found between the 8,000 kg Fleckvieh-system and the 10,000 kg Holstein-Friesian-system (Figure 4). The change in breed resulted in lower profit from non milk returns (purchase of surplus calves and beef from culled cows) due to lower value of beef and bull calves in the case of Holstein-Friesian milk-oriented breed. In further calculations it was assumed that GHG emissions from milk production would be burdened with a carbon tax. Values for GHG emissions were calculated using the system expansion approach with GHG credits for beef output. In the case of a low tax of 10 €/tonne CO_2-eq, total value costs increased only marginally by 0.5 (6,000 kg Fleckvieh-system and 8,000 kg Fleckvieh-system) to 0.7 cent/kg of milk (10,000 kg Holstein-Friesian-system). Assuming a tax of 100€/tonne CO_2-eq, total costs increased up to 11 cent/kg of milk (10,000 kg Holstein-Friesian-system). This resulted in higher total value costs for the 10,000 kg Holstein-Friesian-system compared to the 8,000 kg Fleckvieh-system (Figure 4). In that case the higher value of GHG emissions per kg of milk for the 10,000 kg Holstein-Friesian-system offset the reduction in value adjusted total costs.

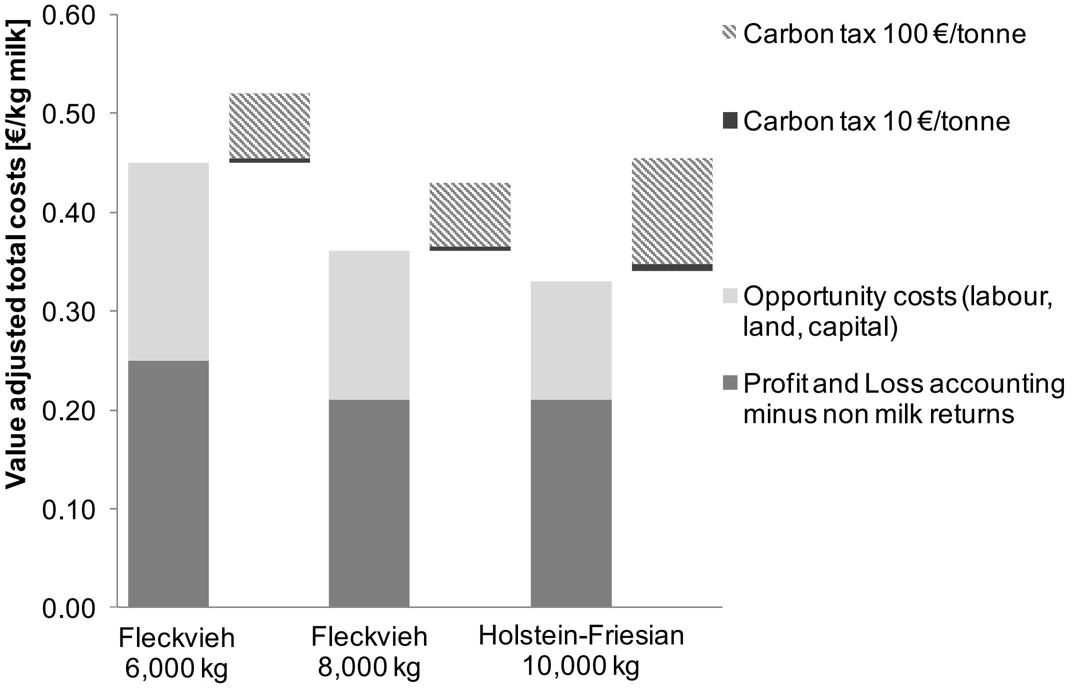

Figure 4: Value adjusted total costs of different dairy cow production systems with a top up of carbon tax on greenhouse gas (GHG) emissions per kg of milk, method to account for milk and beef output in GHG modelling: system expansion (compare material and methods)

Relative Importance Analysis of Input Parameters

To identify sensitivity of model outputs to several input parameters, a sensitivity index was calculated. In the basis scenario, the values of the stochastic model approach (Paper II) of investigated input parameters were set at the mean or most likely value of their probabilistic distributions. The sensitivity of GHG emission outcomes highly depended on the assumption of system boundary (Table 11). Assuming the system boundary of the dairy farm gate and allocating all GHG emission to milk (100% to milk), sensitivity indexes of investigated input parameters were relatively low compared to the extended system boundary (system expansion). This is mainly due to the lower mean values of GHG emission outcomes in case of system expansion where a change in absolute GHG emission outcomes results in a higher relative change. In the case of 100% to milk, GHG emission outcomes were more sensitive to a change in replacement rate than to a change in calving interval. A change in replacement rate results in higher or lower number of heifers needed to replace dairy cows and corresponding GHG emissions of heifer rearing. In contrast a change in calving interval has only marginal effect on GHG emission outcomes. Calving interval influences the number of calves born per cow per year. This co-product of dairy cow production is not accounted for when all GHG emissions at the dairy farm gate are allocated to milk (100% to milk). In the case of system expansion, more calves mean more beef from fattening of surplus calves and a higher GHG credit. Thus, sensitivity of GHG emission outcomes to a change in calving interval was high using system expansion. The assumptions for GHG emissions from suckler cow production play an important role for GHG emission outcomes in the case of system expansion. Due to lower potential beef output, the sensitivity towards the emission factor for beef from suckler cow production was lower for higher-yielding dairy cow production systems.

In the second part of Table 11 the variance of GHG emission outcomes (stochastic model approach, Paper III) was decomposed and most important variables identified. Because of high uncertainty, the emission factor for N_2O emissions from nitrogen input into the soil showed a high contribution to variation of GHG emission outcomes for both system boundaries. Relative contribution of production traits on outcomes variation was low compared to contribution of GHG emission factors which can be explained by their high uncertainty (especially in case of emission factor for beef from suckler cow production). It has to be considered that this is a relative contribution. Thus, results highly depend on the set of uncertain input parameters included in the model. In the first study of the stochastic model approach uncertainty of land use change in the emission factor from soybean meal production was included in probabilistic simulation. Results of this study showed that a contribution of emission factor for soybean meal production explained up to 70% of variation in GHG emission outcomes (Paper II).

Table 11: Sensitivity analysis and identification of relative importance of parameters included in greenhouse gas (GHG) modelling in the study of the stochastic model approach (Paper III)

	System boundary					
	100% to milk[a]			System expansion[b]		
	Production system					
	Fleckvieh 6,000[c]	Fleckvieh 8,000[d]	Holstein -Friesian 10,000[e]	Fleckvieh 6,000[c]	Fleckvieh 8,000[d]	Holstein -Friesian 10,000[e]
Average GHG emission outcomes [kg CO_2-eq/kg of milk] using mean or most likely values for input parameters in the stochastic model approach						
	1.37	1.14	0.92	0.24	0.24	0.47
Sensitivitiy index[f]						
EF N_2O N_{input}	1.4	1.4	1.4	9.0	7.5	3.1
EF $CH_{4\ enteric\ fermentation}$	4.1	3.9	3.9	23.0	18.2	7.7
Calving interval	0.2	0.3	0.4	33.1	26.4	6.6
Replacement rate	2.1	2.2	1.8	0.9	0.7	0.2
EF beef from suckler cow production	NA	NA	NA	-58.1	-45.7	-12.3
Standard deviation of GHG emission outcomes in the stochastic model approach						
GHG emissions [kg CO_2-eq/kg milk]	0.13	0.11	0.09	0.30	0.23	0.14
Variance decomposition[g]						
EF N_2O N_{input}	65	71	77	17	19	36
EF $CH_{4\ enteric\ fermentation}$	6	5	7	1	1	1
Calving interval	0	0	0	3	1	1
Replacement rate	29	26	19	0	0	0
EF beef from suckler cow production	NA	NA	NA	77	78	62

EF=emission factor; [a]100% to milk= all GHG emission at the dairy farm gate are allocated to milk, [b]SE = system expansion = dairy cow production system is given a GHG credit (beef output from dairy cow production is assumed to avoid GHG emissions from suckler cow production); [cde]milk yield (in kg/cow/year) and breed of dairy cow production systems; [f]percentage change in GHG emission outcomes for a 10% change in the given emission source or production trait; [g]relative importance of emission sources: contribution of each emission source on variation of GHG emission outcomes

In the study approach of commercial dairy farms, the method of "dominance analysis" was chosen to decompose R² and identify "variable importance" for each regression model. Milk yield showed the highest contribution within the group of South-Fleckvieh dairy farms, accounting for 55% of variance in GHG emissions per kg of milk and the second highest contribution within the group of West-Holstein-Friesian dairy farms (30%) (Table 12). The replacement rate was the second highest contributor, accounting for 26% of variance in GHG emissions of South-Fleckvieh dairy farms and the highest contributor accounting for 31% of variance in GHG emissions of West-Holstein-Friesian dairy farms. The contribution of nitrogen fertilizer input (18%) and dry matter intake per cow (21%) was high for the group of West-Holstein-Friesian dairy farms compared to South-Fleckvieh dairy farms. Nitrogen fertilizer contributed only marginally (3%) to variance for the South-Fleckvieh dairy farms indicating the variable had the lowest potential to influence GHG emissions per kg of milk for that dairy farm group.

The order of most important predictors of potential beef output in the case of South-Fleckvieh dairy farms was milk yield (46%), cow and calf mortality (27%), replacement rate (15%) and calving interval (12%). The relative importance of milk yield (33%) and replacement rate (28%) was similar within the group of West-Holstein-Friesian dairy farms and followed by calving interval (20%) and cow and calf mortality (19%).

Net crop yield (kg dry matter per ha) was the main contributor to variance of land use per kg of milk, accounting for 58% of variance of South-Fleckvieh dairy farms and 55% for West-Holstein-Friesian dairy farms. The relative importance of milk yield was similar for the MLR models of both dairy farm groups. Dry matter intake per cow and replacement rate had a relatively low impact on variance of land use per kg of milk within both dairy farm groups.

Table 12: Variance decomposition (in %) of greenhouse gas (GHG) emissions per kg of milk, potential beef output per kg of milk and land use per kg of milk for investigated commercial dairy farms (Paper IV)

	Production system	
	South-Fleckvieh 8,560 kg[a]	West-Holstein-Friesian 9,600 kg[a]
GHG emissions per kg of milk		
Milk yield	55	30
Replacement rate	26	31
Dry matter intake cow	16	21
Nitrogen fertilizer application	3	18
Potential beef output per kg of milk		
Milk yield	46	33
Replacement rate	15	28
Animal losses	27	20
Calving interval	12	19
Land use per kg of milk		
Milk yield	26	23
Replacement rate	5	13
Yield own feed production	58	55
Dry matter intake cow	10	9

[a] milk yield (in kg of milk/cow/year) and breed of investigated commercial farms from southern and western Germany

Overview of Main Findings

The main findings of the different studies undertaken in this thesis are summarized in the following:

Greenhouse gas emissions – system boundary of the dairy farm gate

- Lower GHG emissions per kg of milk with increasing milk yield/cow/year
- Model results were confirmed by the commercial farm study approach

Greenhouse gas emissions – expanded system boundary of milk and beef production

- Increase in GHG emissions of combined milk and beef production with a change from lower-yielding dual-purpose dairy cow production systems towards higher-yielding milk-oriented dairy cow production systems if beef derived from dairy cow production (beef from culled cows and fattening of surplus calves) was weighted by beef from suckler cow production

- High variation of predicted GHG emissions due to high uncertainty of emission factor for beef derived from suckler cow production

Uncertainty modelling greenhouse gas emissions

- The emission factor for direct N_2O emissions from nitrogen input into the soil, for land use change from soybean meal production and beef from suckler cow production showed the highest impact on variation of predicted GHG emissions
- Milk yield and replacement rate had the highest impact on variation of predicted GHG emission within investigated groups of South-Fleckvieh and West-Holstein-Friesian commercial dairy farms

Land use and beef output

- Use of arable land and grassland increased with increasing milk yield/cow/year if beef output was kept constant
- South-Fleckvieh dairy farms showed a higher potential beef output compared to West-Holstein-Friesian dairy cow farms
- Milk yield had the highest impact on variation of potential beef output within investigated groups of Fleckvieh and Holstein-Friesian commercial dairy farms

4. Discussion

The impact of dairy cow production systems with different milk yield and breed and variability of production traits on GWP, land use, economic performance and milk and beef output has been addressed in this thesis. In the first part of this section, the study results on GHG emissions related to the different assumptions on system boundary of dairy cow production systems are discussed. In the second part, the results on land use will be set in broader context. Different approaches to evaluate land use and land use change will be discussed indicating possibilities for future research. Furthermore, the different approaches applied in this study to model GHG emissions will be integrated in the context of LCA methods. Finally, further steps on the way to identify sound GHG mitigation options e.g. calculation of GHG mitigation costs are discussed with regard to study limitations and future consideration.

The Choice of System Boundary when Modelling Greenhouse Gas Emissions

System boundary of the dairy farm gate

Results of this study showed that dairy cow production systems with a higher milk yield/cow/year resulted on average in lower GHG emissions per kg of milk with a high probability if the system boundary of the dairy farm gate was considered. This was the case within both modelling approaches (deterministic and stochastic model approach) and in the empirical study of commercial dairy farms. This finding can mainly be explained by the increase in the ratio of dairy cow 'production' to 'maintenance' (Monteny et al., 2006). The associated curvilinear relationship between dry matter intake per kg of milk and milk yield/cow leads to a decrease in CH_4 emissions from enteric fermentation per kg of milk and a decrease in amount of feed requirement per kg of milk (Capper et al., 2009). Accounting for all GHG emissions occurring on- and off-farm, the different approaches undertaken in this thesis resulted in an average decrease of GHG emissions between 0.08 kg CO_2-eq and 0.17 kg CO_2-eq/kg of milk for a 1,000 kg increase in milk yield/cow. Christie et al. (2012) investigated a reduction of 0.10 kg CO_2-eq/1,000 kg of milk produced per cow for Australian dairy farms. Capper et al. (2008) showed that the increase in milk yield/cow because of the use of bovine somatotropin resulted in a decrease in total GHG emissions per kg of milk.

When evaluating the investigated decrease in GHG emissions per kg of milk it has to be considered that the investigated confinement dairy cow production systems are already at a high level of milk yield. This means that the additional increase in milk yield has less leverage compared to extremely low yielding dairy cow production systems, e.g. 3,000 kg of/cow per year where a 1,000 kg increase in milk yield could result in a 0.4 kg CO_2-eq/kg of milk reduction of GHG emissions (Hagemann et al., 2012). Due to the relatively low slope, the improvement in GHG emissions per kg of milk observed in this thesis can easily be negated by increasing GHG emissions from other sources e.g. deterioration of replacement rate. Within the group of investigated commercial dairy farms a 10% increase in replacement rate resulted in a predicted increase in GHG emissions of up to 0.12 kg CO_2-eq/kg of milk. Lucy (2001) points out that low replacement rates in high-yielding dairy herds need to go along with “better feeding, healthier cows, and better reproductive management”. O’Brien et al. (2011) showed that within pasture-based systems, solely a selection of dairy breed strains with a high milk yield results in higher GHG emissions compared to strains that combine both milk production potential and fertility (fertility is highly related to replacement rate in pasture based systems, low fertility means higher amount of culled cows and replacement heifers needed). Thus, the increase in milk yield as an option to decrease GHG emissions per kg of milk needs to go along with a high management ability to avoid an increase in GHG emissions from other sources.

It has to be considered that production mode (conventional production systems), the housing and feeding system (confinement system with cows and heifers indoors all year round) were the same for all investigated dairy cow production systems in this thesis. However, lower-yielding dairy cow production systems are often associated with a different production mode compared to higher-yielding systems. Many studies compare conventional versus organic farming (Cederberg and Flysjö, 2004; Thomassen et al., 2008; van der Werf et al., 2009) or confinement versus pasture-based dairy cow production systems (Arsenault et al., 2009; Flysjö et al., 2011b; O'Brien et al., 2012a;). In that case, differences in GHG emissions from e.g. feed production can overlay the impact of milk yield on GHG emissions per kg of milk (Martin et at., 2009; O'Brien et al., 2012a).When comparing study results with results from literature it also has to be considered that different equations and approaches (definition of system boundaries) are often used to model GHG emissions from dairy cow production systems.

The method chosen to allocate GHG emissions at the dairy farm gate between milk and co-products (surplus calves and culled cows) has a major impact on GHG emissions per kg of milk. Different approaches are suggested and discussed in literature (Flysjö et al., 2011a). This assumption also has an impact on a comparison of dairy cow production systems with different milk yield and breed. Lower-yielding dairy cow production systems produce relatively more calves and beef per kg of milk. Furthermore, calves and beef from lower-yielding dual-purpose dairy breeds have on average a higher value compared to specialised milk breeds (AMI, 2011). The choice of economic allocation method within the deterministic model approach decreased GHG emissions by 21% (6,000 kg Fleckvieh-system) to 9% (10,000 kg Holstein-Friesian-system) compared to 100% to milk (all GHG emissions are allocated to milk). However, each method to allocate GHG emissions between milk and co-product is problematic as milk and beef are joint products. It is impossible to determine the "true" or "correct" allocation. An unfortunate by-product of this contention has been the scant attention paid to establish criteria for choosing particular, albeit arbitrary, allocation schemes from among a variety of alternatives (Flysö et al., 2011a; IDF, 2010; Kristensen et al., 2011; Verrecchia, 1982). If the objective is to quantify, investigate and report GHG emissions from individual dairy farms, GHG emission outcomes should be presented on a per farm basis and per kg of milk. This gives the farmer a first insight into the most important GHG emission sources and possible mitigation options. However, further methods are needed in a second step to identify possible benefits and burdens of co-products from dairy farming in terms of GHG emissions. Some of these methods were investigated in the studies of this thesis and are discussed in the following section.

Expanded system boundary

Different approaches were applied in this study to account for the close link between milk and beef production in GHG modelling. In the deterministic model approach milk and beef output from the 6,000 kg yielding dairy cow production system was set as the basis scenario. The decrease in beef output with increasing milk yield/cow was assumed to be replaced by beef from suckler cow production. The results showed that GHG emissions to produce 6,000 kg of milk and 322 kg of beef were equal assuming a 6000 kg Fleckvieh-system or a 8,000 kg Fleckvieh-system combined with beef from suckler cow production. Greenhouse gas emissions increased when milk and beef was produced by a 10,000 kg yielding dairy cow combined with beef from suckler cow production.

The results of this approach depend highly on the ratio and amount of milk and beef output from the basis scenario. The ratio of milk to beef output per year (kg of milk/kg of beef) for the investigated dairy cow systems was 18 (6,000 kg Fleckvieh-system), 25 (8,000 kg Fleckvieh-system) and 44 (10,000 kg Holstein-Friesian-system). The milk and beef output of different dairy cow production systems can be compared with milk and beef consumption patterns in Germany and various countries worldwide (Table 13). To satisfy milk demand of e.g. an average German consumer (264 kg of milk) 0.033 dairy cows yielding 8,000 kg of/year would be needed. This results in a total amount of 10 kg beef as co-product (beef from culled cows and fattening of surplus calves). Thus, 3 kg of beef from suckler cow production would be needed to satisfy beef demand (13 kg). In the case of German milk and beef consumption patterns the 8,000 kg Fleckvieh-system combined with a certain amount of suckler cow production would result in lowest GHG emissions. In the case where beef demand was lower than the beef output from dairy cow production systems, it was assumed that surplus calves were not fattened. Assuming a beef consumption of 40, 25 and 15 kg of beef/capita, the 6,000 and 8,000 kg Fleckvieh-systems showed lower GHG emissions compared to the 10,000 kg Holstein-Friesian system. The 6,000 and 8,000 kg Fleckvieh-systems resulted in equal GHG emissions. Thus, the lower GHG emissions per kg milk production of the 8,000 kg Fleckvieh system was compensated for by the additional amount of suckler cow beef needed (additional amount of 3 kg of suckler cow beef). The additional amount of suckler cow beef needed in the case of the 8,000 kg Fleckvieh-system was the same for the beef consumption patterns 40, 25 and 15 kg of beef/capita. Only when the amount of beef demand decreased to 5 kg/capita the 10,000 kg Holstein-Friesian system result in lowest GHG emissions to meet milk and beef demand.

For varying milk demands, the 8,000 kg Fleckvieh-system resulted in lowest GHG emissions if milk demand increased to 350 kg of milk. This dairy system delivered roughly the amount of beef that was needed to meet beef demand. The comparison of consumption patterns also showed that GHG emissions of a certain consumption pattern were mainly influenced by amount and ratio of milk and beef consumption and less by the choice of production system.

Table 13: Greenhouse gas (GHG) emissions from milk and beef consumption per capita of different countries assuming that milk and beef is produced by dairy and suckler cow production systems of the deterministic model approach (Paper I), lowest values are presented in bold values

	Consumption pattern [kg/capita/year]		Milk to beef ratio	Production system		
				Fleckvieh 6,000[a]	Fleckvieh 8,000[b]	Holstein-Friesian 10,000[c]
	Milk	Beef		GHG emissions [kg CO_2-eq/capita]		
Germany	264	13	20	410	**391**	426
Variation of consumption pattern						
d	250	40	6	**986**	**986**	1018
e	250	25	10	**655**	**655**	687
	250	15	17	**434**	**434**	467
f	250	5	50	328	280	**252**
g	350	15	23	527	**475**	521
	250	15	17	**434**	**434**	467
h	200	15	13	**413**	**413**	439

[abc] dairy cow production system with 6,000, 8,000, 10,000 kg milk/cow/year, milk and beef output of expanded dairy cow production systems: Fleckvieh 6,000: 6,000 kg of milk and 322 kg of beef; Fleckvieh 8,000: 8,000 kg of milk and 315 kg of beef, Holstein-Friesian 10,000: 10,000 kg of milk and 218 kg of beef, assumed GHG emissions [kg CO_2-eq/unit]: Fleckvieh 6,000: 1.35/kg of milk and 5.6/kg of beef; Fleckvieh 8,000: 1.16/kg of milk and 4.9/kg of beef, Holstein-Friesian 10,000: 0.98/kg of milk and 3.7/kg of beef, if beef as co-product from dairy cow production systems was not enough beef from suckler cow production was taken (22 kg CO_2-eq/kg of beef), if beef as a co-product exceeded beef consumption surplus calves were not fattened, d-h: variation of consumption patterns, [d]on the basis of USA, [g]on the basis of the Netherlands, [h]on the basis of Europe; References: Paper I, Faostat (2012)

In the stochastic model approach, system expansion was applied as a method to account for the link between milk and beef production. System expansion is also recommended by ISO (2006) guidelines as a method to account for co-products in LCA approaches if the unit process to be divided can't be allocated into two sub-processes. Results of the two stochastic model approach studies showed that GHG emissions decreased considerably if system expansion was applied compared to 100% to milk. Depending on the emission factor of beef from suckler cow production and the amount of beef as co-product from dairy cow production GHG emissions per kg of milk decreased on average 25% up to 77% compared to 100% to milk approach. Flysjö et al. (2011a) observed a reduction of 37% using system expansion compared to 100% to milk approach when modelling GHG emissions of an average dairy farm from Sweden and New Zealand. In the studies of the stochastic model approach, it was shown that the emission factor of beef from suckler cow production (ranging between 15.6 and 37.5 kg CO_2-eq/kg of beef) had a high impact on GHG emissions per kg of milk of investigated dairy cow production systems. Flysjö et al. (2011a) state that other sources of meat could be assumed as an alternative to beef from dairy cow production with considerably lower GHG emissions (3.4 kg CO_2-eq/kg of pork meat, 1.9 kg CO_2-eq/kg of poultry meat). This would cause lower credits for beef output making lower-yielding dairy cow production systems less favourable in terms of GHG emissions. The method of system expansion implies the assumption that all beef from dairy cow production is needed on the market and replaces beef from suckler cows. Furthermore, no distinction was made between different beef qualities. It has to be discussed if beef from culled cows can be treated the same way as beef from suckler cow production. Mc Geough et al. (2012) state that e.g. in Canada the primary source of beef is derived from non-dairy cattle to meet particular market demands with mainly traditional beef breeds such as Aberdeen Angus and Hereford. Despite several disadvantages, the method of system expansion is considered to be important to define GHG abatement policies for both milk and beef production, especially in countries where beef as co-product from dairy farming plays an important role in beef consumption (Flysjö et al, 2011a). Approximately 70% of German beef output can be considered as a byproduct of dairy cow production (AMI, 2011). It is also considered to be a valuable approach to identify possible leakage, i.e. to avoid mitigation activities that inadvertently increase global GHGs despite lowering farm or agricultural sector GHG emissions (Franks and Hadingham, 2012).

In the study of commercial dairy farms the link between milk and beef production was accounted for by introducing a new farm indicator i.e. potential beef output (beef from culled cows and fattening of surplus calves outside the dairy farm gate) (Paper IV). All GHG emissions occurring at the dairy farm gate are allocated to milk which ensures full traceability of GHG emission sources. Furthermore, trade-offs between GHG emissions and potential beef output can be identified when comparing dairy cow production systems or GHG mitigation options. However, changes in potential beef output are not weighted in terms of GHG emissions. Thus, no information is given if changes in potential beef output could negate reduction in GHG emissions at the dairy farm gate.

Furthermore, it has to be considered that results of all approaches to account for milk and beef production from dairy cow production studied in this thesis depend highly on assumptions and approaches to calculate beef output from fattening of surplus calves. In most cases no information is available at the dairy farm gate about the system where surplus calves are fattened. Beef output differs depending on e.g. fattening system (e.g. bull fattening, calf fattening), length of fattening period, the fattening characteristics, etc.; Brüggemann, 2011). In this thesis differences in potential beef output assessed by different breeds were studied. However, further possibilities do exist to increase potential beef output per kg of milk from dairy cow production. This includes the production of calves from heifers entering a fattening system, higher weights of fattening bulls and heifers and fewer calves sent to calf fattening systems.

Soil Organic Carbon and Greenhouse Gas Modelling

The differences in management practice as type of residue management, tillage management, fertilizer management (both mineral fertilizers and organic amendments), choice of crop and intensity of cropping management can affect soil carbon stocks and thus annual CO_2 emissions from arable land (IPCC, 2006). Changes in soil organic carbon (SOC) are generally not accounted for in LCA or carbon footprint studies of dairy cow production systems (Flysjö et al., 2012b, O'Brien et al., 2012a; Thomassen et al., 2008; Hörtenhuber et al., 2010 is an exception). Guidelines as PAS 2050 (BSI, 2008) and IDF (IDF, 2010) state that the current choice for standard footprint methodology is not to take changes in SOC into account "because of lack of scientific data" (IDF, 2010). According to these guidelines changes in SOC due to differences in arable or grassland management were not included in GHG modelling in the studies of this thesis. It was assumed that SOC of land used within the investigated dairy and beef production systems is under a steady state.

On average over 80% (South-Fleckvieh) and over 90% (West-Holstein-Friesian) of arable land on investigated farms in the study of commercial dairy farms was cultivated with maize, wheat, barley and triticale. However, only 35% of arable farm land was cultivated with maize within the South-Fleckvieh dairy farms compared to 68% within West-Holstein-Friesian dairy farms. Differences in humus balance and thus SOC between farms might be possible, because of different proportions of maize, known to cause a higher reduction of SOC on arable land compared to wheat or barley (Küstermann et al., 2007). Furthermore, differences in tillage systems between farms might be possible. However, these were not recorded for investigated dairy farms. Modelling GHG emissions of different crop rotations Küstermann et al. (2007) included crop specific coefficients that account for changes in SOC e.g. cultivation of maize induces a reduction of SOC in 0.7 to 1.2 Mg/ha per year. Based on IPCC guidelines (IPCC, 2006) Hillier et al. (2011) included Tier 1 method for estimating carbon stock changes due to changes in management practice within a period of 20 years in GHG modelling of farms. Both Küstermann et al. (2007) and Hillier et al. (2011) showed that increasing SOC through different management practices on arable land could even offset GHG emissions from other sources. However, it needs to be considered that "C accumulation as induced by management shifts are temporarily limited", and that with the development of new steady states, differences in SOC finally fall to zero (Küstermann et al., 2007). Petersen et al. (2013) suggests a method to estimate the effect of soil carbon changes considering also the aspect of time. Adding carbon into the soil means only parts of the carbon will remain in the soil while other parts will be released to the atmosphere each year until a new equilibrium of SOC is reached. Combining the curve of carbon release over time with the Bern Carbon Cycle Model, which takes into account the decay pattern of CO_2 in the atmosphere[2], the total time-integrated atmospheric load of CO_2 avoided by storing the crop residue carbon in the soil (compared to releasing it to the atmosphere) was calculated (Peterson et al., 2013). The study indicated that soil carbon changes included in an LCA study can constitute a major contribution to the total GHG emissions per crop unit with the choice of the time perspective having a huge impact on the results.

However, current studies state that the mitigation of climate change through changes in arable land management is limited (compare a review of Powlson et al., 2011). Whereas e.g. a change from cultivation to minimum or zero tillage of soil was considered for a long time as a method to increase SOC, recent studies found only little difference between the systems provided, account is taken of SOC variation with depth and differences in bulk density (Luo et al., 2010; Powlson et al., 2011). Höper and Meesenburg (2012) state that a positive or negative annual humus saldo should have a positive or negative impact on SOC stocks. However, no correlation between the results of humus balance and SOC was found in 48 arable land fields in the "Bodendauerbeobachtung" (permanent investigation of land) program in Lower Saxony, Germany. The results of the program in Lower Saxony and Bavaria also showed that within a time period of 25 years in 57% of observed fields in Bavaria (92 fields) and in 81% of observed fields in Lower Saxony (48 fields), SOC was at a constant level, indicating a relatively stable level of SOC in the long term (Höper and Schäfer, 2012).

There are several limitations to increasing SOC in the soil as an option to mitigate GHG emissions discussed in literature:

- The process of increase/decrease in SOC is reversible: the change in land management can affect SOC but it has to be continued indefinitely to maintain the changes in SOC (Höper and Schäfer, 2012; Powloson et al., 2011).
- Changes in SOC induced by land management changes may either "increase or decrease fluxes of powerful greenhouse gases such as N_2O or methane" (Powlson et al., 2011).
- Limitation of carbon sequestration due to physical limitations (i.e. clay and silt content of the soil) (Wiesmaier, personal communication, March, 2013).

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[2] When carbon is released to the atmosphere in the form of CO_2, it will follow a decay pattern due to absorption sinks (mainly in the oceans) (Petersen et al., 2013).

Nevertheless, the amount of carbon in soil can be considered as an important sustainability indicator with positive impacts on soil quality aspects, such as structure, erosion control, water holding capacity and nutrient availability and supply (Brock et al., 2012; Powlson et al., 2011; Shepherd et al., 2002). Thus, soil organic matter might be a useful and robust indicator for soil quality which should be accounted for in LCA studies (Canalas et al., 2007).

The potential of grassland as a carbon sink is also debated controversially in literature. Whereas some studies show a high potential of grassland to continuously sequester carbon (Sousanna et al., 2007), steady states are observed in other studies (Höper and Schäfer, 2012). Accordingly, the inclusion/exclusion of carbon sequestration in grassland differs among LCA studies and guidelines (Bellarby et al., 2013; Nguyen et al., 2013b; Pelletier et al., 2010).

Due to lack of farm specific data on land management and the ongoing scientific discussion, the impact of soil management on SOC was not included in GHG modelling of this thesis following the PAS 2050 guidelines. However, with improved scientific understanding, the inclusion of GHG emissions from changes in SOC should be considered in future studies (BSI, 2008).

Land Use Change and Greenhouse Gas Modelling

If land use change through conversion of forest land to grassland or arable land (deforestation) was accounted for, agriculture contributes 17-32% of total global GHG emissions (Bellarby et al., 2008). This is up to 50% higher compared to without deforestation (Smith, 2012). Greenhouse gas emissions from land use change include changes in biomass (above-ground and below-ground), dead organic matter and SOC (IPCC, 2006). Changes in SOC do occur over a period of years to decades (a period of 20 years is assumed until a new equilibrium is established after conversion according to IPCC, 2006). If agricultural expansion is considered as the driving force of land use change, GHG emissions from this source need to be considered in modelling GHG emissions of agriculture. Up to date there is no shared consensus on how to include GHG emissions from land use change in modelling GHG emissions from agricultural systems, as it is very difficult and complex to establish the drivers behind land use change (Flysjö et al., 2012b). According to

Schmidt et al. (2012) two types of land use change can be distinguished: direct land use changes and indirect land use changes. Direct land use change is defined as the consequences of what you do to the land that you occupy. Indirect land use change is defined as the upstream consequences of the occupation of land, regardless of what you do to it (Schmidt et al., 2012). Methods to account for the two different types of land use change and possible impacts on results of this thesis will be discussed in the following section.

Direct land use change

The main sources of GHG emissions from land use change reported in literature are conversion of forest to grassland or cropland and grassland to cropland (Poeplau et al., 2011). The use of drained peat land with a high content of SOC into agricultural land plays a specific role. In Germany peat land accounts for only 6% of total agricultural land area. However, 93% of total GHG emissions in Germany from land use and land use change in 2010 were derived from peat land (Gensior et al., 2012).

Modelling of direct land use change is included in the IPCC (2006) guidelines, in several LCA guidelines e.g. PAS 2050 (BSI, 2008), IDF (2010) and implemented in LCA models (e.g. COOL farm tool, Hillier et al., 2011; FAO, 2010). It is recommended to assess the GHG emissions arising from direct land use change occuring during a period of not more than 20 years (BIS, 2008). Thus, 5% of total GHG emissions arising should be included each year in GHG modelling of a product.

Production of soybean meal is considered as one of the main drivers of deforestation e.g. in the Brazilian Amazon (Morton, 2006). As soybean meal is an important feed ingredient, especially in high-yielding dairy cow production systems with maize silage, land use change from soybean meal production is often included in GHG modelling of dairy cow production systems (FAO, 2010).

In the study of the stochastic model approach (Paper II) a range of GHG emission factors for soybean meal production was included in probabilistic simulation with different values of GHG emissions derived from deforestation. Results showed that variation of emission factor for soybean meal production had a high impact on variation of GHG emissions per kg of milk especially within high-yielding dairy cow production systems. Flysjö et al. (2012b) investigated the impact of different values for land use change included in the emissions factor of soybean meal on GHG emission per kg of milk for organic and conventional dairy farms in Sweden. The GHG emissions per kg of milk increased from 4 to 83%, depending on the amount of soybean meal fed to dairy cows, the value of GHG emissions from land use change and the considered system boundary.

However, recent studies point out that in a world with an increasing demand for food, any occupation of land, regardless of if it takes place in Europe or South America, contributes to pressure for land clearance for increased food production elsewhere (Powloson et al., 2011; Nguyen et al., 2013a). Thus, different approaches are developed to include the so-called indirect land use change in GHG modelling.

Indirect land use change – consideration of total land occupation

"Indirect LUC [land use change] is defined as the upstream consequences of the occupation of land, regardless of what you do to it" (Schmidt et al., 2012). The concept of indirect land use first occured in the context of biofuel production (Searchinger et al., 2008) where land from food crops is converted to biofuel production (Powlson et al., 2011).

Searchinger et al. (2008) state that "barring biofuels produced directly on forest or grassland would encourage biofuel processors to rely on existing croplands, but farmers would replace crops by plowing up new lands". This could be transfered in the same way to production of protein sources in dairy farming. If e.g. rapeseed meal is cultivated in Germany to avoid the import of soybean meal, the extra ha of rapeseed could displace e.g. wheat production and thus result in land clearance elsewhere to produce an additional amount of wheat (Heißenhuber et al., 2013).

Various approaches have been developed recently to account for indirect land use change and differences in land occupation in LCA studies (Audsley et al., 2009; Berlin and Uhlin, 2004; Schmidinger and Stehfest, 2012; Schmidt and Dalgaard, 2012; Tuomisto et al., 2012). Two main approaches considering total land occupation in LCA studies can be distinguished and will be explained by examples from literature in the following:

(1) Accounting for historic and future land use changes

Audsley et al. (2009) assumes that all demands for agricultural land contribute to commodity and land prices and thus to land use change. Consequently, global emisisons from land use change should be allocated to global demand for agricultural land. The GHG emissions from land use change occurring between 2000 and 2005 and the proportion of deforestation attributable to commercial agriculture were identified. A single land use change emission of 1.43 tonnes of CO_2-eq/hectare for agricultural land use was calculated. No distinction is made between differences in type of land use (e.g. arable land, pasture). However, Audsley et al., (2009) suggests the inclusion of a “credit” for agricultural production systems that occupy marginal or degraded land which “would not have been used for any other purpose” (Audsley et al., 2009) and therefore avoid indirect land use change.

In the model of Schmidt et al. (2012) indirect land use change is defined as the link between use of land and the global effects on land use changes and intensification (Figure 5). If land that produces a certain product A is changed to produce a different product B, the loss in product A can only be balanced by transformation on non-cultivated land (e.g. b_{before} to b_{after}, Figure 5), intensification or change in food consumption pattern.

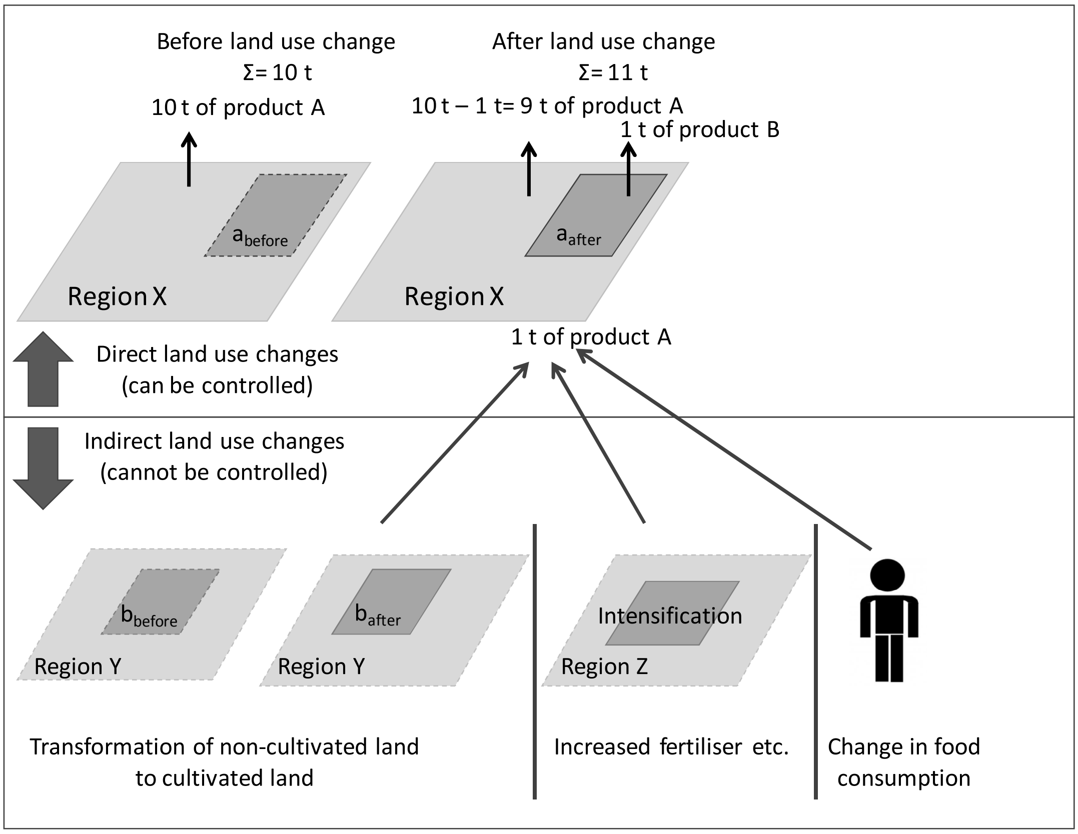

Figure 5: Illustration of indirect land use change according to Schmidt et al. (2012)

It is assumed that current demand for land causes current land use changes. Land supply is categorised into in three main sources: land already in use, expansion of land (which may cause deforestation), and intensification. Expansion of land and intensification is associated with GHG emissions. To calculate GHG emissions from expansion of land, a land use change matrix showing transformation of land use e.g. from primary forest to arable land or grassland to rangeland is established, based on FAO statistics. The amount of land use is linked with GHG emissions of land use using net prime productivity (NPP) values. First, land use per product (m^2/kg of product) is calculated based on product yields. Second, values of potential NPP (depending on region and type of land) for the occupied land (kg C/m^2) are taken from Haberl et al. (2007). Third, NPP per land use is linked with values of GHG emissions per NPP from the model of Schmidt et al. (2012). Thus, the occupation of land with high production potential measured in NPP will result in higher GHG emissions because of indirect land use change compared to occupation of land with lower NPP. Case studies showed that GHG emissions from land occupation can yield up to 8.9 tonne CO_2-eq/ha of arable land use in Denmark using the model of Schmidt et al. (2012).

(2) Accounting for opportunity costs of land use

Schmidinger and Stehfest (2012) do not account for real changes in land use but assume that occupation of land affects global warming as “it prevents natural vegetation from regrowth and thus from carbon up-take”, which can be expressed as “missed potential carbon sink”. The calculation of GHG emissions from missed potential C sink is based on land use needed per kg of product, C sink that occurs when land use is regrowing to natural vegetation during a certain period of time and the time horizon over which the potential CO_2 uptake is annualized. Results are explored for three different time horizons namely 100 years (this is assumed to be the time when the vegetation is coming close to its equilibrium state) 30 years (time horizon often used for allocating emissions from land use change) and 50 years (intermediate information).

Berlin and Uhli (2004) also combine LCA modelling with opprotunity cost principles. The concept is based on the assumption that the use of limited resources such as land, “will lead to a choice between different use alternatives”. Each choice to be made entails the sacrifice of the alternative not chosen – which is called opportunity cost. The utility that could be derived from an alternative land use is expressed in reduced amount of GHG emissions. Two different dairy cow production systems are compared in terms of GHG emissions. Differences in land use are accounted for by assuming that the system with lower land use can produce energy crops (i.e. Salix) on the “free” land area and thus contribute to reduce fossil fuel (Berlin and Uhli, 2004).

Greenhouse gas emissions per kg of milk from different studies applying different methods to account for direct and indirect land use change are summarized in Table 14. It is shown that GHG emissions per kg of milk increase considerably throughout all studies if land use change was incuded in GHG modelling. The study of Flysjö et al. (2012b) shows that the ranking of different production systems in terms of GHG emissions could change depending on the applied method of land use change. Mean GHG emissions per kg of milk from organic milk production was higher compared to conventional milk production. If direct land use change from soybean meal was accounted for, GHG emissions from conventional milk production would result in a higher mean value. The order changed again if the approach of indirect land use change was considered, as more land was needed in organic farms, emphasizing the high impact GHG emissions from land use change can have on model results.

Table 14: Impact on greenhouse gas (GHG) emissions of milk production expressed in CO_2-eq/kg of milk when applying different approaches to account for direct and indirect land use change (LUC)

	Country of dairy farm origin					
	Sweden (Flysjö et al., 2012b)		Sweden (Schmidt and Dalgaard, 2012)			Netherlands (Schmidinger and Stehfest, 2012)
	Production system					
	Organic milk	Conventional milk	N.A	N.A	N.A	N.A
	Modelling approach					
Method accounting for land use change	System boundary - dairy farm gate		Expanded system boundary, consequential[a]	System boundary - dairy farm gate, attributional[b]	IDF (2010)	System boundary - dairy farm gate
No land use change included	1.13	1.07	0.51	1.25	1.09	1.2
Direct LUC included for soybean meal	1.23	1.42			1.72	
Indirect LUC according to Audsley et al. (2009)	1.60	1.32				
Indirect LUC according to Schmidt and Dalgaard (2012)	2.91	2.07	1.15	1.30		
Opportunity cost approach according to Schmidinger and Stehfest (2012)						1.7

[a] atttributional modelling: the land already in use is included in land supply (less GHG emissions as less area is assumed to be converted or intensified);
[b] consequential modelling: excludes land already in use which means that land can only be supplied through expansion or intensification

Results from the deterministic model approach in the first study of this thesis showed that land use per kg of milk decreased with increasing milk yield considering the system boundary of the dairy farm gate. Thus, similar to Flysjö et al. (2012b) applying the approach of indirect land use change higher-yielding dairy cow production systems might be burdened with lower amounts of GHG emissions. However, considering the extended system boundary it was shown that the basis scenario (6,000 kg Fleckvieh-system) had the lowest occupation of land (1.24 ha per 6,000 kg of milk and 322 kg of beef) compared to 8,000 kg Fleckvieh-system combined with suckler cow production (1.41 ha per 6,000 kg of milk and 322 kg of beef) and the 10,000 kg yielding Holstein-Friesian dairy cow production system combined with suckler cow production (1.61 ha per 6,000 kg of milk and 322 kg of beef) (Paper I). Both grassland and arable land would increase with increasing milk yield. The increase in grassland can be explained by the assumption that suckler cow production mainly takes place on permanent grassland. The increase in arable land can be explained by higher amounts of concentrate within higher-yielding dairy cow production systems. Applying the approach of system expansion in the case of land use (avoided land use through avoided suckler cow beef production is credited to dairy cow production) would result in land use (m^2/kg of milk) of 0.13 (6,000 kg Fleckvieh-system), 0.42 (8,000 kg Fleckvieh-system) and 0.76 (10,000 kg Holstein-Friesian-system). Thus, if indirect land use change was included assuming the expanded system boundary lower-yielding dairy cow production systems might be burdened with lower amounts of GHG emissions. Similar findings are discussed by Schmidt and Dalgaard et al. (2012).

When accounting for land use in GHG modelling of agricultural systems it is important to distinguish between permanent grassland and arable land. The use of grassland in Germany by ruminants might put less pressure on land use change as it can’t be used for any other purpose. This aspect is either not included in indirect land use change modelling approaches (Audsely et al., 2009) or only for marginal rangeland (Schmidt et al., 2012). Using the opportunity cost approach of Schmidinger and Stehfest (2012) it can be argued that the occupation of grassland by livestock is connected with opportunity cost in terms of forgone possibility to store C by planting, e.g. energy forest. However, this argument may not be valid for many places in Germany where grassland provides important ecosystem services (Flessa et al., 2012; IEEP, 2009). If it is desired by society to keep grassland sustained, then livestock production is the only economic possibility to preserve grassland for human nutrition (IEEP, 2009). Cereal-fed livestock systems are more efficient in terms of total feed conversion efficiency (kg cereals consumed/kg of animal weight gain) (Garnett, 2009). However, efficiencies of energy and protein on the basis of human-edible food produced per unit of human-edible feed consumed per animal are higher for ruminants than for monogastric animals (Gill et al., 2010). The study of the deterministic model approach showed that demand for grassland decreases with increasing milk yield/cow due to a higher demand of energy content per kg dry matter intake. Thus, the proportion of human-edible feed sources in the ration increases (compare Paper I). Comparable to weighting differences of beef output from different dairy cow production systems in terms of GHG emissions, the evalutation of differences in land use is always ongoing with a high uncertainty and assumptions on current and future land use changes and demand. However, consideration of differences in land use in GHG modelling can give insight if changes in production systems can results in possible leakage effects due to changes in land use. Thus, when comparing GHG emission of different dairy or beef production systems it is important to clearly identify and report the amount and type of land occupation in order to provide indication of possible leakage effects.

The Life Cycle Assessment Method

Modelling of GHG emissions in the studies of this thesis is mainly based on LCA guidelines which are also applied by many studies modelling GHG emissions from dairy cow or beef production systems (O'Brien, 2012a, b; Thomassen et al., 2008). "Life Cycle Assessment is a tool to assess the potential environmental impacts and resources used throughout a product's [goods and services] life-cycle, i.e., from raw material acquisition, via production and use phases, to waste management" (Finnveden et al., 2009). The method of LCA is standardized according to ISO 14040 and 14044 (ISO, 2006a, b) and provides an important basis for undertaking an LCA study but is not specified to certain products such as milk and beef production. There are four phases in an LCA study: Goal and Scope definition (includes the reasons for carrying out the study, the intended application, and the intended audience, functional unit and system boundary); Life Cycle Inventory Analysis (collection of data and calculation of environmental impact, e.g. GHG emissions per functional unit); and Interpretation (results from the previous phases are evaluated in relation to the goal and scope in order to reach conclusions and recommendations)

(Finnveden et al., 2009; Flysjö, 2012a). Two main types of LCA can be distinguished in modelling GHG emissions i.e. attributional and consequentional LCA, even though the line between the two approaches is not always clear in many LCA studies (Flysjö, 2012a). Attributional LCA (ALCA) is defined "by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems" (descriptive approach). Average data for a system are chosen to represent the average environmental burdens for producing a unit of a product. Consequential LCA (CLCA) is defined "by its aim to describe how environmentally relevant flows will change in response to possible decisions" (change-oriented approach). Marginal data are chosen to represent the effects of a small change in the output of a product from a system on the environmental burdens of the system (Finnveden et al., 2009, for a detailed description of CLCA compare Weidema et al., 2009). Audsley et al. (2009) states that ALCA is useful for allocating responsibility for e.g. GHG emissions. This should be based as closely as possible on the "causal relationship between the emissions and the entity to which they are allocated". It helps to identify "hot-spots" of GHG emissions in the life cycle of a product and thus possible mitigation options (Audsley et al., 2009). However, it does not show the full complexities and consequences of accessing a GHG mitigation option. Identified options should be investigated further to determine the full consequences of a change in e.g. production system. This requires a CLCA approach.

In the studies of this thesis an ALCA approach was undertaken to model GHG emissions from various dairy cow production systems. This means that e.g. the calculation of GHG emissions from energy mix is based on the emission factor of the current energy mix. In the case of CLCA, the energy mix that provides one additional unit of energy would have to be figured out. The methods to account for co-products in dairy farming can also be distinguished in terms of ALCA and CLCA approach. Whereas the allocation of GHG emissions between milk and co-product is a typical ALCA approach, the method of system expansion is preferably used in CLCA approaches. In case of system expansion it is assumed that the consequences of an increase or decrease in beef output from dairy farming is a decrease or increase in beef supplied from suckler cow production systems. This example shows that CLCA modelling is based on often highly uncertain assumptions (e.g. future trend in beef consumption). The ranking of GHG intensity of studied dairy cow production systems is based on the undertaken approach to account for co-products. Consequential LCA should be preferably used for decision making but not when the uncertainties in the CLCA approach outweigh the insight gained from it (Finnveden, 2009). Despite the high uncertainty, the CLCA approach adopted in the case of co-product handling in this study gave important insight into possible GHG leakage of increasing milk yield as an option to reduce GHG emissions from dairy cow production. Even though not investigated for the production systems of this thesis, Schmidt and Dalgaard (2012) showed that the choice of method (ALCA or CLCA) in terms of handling indirect land use change has a high impact on GHG emissions from dairy cow production. For a detailed description of the differences between ALCA and CLCA in modelling GHG emissions from dairy cow production compare Schmidt and Dalgaard (2012) and Thomassen et al. (2008).

Several limitations of GHG modelling based on LCA approach are mentioned in literature (Finnveden et al., 2009) and also apply to this study:

(1) GHG modelling based on LCA is very data intensive, and lack of data can limit the conclusions that can be drawn from a certain study (e.g. lack of site specific data on GHG emissions from soil investigating commercial dairy farms, data on manure storage or management systems of investigated commercial dairy farms in this thesis). In the second study of the stochastic model approach (Paper III) uncertainty of main model parameters was classified. It was shown that the emission factor for N_2O from nitrogen input into the soil incorporates time- and site-specific uncertainty. The uncertainty of the emission factor for N_2O emissions from nitrogen input into the soils had a high impact on GHG emission outcomes of modelled dairy cow production systems. A high sensitivity of model outcomes on N_2O emissions was also found by several other studies in literature (Flysjö et al., 2011; Tuomisto et al., 2012). In certain regions or soils, N_2O emissions can be extremely high. For these soils or regions outcomes of this study might be different due to changes in N_2O emissions of nitrogen input into the soil. Due to lack of site-specific data average emission factors for N_2O emission from nitrogen input into the soil are chosen in most studies modelling GHG emissions from dairy or beef production systems. However, site-specific emission factors could help to identify the production systems that best suit the specific region or soil.

(2) Not all types of impacts are well covered in a typical LCA. In this study only the impact on GWP and land use of different dairy cow production systems was investigated. A full LCA would include further impact assessments as e.g. eutrophication and acidification. In further studies trade-offs with other environmental aspects (Finkenbeiner, 2009) would provide further important

information on the environmental soundness of dairy and beef production systems. Additionally, further environmental impacts exist which are not yet fully established in LCA approaches (e.g. biodiversity).

Mitigation Costs

The first two steps on the way to reduce GHG emissions from dairy cow production are to identify GHG mitigation options and the potential of these options to reduce emissions. With regard to the choice between different options of mitigating GHG emissions, it is of special importance to identify those options which are the most economically efficient. The cost-effectiveness of different GHG mitigation options is measured e.g. by comparing costs and GHG emissions of a basis scenario with costs and GHG emissions of the mitigation option (Moran et al., 2011). Results of our study showed that considering the system boundary of the dairy farm gate GHG emissions and costs per kg of milk decreased with increasing milk yield/cow (Table 6). This result agrees with Thomassen et al. (2009) who found a high negative correlation of GHG emissions per kg of milk and labour productivity mainly affected by annual milk production per cow. Moran et al. (2011) calculated a cost effectiveness of 224£/t CO_2-eq for the use of bovine somatotropin in UK dairy farms due to an increase in milk yield/cow. This means that GHG mitigation in that case even decreases costs of milk production. However, it has to be considered that "The failure of livestock producers to carry out farm-management changes that would generate emissions reductions at a net profit may indicate attitudinal and social barriers to changing farming practices" (Cooper et al., 2013). These costs need to be identified to implement GHG abatement options in dairy farming. Results of this thesis also showed that comparing cost-effectiveness of GHG mitigation options, considering the system boundary of the dairy farm gate does not account for the close interlink of milk and beef production and can thus result in possible leakage of GHG emissions. The limitations of calculating GHG abatement costs considering the system boundary of the dairy farm gate are summarized and discussed by Moran et al. (2011): (1) agricultural systems are biologically complex and incorporate a high epistemic and variability uncertainty; (2) improvements due to changes in one system can affect emissions elsewhere due to leakage effects; (3) models do not include all external benefits and costs in the calculation of GHG abatement costs.

Ignoring external costs and benefits when evaluating abatement costs can lead to recommendations for a particular production system that omits potentially important economic, social and environmental knock-on effects (Bockel et al., 2012; Siebert, 2008). Therefore, Bockel et al. (2012) suggests the creation of an externality assessment matrix to evaluate different GHG abatement options. An externality of higher-yielding dairy cow production systems is e.g. the management ability of the farmer: higher milk yields place high demands on the management abilities of farmers (Roemer, 2011). Further examples relevant to lower-yielding dairy cows relate to animal welfare and nutrition: a lower milk yield has a positive effect on fertility and vitality of dairy cows (animal welfare), low-yielding cows are able to utilize high fibre and low nutrient diets, which means lower competition with human nutrition, and generally results in lower nutrient surplus on a per-farm basis (due to lower concentrate intake) (Knaus, 2009).

Instead of calculating mitigation costs the real question is, which systems have highest profits when emissions are costed (anonymous reviewer)? This question could be answered by assuming a C tax on GHG emissions of milk and beef production. Assuming that all GHG emissions of dairy farms are allocated to milk, a possible C tax would favour higher-yielding dairy cow production systems because of lower GHG emissions per kg of milk. Thus, a further incentive would be given to favour higher-yielding dairy cow production systems. If a C tax is also established on beef production systems the price of calves from suckler cow production systems would increase, as they are burdened with a high amount of GHG emissions whereas calves from dairy cow production systems are not burdened with any costs from GHG emissions. Thus, the price of calves and beef from dairy farms could increase. Depending on the amount of calves produced per kg of milk, the fattening characteristics of calves, the changes in beef demand profitability of lower-yielding dairy cow production systems could increase.

Figure 4 showed that assuming a carbon tax of 100 €/tonne CO_2-eq would result in an increase in total costs of the 10,000 kg Holstein-Friesian-system which is higher when compared to the 8,000 kg Fleckvieh-system. Again it has to be considered that this result depends highly on model assumptions.

The studies of this thesis mainly focused on the identification of GHG mitigation options and possible GHG emission leakage related to production traits in dairy farming. Further studies should focus on cost-effectiveness and externalities of studied GHG mitigation options.

Environmental Impact on a Macro Level

In the studies of this thesis the amount of GHG emissions per unit of product (milk and beef) was investigated for different dairy cow production systems. This can be considered as the technology part of the IPAT formula which gives insight into the overall (macro level) impact of human activities on the planet and the natural environment (Belz and Peattie, 2013). The overall environmental impact (I) of different human activities is the result of three factors: population (P), consumption per person (affluence, A) and technology (T). Thus, it has to be considered that technology is just one part of the overall environmental impact and that there might be interaction between technology and population or affluence (Belz and Peattie, 2013). The possible interaction between technology and affluence is defined in literature as rebound effect (Druckman, 2012). The rebound effect "deals with the fact that improvements in efficiency often lead to cost reductions that provide the possibility to buy more of the improved product or other products or services" (Thiesen et al., 2008). Thus, the reduction of e.g. GHG emissions per kg of milk or beef can be - partly or completely - offset by an increase in demand due to lower cost per kg of milk or beef. The increase in economic activity deriving from saving in costs is also likely to increase the demand for other products or resources. General equilibrium models or the incorporation of marginal consumption in consequential LCA studies can provide first insights into such rebound effects (Finnveden et al., 2009; Thiesen et al., 2008).

Conclusions and Outlook

The first research objective aimed to identify the impact of increasing milk yield/cow within a confinement feeding and housing regime on GHG emissions. Results found in this thesis depended highly on the underlying assumptions on system boundaries. Increasing milk yield/cow resulted in lower GHG emissions per kg of milk at the dairy farm gate when reduction in beef production was not accounted for. However, model outputs showed that this would not be the case, if beef production is intended to be constant and milk yield/cow increases. If the increase in milk yield was ongoing with a change in breed, an increase in GHG emissions was observed. Additionally, both demand for grass and arable land increased with increasing milk yield and a constant amount of milk and beef production, which might have further impact on GHG emissions. If the current trend in the demand for milk and beef remains at the same level in Germany and other European countries, a holistic approach will be required to evaluate whether further increasing milk yield/cow is a valid strategy to mitigate GHG emissions or not. Regarding the modelled GHG and land use efficiency, the ongoing specialization in both milk and beef production has to be questioned. The extent to which total GHG emissions increase with increasing milk yield/cow greatly depends upon the amount of beef that has to be compensated for and upon the kind of meat (beef, pork or poultry) which compensates for beef reduction as a co-product from dairy cows. Methods such as system expansion assume that beef from dairy cow production systems (culled cows, fattening of surplus calves) is needed on the market and will replace beef from suckler cows. The lack of data relating to which suckler cow beef production system should be chosen to credit beef production from dairy cow production systems gives a high degree of variation in results. Information where beef would come from, if it was not produced as a co-product from dairy cow production would be needed. These data are difficult to determine at a regional or international level. Further studies could determine how a change in the ratio of milk to beef demand and the demand for high quality beef would influence study outcomes. Concerning both milk and beef production at regional and global levels, this result should help policy and decision makers to find appropriate measures to mitigate GHG emissions from milk and beef production. Greenhouse gas abatement policies e.g. carbon taxes, or agri-environmental policies need to capture both milk and beef production systems to avoid GHG emission leakages.

The amount and type of land use per kg of milk was investigated for various dairy and beef production systems. However, possible impacts of differences in the amount of land use on GHG emissions, due to indirect land use change, were not evaluated. Higher-yielding dairy cow production systems are more reliant on arable land and high-quality grassland because of the demand for feed with high energy content. As the amount of arable land is limited, (conversion of grassland to arable land is not allowed or possible in many regions) and products from arable land can directly be consumed by humans, a special focus should be given to the differences in type of land use and different feed qualities between various dairy cow production systems in order to avoid negative effects on food security.

Stochastic model approaches showed that uncertainty in GHG emissions from land use change in the case of soybean meal production had a large single impact on variation of total GHG emissions especially within high-yielding dairy cow production systems. However, the inclusion of direct land use change from soybean meal production is just a first approach and does not account for opportunity costs of land use or indirect land use change. Furthermore, the aspect of time was not included in this study when calculating GHG emissions from land use change. Emissions from land use change occur over a period of time with a decreasing amount of emissions per year (Poeplau et al., 2011). The interrelationship between dairy and beef production and GHG emissions from land use and land use change should be focused on future research, including the differences in type and quality of land and the aspect of time.

Uncertainty of N_2O emissions from nitrogen input into the soil was also shown to have a high impact on variation of GHG emissions. This variation stems from uncertainties predicting N_2O emissions (epistemic uncertainty) but also from inherent variability of N_2O emissions over time and space. The uncertainty of predicted GHG emissions can be reduced by increasing the precision in predicting N_2O emissions. However, this additional information does not reduce GHG emissions itself. Knowing site specific variability of N_2O emissions can help to reduce GHG emissions by specific management (e.g. reduced soil compaction, adopted manure management, choice of suitable crops). On fields or sites with high N_2O emissions the focus should be less to find the optimal dairy or beef production system and more to apply land use systems, which could reduce N_2O emissions on these sites.

In the study of commercial dairy farms the main objective was to identify the relative importance of production traits on variation of GHG emissions, beef output and land use of dairy farms. Even though GHG emissions/kg of milk was significantly lower for West-Holstein-Friesian dairy farms, variation between farm groups was low compared to within group variation. This indicates a higher potential to improve GHG emissions/kg of FPCM within investigated production systems compared to changing production modes. Milk yield and replacement rate were identified as the most important variables explaining variation of GHG emissions. However, achieving low replacement rates in high-yielding dairy herds requires "better feeding, healthier cows, and better reproductive management" (Lucy, 2001) and optimal husbandry conditions. Thus, to mitigate GHG emissions of high-yielding dairy farms, the focus should be on optimisation of milk yield and replacement rate rather than solely focusing on increasing milk yield/cow.

Potential beef output and land use per kg of milk were calculated for each farm to evaluate the risk of possible GHG emission leakage. South-Fleckvieh dairy farms showed considerable higher potential beef output compared to West-Holstein-Friesian dairy farms. Although, MLR models showed increasing milk yield/cow and reducing replacement rates resulted in lower GHG emissions/kg of milk, the opposite effect was observed for potential beef output. Thus, there was a trade-off with potential beef output/kg of milk. However, this result was very sensitive to assumptions made to calculate potential beef output, e.g. characteristics of beef fattening systems. Further possibilities do exist to increase potential beef output/kg of milk from dairy farms which were not investigated in this study. This includes the production of calves from heifers entering fattening systems, higher weights of fattening bulls and heifers, reducing the proportion of calves sent to calf fattening systems or the use of sexed semen.

In the cases where trade-offs occur between GHG emissions, potential beef output and land use per kg of milk, it needs to be considered that GHG emission leakage could occur. This is of special importance when implementing GHG mitigation policies. In a search for GHG mitigation options those parameters should be focused on which do not have an impact on the other indicators e.g. dry matter intake efficiency, nitrogen use efficiency or calving interval. However, our study showed that these parameters are less important compared to milk yield and replacement rate and provide less potential to reduce GHG emissions.

Only confinement dairy cow production systems with cows kept indoors all year round were studied in this thesis. Because of the strong interrelationship between dairy cow production, land use through feed requirement and GHG emissions, differences in type and quality of feed should be focused on in further studies. It is also important to identify the costs of different GHG mitigation options in agriculture to make them comparable to options of different industry sectors. Furthermore, it has to be considered that climate change is not the only key environmental issue. Many GHG mitigation options will touch on other environmental issues such as soil degradation, resource scarcity and biodiversity or animal welfare, which need to be considered in developing sustainable dairy and beef production systems.

Some key conclusions from the studies of this thesis for different stakeholders are summarized in the following:

Farmers: the high variability within production systems indicates the possibility to improve GHG emissions at the dairy farm level. It is important for farmers to consider the interrelationships and side effects of individual production trait improvements, e.g. increase in milk yield/cow requires higher attention to herd management to avoid negative impacts on longevity. It is also important to provide information to farmers as to whether a reduction in GHG emissions on the farm could result in increased emissions from other systems (e.g. if improvement in GHG emissions/kg of milk is accompanied by a decrease in dairy beef output). Those parameters should be focused on that provide net improvements, e.g. dry matter intake efficiency or nitrogen use efficiency.

Policy-makers: If GHG abatement policies are to be developed for livestock production systems, milk and beef production systems need to be investigated beyond the typical system boundaries of the farm gate. The interrelationship of milk and beef production and land use need to be considered to avoid a shift of GHG emissions from one sector or country to another.

Scientists: due to high uncertainties when predicting GHG emissions from dairy cow and beef production systems, it is important to clearly present underlying methods used. Applying system analysis, it is important to identify and show interrelationships within and between different systems. A single focus on GHG emissions of different dairy cow production systems is problematic because of various other sustainability impact categories (e.g. biodiversity, economic sustainability). Trade-offs and synergies between the diverse impact categories need to be studied to take a further step towards sustainable milk and beef production systems.

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Appendix: Research Papers

Paper I

Zehetmeier, M., Baudracco, J., Hoffmann, H. and Heissenhuber, A., 2012. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. Animal. 6 (1), 154–166.[3]

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[3] The first author conducted the modelling, analysed and discussed the results. She composed the tables and graphs, wrote the first complete draft of the paper and revised the paper.

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Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach

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Milk yield per cow has continuously increased in many countries over the last few decades. In addition to potential economic advantages, this is often considered an important strategy to decrease greenhouse gas (GHG) emissions per kg of milk produced. However, it should be considered that milk and beef production systems are closely interlinked, as fattening of surplus calves from dairy farming and culled dairy cows play an important role in beef production in many countries. The main objective of this study was to quantify the effect of increasing milk yield per cow on GHG emissions and on other side effects. Two scenarios were modelled: constant milk production at the farm level and decreasing beef production (as co-product; Scenario 1); and both milk and beef production kept constant by compensating the decline in beef production with beef from suckler cow production (Scenario 2). Model calculations considered two types of production unit (PU): dairy cow PU and suckler cow PU. A dairy cow PU comprises not only milk output from the dairy cow, but also beef output from culled cows and the fattening system for surplus calves. The modelled dairy cow PU differed in milk yield per cow per year (6000, 8000 and 10 000 kg) and breed. Scenario 1 resulted in lower GHG emissions with increasing milk yield per cow. However, when milk and beef outputs were kept constant (Scenario 2), GHG emissions remained approximately constant with increasing milk yield from 6000 to 8000 kg/cow per year, whereas further increases in milk yield (10 000 kg milk/cow per year) resulted in slightly higher (8%) total GHG emissions. Within Scenario 2, two different allocation methods to handle co-products (surplus calves and beef from culled cows) from dairy cow production were evaluated. Results showed that using the 'economic allocation method', GHG emissions per kg milk decreased with increasing milk yield per cow per year, from 1.06 kg CO_2 equivalents (CO_{2eq}) to 0.89 kg CO_{2eq} for the 6000 and 10 000 kg yielding dairy cow, respectively. However, emissions per kg of beef increased from 10.75 kg CO_{2eq} to 16.24 kg CO_{2eq} due to the inclusion of suckler cows. This study shows that the environmental impact (GHG emissions) of increasing milk yield per cow in dairy farming differs, depending upon the considered system boundaries, handling and value of co-products and the assumed ratio of milk to beef demand to be satisfied.

Keywords: milk yield, dairy cow, greenhouse gas emissions, beef production, co-product

Implications

If the current trend in the demand for milk and beef remains at the same level in Germany and other European countries, a holistic approach will be required to evaluate whether increasing milk yield per cow is a valid strategy to mitigate greenhouse gas (GHG) emissions. The approach used in this study accounts for GHG emissions associated not only with milk production, but also with beef production. This study shows that if both milk and beef production are to remain constant, considerably increasing milk yield per cow could result in higher GHG emissions.

Introduction

Increasing milk yield per cow in dairy farms has been proposed as one strategy to reduce greenhouse gas (GHG) emissions in agriculture, as less cows are needed to produce the same amount of milk (Monteny *et al.*, 2006; Steinfeld and Wassenaar, 2007; Smith *et al.*, 2008). As methane (CH_4) from enteric fermentation contributes to approximately 50% of total GHG emissions in dairy farms (Hörtenhuber *et al.*, 2010), reducing the number of cattle seems to be the main strategy to reduce GHG emissions. CH_4 emissions related to milk yield (g CH_4/kg milk) decline as milk yield per cow increases (Flachowsky and Brade, 2007). However, the strategy of increasing milk yield per cow to mitigate GHG emissions

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is focused only on emissions related to milk production, and therefore, it does not consider the amount of GHG emissions associated with beef production as a co-product. If a constant demand for beef is to be met, the loss of beef production due to less dairy cows has to be compensated for by increasing the number of suckler cows (Martin and Seeland, 1999).

The quota system for milk production in the European Union (EU), including Germany, together with the continuous increase in milk yield per cow have resulted in less total dairy cows producing a similar total amount of milk, with a reduced amount of beef produced as a co-product of the dairy system (von Witzke and Noleppa, 2010). In the season 1999 to 2000, the 27 EU member countries (EU-27) had a net trade (export minus import) of 0.37 million tons of bovine meat and a net trade of 2.3 million tons of dairy products. By the season 2008 to 2009, although dairy products' net trade remained relatively constant (2.2 million tons), the EU-27 changed from being a net exporter to a net importer of 0.15 million tons of bovine meat (Eurostat, 2010). Thus, self-sufficiency for beef decreased from 104% in 1999 to 98% in 2008 (Weiß and Kohlmüller, 2010).

Cederberg and Stadig (2003) estimated that approximately 50% of European beef production is a co-product of the dairy sector. In Germany, approximately 70% of total beef production can be considered a co-product of the dairy sector (own calculations according to Weiß and Kohlmüller, 2010). Milk yield per cow per year has increased from 6700 to 9300 kg in the United States and from 4900 to 6600 kg in Germany between 1990 and 2009 (Food and Agriculture Organization of the United Nations Statistics (FAOSTAT), 2010). With increasing milk yield per cow, milk and beef production tend to be more independent. High specialization of milk and beef production can be observed in the United States where the share of beef cows of total cows is approximately 78% (United States Department of Agriculture (USDA), 2010). However, in some regions of the world, such as Southern Germany, Austria and Switzerland, beef production as a co-product of the dairy sector still plays an important role, with dual-purpose cows as a key component.

The objective of this study was to determine the effect of increasing milk yield per cow on total GHG emissions, land use and economic performance for German dairy systems under two different scenarios: constant milk but decreased beef output (Scenario 1); and constant milk and beef output (Scenario 2). The originality of this study comes from its holistic approach, which integrates dairy and beef production to estimate GHG emissions.

Material and methods

Model overview

A model was developed, using MSExcel®, to estimate the effects of increasing milk yield per cow on GHG emissions and on side effects such as milk and beef production, feeding costs, type of land use and labour. The model incorporates several animal production systems for milk and beef production, as well as the cultivation of agricultural land needed to provide feed to the animals. The model makes all calculations based on production units (PUs) to connect milk and beef production. Two types of PU were defined (Figure 1), namely dairy cow PU (DU) and suckler cow PU (SU). A DU is defined as a dairy cow that produces milk and beef. Beef production comes not only from cull cows but also from fattening of surplus heifers, bulls and cull calves. Three types of DU were simulated by changing the breed and the level of milk yield as follows:

(i) Milk yield of 6000 kg/cow per year using dual-purpose Fleckvieh (FV) cows (DU-6).

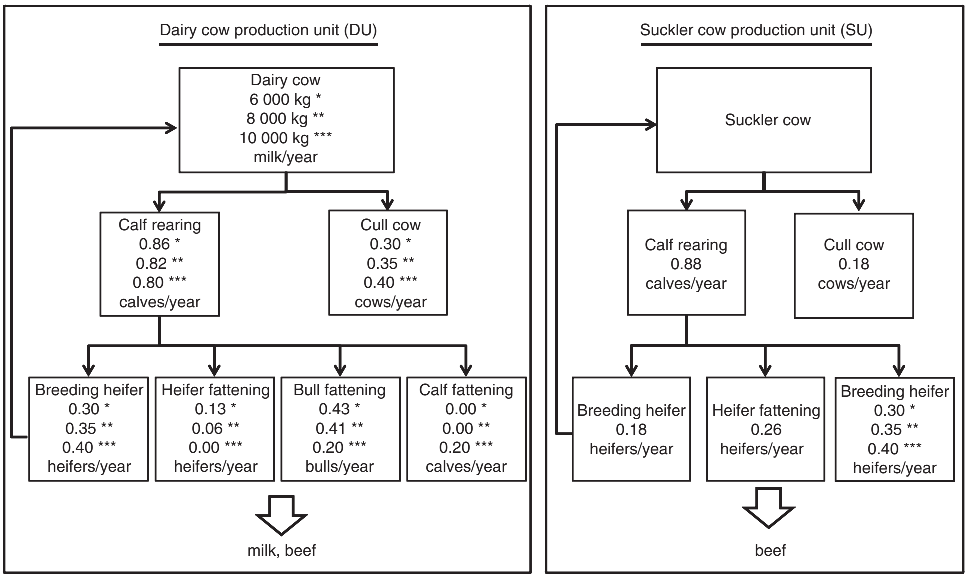

Figure 1 Diagrammatic representation of the dairy cow production unit (DU) and the suckler cow production unit (SU). Calves per cow per year were calculated taking into account assumptions for calving interval and calf losses due to diseases of 8%; the same number of stars means that the animals belong to the same production unit.

Table 1 *Production and management assumptions considered for the modelled animals*

	SU	DU-6	DU-8	DU-10
Calving interval of dairy cow (days)[a]	385	393	408	423
Replacement rate of dairy cow (%)	0.175[e]	0.30	0.35[b]	0.40
Final weight (kg/animal) for fattening animals (dressing out in %)				
Culled cows	660[e] (51)[d]	720[c] (51)[d]	690[c] (48)[d]	
Bull fattening	700[d] (58)[d]	700[d] (58)[d]	600[d] (56)[d]	
Calf fattening			180[e] (54)[d]	
Heifer fattening	550[e] (54)[d]	550[e] (54)[d]	500[e] (52)[d]	
Feed intake (kg DM/animal per year; composition in %)				
Suckler cow/dairy cow[f]	4809*	6058**	6870**	7608***
Grass silage	31	46	39	32
Maize silage	0	34	28	24
Pasture	52	0	0	0
Hay	13	9	8	7
Concentrates	4	11	25	37
Heifer rearing[g] (kg DM/animal per rearing period; composition in %)	3909*	5615**		5624***
Grass silage	58	52		52
Maize silage	0	34		34
Pasture	29	0		0
Hay	12	8		8
Concentrates	1	6		6
Bull fattening[h] (kg DM/animal per fattening period; composition in %)	2880*	3607**		3467***
Maize silage	66	62		61
Hay	3	5		5
Concentrates	31	33		34
Calf fattening[h] (kg DM/animal per fattening period; composition in %)				227***
Milk replacer				100
Heifer fattening[g] (kg DM/animal per fattening period; composition in %)	2323*	3248**		
Grass silage	33	39		
Maize silage	53	46		
Hay	0	1		
Concentrates	14	14		

SU = suckler cow production unit; DU = dairy cow production unit.

[a] Haenel (2010).

[b] ADR (2010).

[c] Haiger and Knaus (2010).

[d] Landeskuratorium der Erzeugerringe für tierische Veredelung in Bayern unpublished results.

[e] KTBL (2008).

[f] Including calf rearing till *270 to 290 kg; **85 kg; *** 50 kg.

[g] Initial weight heifer rearing/fattening: * 270 kg, ** 85 kg, *** 50 kg.

[h] Initial weight bull/calf fattening: * 290 kg, ** 85 kg, ***50 kg.

(ii) Milk yield of 8000 kg/cow per year using dual-purpose FV cows (DU-8).

(iii) Milk yield of 10 000 kg/cow per year using Holstein–Friesian (HF) cows (DU-10).

Assumptions for milk and beef production in the model were chosen to represent typical German production systems. Average recorded milk yield of German dairy cows in 2009 was 7980 kg milk/cow per year (Arbeitsgemeinschaft Deutscher Rinderzüchter (ADR), 2010). Thus, the three types of cows simulated represent the average situation of milk yield per cow per year in Germany (8000 kg), a situation with lower milk yield than the average (6000 kg milk/cow per year) representing average dual-purpose dairy cows and a situation with greater milk yield (10 000 kg milk/cow per year) than the average, representing HF dairy herds. It is assumed that all surplus calves from DU-6 and DU-8 are fattened as bulls or heifers, whereas 50% of bull calves from DU-10 were assumed to be fattened as calves, given the breeds used in each case.

As shown in Figure 1, SU includes the suckler cow and the associated animal categories: heifer rearing, bull and heifer fattening. FV was chosen as the breed for the modelled SU, because it is one of the most important breeds for suckler cow production systems in Germany. Beef output from culled cows, bulls and heifers fattening is calculated for the SU.

Production and management data used in the model

Animal production. Management and production assumptions for the modelled PU are shown in Table 1. Higher replacement rates for higher yielding dairy cows were assumed, in order to account for the higher replacement rate reported for

Table 2 *Production and management assumptions considered for the modelled feed production*

	Grass silage (4/3 cuts)	Maize silage	Hay	Pasture	Winter wheat	Barley	Corn	Soyabean meal[a]
Yield (tonne DM/ha)	8.6/7.2	14.0	6.8	6.0	6.4	5.1	8.5	1.9
Energy (MJ NEL/kg DM)	6.05/5.94	6.45	5.12	5.92	8.51	8.08	8.39	8.63
Energy (MJ ME/kg DM)	10.12/9.98	10.70	8.83	9.97	13.37	12.84	13.29	13.75
Protein (CP/kg DM)	169/163	81	115	150	138	124	106	510
Diesel (l/ha)	118/90	111	106	24	88	83	82	
Seeds (kg/ha)	8/0	33	0	0	169	151	33	
Peticides (kg/ha)	2/0	5.1	0	0	4.1	2.9	5.1	
Lime (kg CaO/ha)	150/150	400	150	150	400	400	400	

DM = dry matter; NEL = net energy lactation; ME = metabolizable energy.
[a]average yield of soyabeans during 2004 to 2008 from USA, Brazil, Argentina (FAOSTAT, 2010); characteristics of soybeans: 87% DM, 20.8% oil (Dalgaard *et al.*, 2008).

systems with higher milk yield per cow per year (Lucy, 2001; Dillon *et al.*, 2006). Age at first calving was set at 27 months for all replacement heifers included in the model.

Dairy cows, replacement heifers, bulls and heifers for fattening were assumed to be indoor all-year-round. Forage composition for all modelled dairy cows was set to represent a common German feeding system (Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL), 2008), with 50% grass silage, 40% maize silage and 10% hay. Total dry matter intake (DMI) and the proportion of concentrates in dairy cows ration were calculated in order to satisfy requirements for metabolizable energy and crude protein (CP; Gesellschaft für Ernährungsphysiologie (GfE), 2001), accounting for limitation on DMI (Gruber *et al.*, 2006). The equation used to predict DMI was built and validated by Gruber *et al.* (2006), using a data set comprising 2264 dairy cows from different research institutes and breeds in Germany, Austria and Switzerland. Gruber *et al.'s* (2006) equation takes into account the following parameters: breed, country, live weight, milk yield, amount of concentrates fed, metabolizable energy content of forage and the ratio of CP to energy in the diet. Feed rations for calf and heifer rearing, suckler cows, bull and heifer fattening were calculated to satisfy required CP and metabolizable energy (GfE, 1995 and 2001) based on common German production systems (Deutsche Landwirtschafts-Gesellschaft (DLG), 2005; KTBL, 2008) (Table 1). Suckler cows and associated replacement heifers were assumed to be on pasture for 185 days/year from mid-April to mid-October and were housed in straw-based systems for the rest of the year.

Concentrate composition for all modelled animals was assumed to be made up of wheat, barley and soyabean meal. For the 10 000 kg yielding dairy cow, corn was supplemented as a slow digestible carbohydrate.

It is assumed that surplus male and female calves from modelled FV dairy cows (6000 and 8000 kg yielding dairy cows) are passed to bull and heifer fattening at a weight of 85 kg, and calves from the modelled HF dairy cow (10 000 kg yielding dairy cow) at a weight of 50 kg, representing German production systems (Brüggemann, 2011).

Forage and crop production. Model assumptions used for forage and crop production are shown in Table 2. Feed quality values were taken from DLG feed tables (DLG, 1997). Information about quantities of lime, pesticide, seed and diesel input used in forage and crop production (Bayerische Landesanstalt für Landwirtschaft (LfL), 2006; KTBL, 2008) were necessary for the calculation of GHG emissions and are shown in Table 2.

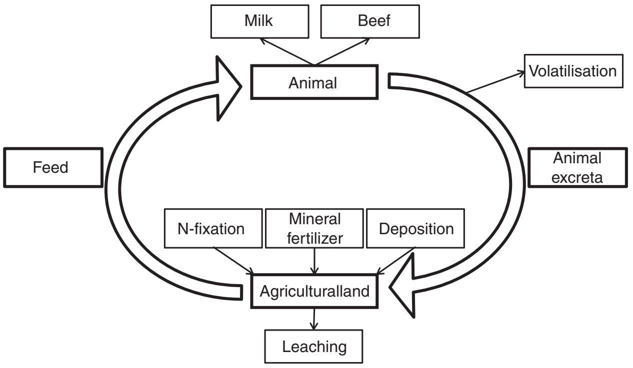

Figure 2 Diagrammatic representation of the nitrogen (N) cycle incorporated in the model

The nitrogen (N) cycle plays an important role in the calculation of GHG emissions in cattle production systems. On the one hand, excreted N can be used as fertilizer for forage and crop production, which in turn reduces the amount of purchased mineral fertilizer. On the other hand, it is a source of direct (manure storage, N_2O emissions from soils due to manure input) and indirect (ammonia volatilization and nitrate leaching) N_2O emissions (Olesen *et al.*, 2006). N content in animals' excreta was calculated according to DLG (2005). Thus, excreta-N was calculated as the difference between N intake from forage and concentrates and N retained as animal products (i.e. milk and live weight gain). The available manure from animals was assumed to be applied on the land used for forage and crop production according to 'good agricultural practice' (LfL, 2007) with the exception of land used for soyabean meal production as soyabean meal was assumed to be imported. In the forage and crop production areas, a soil N balance was calculated as the difference between N inputs (manure application, deposition and fixation) and N output (N in the crop harvested, losses through nitrate leaching and ammonia volatilization) (Figure 2). N fixation was assumed to be 50 kg N/ha per year for grassland-3 cuts, hay and pasture, and 30 kg N/ha per year for grassland-4 cuts. The N required to equalize inputs and outputs was assumed to be added as mineral fertilizer. Phosphate and potassium balance were calculated using a similar procedure to the N balance.

Economic calculations for the costs of forage production were mainly based on data from LfL (2006) and KTBL (2008). Full cost accounting includes all variable and fixed costs of average German forage production. Prices for wheat, barley, corn and soyabean meal were 132 €/tonne, 128 €/tonne, 141 €/tonne and 257 €/tonne, respectively, based on 5-year average market prices (2005 to 2009; Schaack *et al.*, 2010).

Calculation of GHG emissions

Calculations of GHG emissions in the model were made for primary and secondary sources of CH_4, N_2O and CO_2 emissions. Primary sources of GHG emissions are those occurring on-farm during feed production, maintenance of animals and manure management. Secondary sources of GHG emissions include emissions occurring off-farm, for instance, those generated during production of fertilizer, pesticides or diesel (Rotz *et al.*, 2010). In order to standardize, all gases are expressed as CO_2 equivalents (CO_{2eq}). The global warming potential is calculated according to Intergovernmental Panel on Climate Change (IPCC, 2007), set at 25 kg CO_{2eq}/kg of CH_4 and 298 kg CO_{2eq}/ kg of N_2O (100-year horizon). Emissions from the production of capital goods such as buildings and machinery are not accounted for following recommendations from the British Standards Institution (BSI, 2008).

Primary source GHG emissions

Primary source emissions considered in the model comprise CH_4 emissions from enteric fermentation, CH_4 and N_2O emissions from manure storage and N_2O emissions related to N input introduced into the soil. Furthermore, CO_2 emissions from liming and indirect N_2O emissions from N leaching were included in the model. Indirect N_2O emissions from ammonia volatilization were not included in the model.

Enteric fermentation. For dairy cows, CH_4 emissions from enteric fermentation were predicted according to Kirchgeßner *et al.* (1995):

$$CH_4 = 63 + 79 \times CF + 10 \times NfE + 26 \times CP - 212 \times EE \tag{1}$$

where 'CH_4' is the CH_4 release from dairy cows (g/day), 'CF' is the intake of crude fibre (kg/day), 'NfE' is the intake of N-free extract (kg/day), 'CP' is the intake of CP (kg/day) and 'EE' is the intake of ether extract (kg/day). For all other animals, CH_4 emissions from enteric fermentation were predicted according to IPCC (2006, equation 10.21):

$$CH_{4ent} = GE \times x_{CH_4}/\eta_{CH_4} \tag{2}$$

where 'CH_{4ent}' describes enteric CH_4 emissions (kg/animal per year), 'GE' is the intake of gross energy (MJ/animal per year); 'η' is the energy content of CH_4 (55.65 MJ/kg CH_4) and 'x_{CH4}' is the CH_4 conversion rate of feed energy to CH_4 (MJ/MJ). CH_4 conversion rate was assumed to be 0.065 for rearing and beef cattle and 0.02 for calves up to 125 kg live weight (Haenel, 2010).

Manure management. CH_4 and N_2O emissions from manure management occur mainly from liquid slurry and farmyard manure during storage. Standard barn and manure storage systems were assumed in the model according to KTBL (2008), with free stall barns with slatted floors for dairy cows and rearing heifers and boxes with slatted floors for bulls and heifers for fattening. Liquid slurry was stored in open slurry tanks. Calves were assumed to be bedded in straw-based systems until the weight of 125 kg. CH_4 emissions from manure storage were calculated according to IPCC (2006, equation 10.23):

$$E_{CH_4} = VS \times Bo \times 0.67 \times MCF/100 \tag{3}$$

where 'VS' is the amount of volatile solids excreted (kg/animal per year); 'Bo' is the maximum CH_4 production capacity (m^3/kg CH_4) and 'MCF' is the CH_4 conversion factor. Volatile solids were calculated on the basis of digestibility of organic matter, GE of feed intake and ash content of manure (Haenel, 2010). The ash content of manure was assumed to be 0.08 kg/kg (IPCC, 2006). The 'Bo' was assumed to be 0.24 m^3/kg CH_4 for dairy cows and 0.18 m^3/kg CH_4 for all other modelled animals (Haenel, 2010). CH_4 conversion factors of 0.1, 0.02 and 0.01 were used for slurry, farmyard manure and pasture excretion, respectively (Haenel, 2010). Calculations for N_2O emissions from manure storage were based on N excretion and an emission factor 0.005 for solid storage and slurry (IPCC, 2006, equation 10.25).

Soil N_2O and CO_2 emissions. The N_2O emissions from production of forages and crops (used to feed animals) are an important source of GHG emissions in animal production systems. Lovett *et al.* (2006) and Hörtenhuber *et al.* (2010) reported that N_2O emissions from production of forages and crops represent up to 12% of total GHG emissions from Irish and Austrian dairy farms, respectively. The N_2O emissions in this study were calculated on the basis of N input into the soil in the form of mineral fertilizer, manure and crop residues. A default emission factor of 0.01 kg N_2O-N/kg N input was used for N_2O emissions from all types of N input except N excretion of pasture cattle. Emissions due to animal excreta during grazing were calculated using an emission factor of 0.02 kg N_2O-N/kg N excreted (IPCC, 2006).

Owing to leaching, 20 kg N/ha of grassland and 30 kg N/ha of arable land were assumed to be lost each year (LfL, 2007). The input of N into surface and ground waters give rise to indirect N_2O emissions (Haenel, 2010). An emission factor of 0.0075 kg N_2O-N/kg N input was used to calculate indirect N_2O emissions from N leaching.

To avoid acidification, 150 kg CaO/ha grassland per year and 400 kg CaO/ha arable land per year were assumed to be applied (LfL, 2007). CO_2 emissions due to liming were

Table 3 *Emission factors for modelled second source greenhouse gas emissions*

Source	Emission factor (kg CO_{2eq}/unit)	Unit	Reference
Electricity production	0.605	kWh	Umweltbundesamt (2010)
Diesel production	0.374	l	Rotz *et al.* (2010)
Mineral fertilizer production			
N ($CO_2 : CH_4 : N_2O$)	7.51 (38 : 2 : 60)[a]	kg	Patyk and Reinhardt (1997)
P_2O_5 ($CO_2 : CH_4 : N_2O$)	1.18 (95 : 4 : 1)[a]	kg	Patyk and Reinhardt (1997)
K_2O ($CO_2 : CH_4 : N_2O$)	0.67 (93 : 5 : 2)[a]	kg	Patyk and Reinhardt (1997)
Seed production			
Grass	1.94	kg	Ecoinvent (2007)
Maize	2.05	kg	Ecoinvent (2007)
Winter wheat	0.64	kg	Ecoinvent (2007)
Barley	0.47	kg	Ecoinvent (2007)
Pesticides	5.37	kg	Biskupek *et al.* (1997)
Milk replacer	2.10	kg	Neufeldt and Schäfer (2008)
CaO	0.12	kg	Patyk and Reinhardt (1997)
Soyabean meal production	0.34	kg	Dalgaard *et al.* (2008)

CO_{2eq} = kg CO_2 equivalents.
[a] The data in brackets are percentages of total CO_{2eq}.

assumed to be 0.785 kg CO_2/kg CaO input (Patyk and Reinhardt, 1997). The emission factor from diesel consumption was set at 2.637 kg CO_{2eq}/kg diesel (Rotz *et al.*, 2010).

Secondary source GHG emissions

Emissions occurring during the production of electricity, diesel, mineral fertilizer, crop seeds and soyabean meal (which was assumed to be produced off-farm) were estimated and integrated into the model using the emission factors shown in Table 3. Electricity required for milking-related activities was set at 0.056 kWh/kg milk (Kraatz, 2009), whereas electricity consumption for all other animals was calculated according to KTBL (2008). Inputs for diesel, seed, pesticide and lime consumption used in forage and crop production are shown in Table 2.

Modelled scenarios

The influence of increasing milk yield per cow per year on GHG emissions and on other side effects was analysed under two scenarios. The first was designed to keep milk production constant (1 DU-6, 0.75 DU-8 and 0.60 DU-10) while increasing milk yield per dairy cow. This results in reduced beef production as a co-product (Figure 3; Scenario 1). The second was designed to keep milk and beef production constant, adding SU to compensate for the beef production lost as the number of cows is reduced with increasing milk yield per cow (Figure 3; Scenario 2).

To determine GHG emissions per kg milk and per kg beef within Scenario 2 (constant beef), milk and beef production of the modelled PU were separated using different methods of co-product handling (Figure 4). A co-product of the dairy cow is beef from culled cows and surplus calves. According to International Organization for Standardization (ISO, 2006), different methods can be used to handle co-products when calculating GHG emissions. In this study, the 'no allocation' and the 'economic allocation' methods were used.

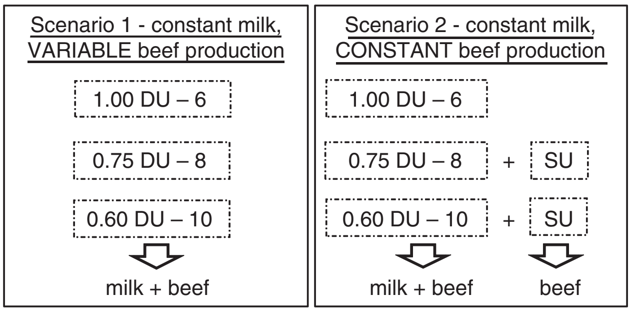

Figure 3 Considered scenarios in the modelling (DU = dairy cow production unit; SU = suckler cow production unit – see Figure 1).

'No allocation' means that all emissions occurring in the process of milk production (GHG emissions from dairy cow including replacement heifer and rearing calves) were related to milk output (left side of Figure 4). Beef production includes beef from culled cows, beef from heifer and bull fattening and from suckler cow. As GHG emissions occurring in the dairy production system were not allocated between milk and co-products, beef from culled cows and calves for bull and heifer fattening were not loaded with GHG emissions. Thus, emissions per kg beef were those occurring during bull and heifer fattening and suckler cow production.

'Economic allocation' considers the value of milk and co-products (surplus calves and beef from culled cows). In the 'economic allocation' method, GHG emissions occurring in the process of milk production are allocated to milk and co-products according to their economic value using the following equation:

$$e_m = \frac{p_m \times a_m}{p_m \times a_m + p_b \times a_b + p_c \times a_c} \tag{4}$$

where e_m is the proportion of GHG emissions allocated to milk, p_m is the price of milk (€/kg milk), a_m is the amount of milk (kg/year), p_b is the price for beef from culled cows (€/kg beef), a_b is the amount of beef from culled cows (kg/year), p_c is the price for surplus calves (€/calf) and a_c is the amount of surplus calves/year. Prices for milk (30.8 C_t/kg milk), beef and surplus calves were calculated on the basis of a 5-year average of German statistical data (2005 to 2009; Wohlfahrt *et al.*, 2008; Gorn and Schoch, 2010). In the 'economic allocation' method, the proportion of GHG emissions allocated to co-products is 1-e_m. Thus, emissions per kg beef include emissions allocated to beef from culled cows and calves derived from dairy cow production and emissions occurring during bull and heifer fattening and suckler cow production.

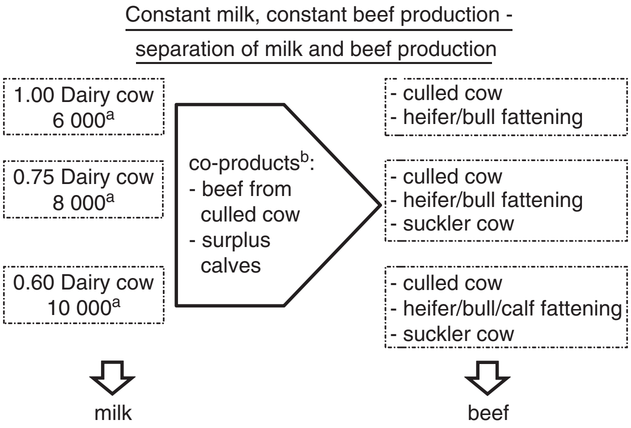

Figure 4 Separation of milk and beef production within Scenario 2. [a]including breeding heifer. [b]methods for handling co-products from dairy cow production: 'No allocation': co-products are not loaded with GHG emissions from dairy cow production; 'Economic allocation': co-products are loaded with greenhouse gas (GHG) emissions from dairy cow production systems according to equation (4).

Results

Scenario 1: constant milk, variable beef production

GHG emissions. The DU-6 had a milk output of 5770 kg/year (4% of milk produced assumed to be used for calves, own consumption or wasted) and a beef output of 322 kg/year (Table 4). From total beef production, 34% came from culled dairy cow, and the remaining from heifer and bull fattening of surplus calves. Modelled GHG emissions per DU-6 included emissions derived from dairy cow, rearing heifer, bull and heifer fattening were 9578 kg CO_{2eq}/year (Table 4). Estimated CH_4 emissions from enteric fermentation and N_2O emissions from N input into soils accounted for approximately 50% and 15% of total GHG emissions, respectively. GHG emissions, for a constant level of milk output and decreasing associated beef output, decreased from 9578 kg CO_{2eq} (DU-6) to 6141 kg CO_{2eq}/year (0.6 DU-10). As CH_4 emissions from enteric fermentation accounted for approximately 50% of total GHG emissions, reduction in animal numbers influenced total GHG output considerably.

Milk and beef outputs. As milk yield per cow increased, the number of dairy cows required to keep milk output constant

Table 4 *Model output for Scenarios 1 and 2*

	Scenario 1[a]			Scenario 2[b]	
	DU-6	0.75 DU-8	0.6 DU-10	0.75 DU-8 + 0.27 SU	0.6 DU-10 + 0.59 SU
Beef output (kg/year)	322	236	131	322	322
Costs (€/year)					
Forage	1076	776	551	982	1007
Concentrates	339	382	419	420	504
Working hours (ha/year)					
Feed	9	8	6	10	11
Animal husbundry	50	37	30	45	47
Land use (ha/year)					
Grassland	0.58	0.43	0.34	0.67	0.85
Arable land	0.66	0.66	0.58	0.74	0.75
GHG emissions (kg CO_{2eq}/year)					
Primary source emissions					
Enteric fermentation	5055	3933	2977	4963	5263
Manure	1321	1050	831	1190	1141
Soil N_2O	1364	1114	915	1580	1948
CO_2 from liming/diesel consumption	479	410	339	497	531
Secondary source emissions					
Mineral fertilizer	722	582	472	720	778
Diesel/electricity	270	263	262	274	285
Bought in feedstuff production	317	289	303	318	368
Others	50	48	42	52	51
Total	9578	7689	6141	9594	10 365

DU = dairy cow production unit; SU = suckler cow production unit; GHG = greenhouse gas; CO_{2eq} = kg CO_2 equivalents.

[a]Scenario 1: constant milk production; variable beef production; model outputs refer to a constant level of 5770 kg milk.

[b]Scenario 2: constant milk and constant beef; model outputs refer to a constant level of 5770 kg milk and 322 kg beef.

Table 5 *Modelled GHG emissions for Scenario 2*

	Scenario 2		
	DC 6000 (including rearing heifer)	0.75 DC 8000 (including rearing heifer)	0.6 DC 10 000 (including rearing heifer)
No allocation[a]			
GHG emissions (kg CO_{2eq}/kg milk)	1.35	1.13	0.98
Beef derived from	Culled cows, bull and heifer fattening*	Culled cows, bull and heifer fattening* + 0.27 PU SC	Culled cows, bull and calf fattening** + 0.59 PU SC
GHG emissions (kg CO_{2eq}/kg beef)	5.55	9.54	14.63
Economic Allocation[b]			
GHG emissions (kg CO_{2eq}/kg milk)	1.06	0.93	0.89
Beef derived from	Culled cows, bull and heifer fattening*	Culled cows, bull and heifer fattening* + 0.27 SU	Culled cows, bull and calf fattening** + 0.59 SU
GHG emissions (kg CO_{2eq}/kg beef)	10.75	13.13	16.24

DC = dairy cow; GHG = greenhouse gas; CO_{2eq} = kg CO_2 equivalents; PU = production unit; SU = suckler cow production unit.

[a] All GHG emissions occurring in dairy cow production and heifer rearing are allocated to milk.

[b] GHG emissions occurring during dairy cow production and heifer rearing are allocated to milk according to their economic value (equation 4); initial weight bull and heifer fattening: *85 kg; **50 kg.

Scenario 2: separation of constant milk and constant beef production.

(5770 kg) declined. On the basis of the milk output of a DU-6, only 0.75 DU-8 and 0.60 DU-10 were needed to keep milk output constant. With increasing milk yield per cow, beef output decreased from 322 kg (DU-6) to 236 kg (0.75 DU-8) and to 131 kg/year (0.6 DU-10). This was the result of a decline in the number of both culled cows and fattening cattle, in addition to a less-efficient process of fattening for HF cattle. Ratio of milk to beef production (kg/kg) was 18 for DU-6, 25 for DU-8 and 44 for DU-10.

Land use, costs and labour. Demand for grassland decreased with increasing milk yield from 0.58 ha (DU-6) to 0.43 ha (0.75 DU-8) and 0.34 ha/year (0.6 DU-10), because of decreasing number of animals and a decreasing proportion of grass silage in the diet (Table 5). Demand for arable land (includes land used to produce maize silage, concentrates and soyabean meal of the animals rations) remained constant at 0.66 ha for DU-6 and 0.75 DU-8. However, demand for arable land decreased from 0.66 to 0.58 ha for 0.6 DU-10, as fattening of HF calves was included with a diet based on milk replacer (Table 4). Both costs for forage production and working hours decreased considerably as the milk yield per cow increased from 6000 kg to 10 000 kg/year, assuming constant milk output of 5770 kg/year (Table 4, Scenario 1). Assuming labour costs of 10 €/h, feed and labour costs decreased approximately 35%, with increasing milk yield from 6000 to 10 000 kg milk/cow per year, which would result in increasing profit with increasing milk yield/cow per year.

Scenario 2: constant milk and constant beef production

The second scenario simulated was one with both milk and beef outputs constant. This was done by combining DU and SU. Milk and beef output were constrained at 5770 kg/year and 322 kg/year, respectively, based on one DU-6.

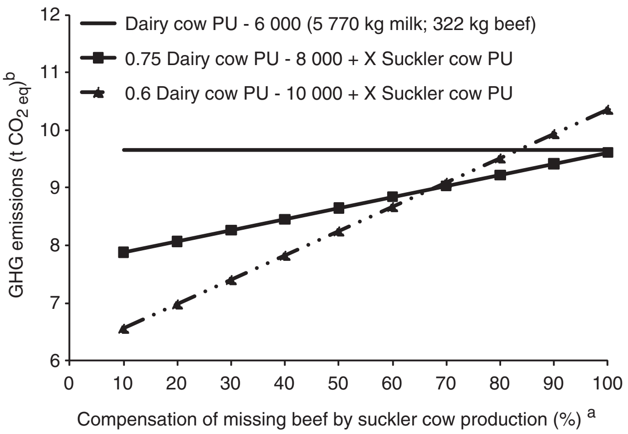

Figure 5 Greenhouse gas (GHG) emissions resulting from different rates of compensation of missing beef by suckler cow production at a constant level of milk production (5770 kg); X: ranging from 0 to 0.27 SU for 0.75 DU-8 and from 0 to 0.59 SU for 0.6 DU-10. [a] 100% compensation of missing beef means beef output is equal to 322 kg based on one DU 6000 kg milk/cow per year (see Figure 1). [b] The amount of CO_{2eq} refer to a constant amount of milk (5770 kg milk) and to a varying amount of beef indicated in the X-Ache (SU = suckler cow production unit; DU = dairy cow production unit).

GHG emissions. Total modelled GHG emissions were 9578 kg CO_{2eq} for one DU-6, 9594 kg CO_{2eq} for 0.75 DU-8 and 10 365 kg CO_{2eq} for 0.6 DU-10, including SU in the two latter cases, assuming a constant amount of 5770 kg milk and 322 kg beef output (Table 4). The influence of increasing milk yield per cow on total GHG emissions in our study depended mainly on the amount of beef (as a co-product) that was compensated by beef production from suckler cows (Figure 5). The 10 000 kg yielding dairy cow resulted in the lowest GHG emissions up to a beef compensation rate of 68%. However, from a rate of beef compensation of 68% and 80% upwards, the DU-10 resulted in more GHG emissions than DU-8 and DU-6, respectively. The DU-8 showed similar GHG emissions as DU-6 at a rate of beef compensation of 100% (Figure 5).

Milk and beef outputs. With increasing milk yield per cow to 8000 and 10 000 kg/year, the inclusion of 0.27 and 0.59 SU were needed, respectively, to keep beef output constant at 322 kg/year (Figure 3 and Table 4).

Land use, costs and labour. As the diet of suckler cows was mainly based on grass, demand for grassland increased in the modelled scenario of constant milk production (one DU-6, 0.75 DU-8 and 0.60 DU-10) and constant beef production. In this scenario, in which suckler cows were included to keep beef output constant, demand for labour remained nearly constant and demand for total land increased (Table 4; Scenario 2). Within Scenario 2, DU-8000 kg (plus SU) showed the lowest demand for labour and the lowest feeding costs.

Scenario 2: constant milk and beef production – allocation methods

In order to show the impact of increasing milk yield per cow on GHG emissions per kg milk and per kg beef, milk and beef production of the modelled PU in Scenario 2 were separated using different methods of co-product handling (Figure 4), namely 'no allocation' and 'economic allocation'.

No allocation. Using the 'no allocation method', emissions of 1.35 kg CO_{2eq}/kg milk and 5.55 kg CO_{2eq}/kg beef for DU-6 were estimated. With increasing milk yield per cow and year, GHG emissions per kg of milk decreased from 1.35 to 1.13 and 0.98 kg CO_{2eq} as milk yield per cow increased from 6000 to 8000 and 10 000 kg milk, respectively. However, beef produced from suckler cows (to compensate for the decline of beef produced as co-product) as a proportion of total beef production increased with increasing milk yield per cow. Therefore, emissions per kg of beef output increased from 5.55 kg CO_{2eq} (DU-6, with no beef from suckler cow production) to 14.63 kg CO_{2eq}/kg beef output (0.6 DU-10, 59% of beef derived from suckler cow production; Table 5).

Economic allocation. The 'Economic allocation' method allocates GHG emissions from dairy cow production between milk and co-products according to their economic value. This resulted in lower GHG emissions per kg of milk but higher GHG emissions per kg of beef for the modelled scenarios in comparison with the 'no allocation' method (Table 5). 'Economic allocation' resulted in 10.75 kg CO_{2eq}/kg beef for DU-6. GHG emissions per kg of beef increased in comparison with emissions estimated with 'no allocation', as beef from culled cows and calves for fattening were loaded with GHG emissions from milk production using the 'economic allocation' method. Calves from HF dairy cows (DU-10) were less valuable than calves from FV cows (DU-6 and DU-8). Thus, when 'economic allocation' was performed, more GHG emissions were allocated to milk for the 10 000 kg yielding dairy cow than for the other modelled dairy cows.

For both allocation methods, GHG emissions per kg milk decreased with increasing milk yield; however, the reduction of GHG emissions per kg milk was much higher within the 'no allocation' method than within the 'economic allocation' method. From dairy cow 8000 kg milk/year (including heifer) to dairy cow 10 000 kg milk/year (including heifer), GHG emissions decreased 0.15 kg CO_{2eq}/kg milk using the 'no allocation' method and 0.04 kg CO_{2eq}/kg milk using the 'economic allocation' method.

Discussion

The main objective of this study was to investigate the effect of increasing milk yield per cow on GHG emissions and on other side effects, not stopping at the dairy farm gate but looking at the whole system of milk and beef outputs. Two scenarios were defined: constant milk production (one DU-6, 0.75 DU-8 and 0.60 DU-10) and decreasing beef production, as milk yield per cow increased (Scenario 1); and both milk and beef production constant, by compensating the decline of beef production as co-products with beef production from suckler cows (Scenario 2).

Model limitations

GHG emissions. There is still a high uncertainty associated with equations and emission factors used to predict GHG emissions in agriculture (IPCC, 2006). Thus, further model calculations were carried out replacing equation 4 (equation to predict CH_4 emissions from dairy cows) and emission factors used in this model (N_2O emissions from N input into the soil) to see the effect on results shown in Table 4. Two additional equations predicting CH_4 emissions from dairy cows were tested – an equation derived from Schils *et al.* (2006) considering different diet compositions and an equation described in IPCC (2006, equation 10.21). Total GHG emissions increased by up to 7% when these two equations were used in comparison with the modelled scenarios shown in Table 4. However, it did not change the trend towards a decrease in GHG emissions for Scenario 1 and the trend towards an increase in GHG emissions for Scenario 2, as milk yield per cow increased. Furthermore, emission factors of 0.01 kg N_2O-N/kg N and 0.02 kg N_2O-N/kg N for the prediction of direct N_2O emissions from managed soils were replaced by the uncertainty range given in IPCC (2006) (0.003 to 0.3 and 0.007 to 0.6, respectively). Total GHG emissions shown in Table 4 decreased by up to 10% using the lower emission factors and increased by up to 38%, including the higher emission factors into the model. Again, this did not affect the relative trend observed for the modelled scenarios shown in Table 4.

Hindrichsen *et al.* (2006) reported higher CH_4 emissions from slurry of dairy cows offered forage supplemented with concentrates in comparison with dairy cows offered a forage-only diet. This is not considered in the IPCC (2006, equation 10.23) used in the model. If this was considered, it would result in slightly higher GHG emissions for higher-yielding dairy cows.

General model assumptions. Model assumptions as breed of dairy and suckler cows, calving interval, replacement rate and feeding system are based on typical German production systems. A change in breed for suckler cows could increase fattening efficiency of bulls (ADR, 2010) and heifers and result in less suckler cows needed to replace beef reduction in the model. A change in the feeding system of fattening bulls from forage based on maize silage to pasture could decrease daily gains and increase the number of suckler cows. Furthermore, assumptions of calving interval and replacement rate influence the number of calves per cow available for fattening and thus beef output considerably.

The influence of model assumptions and uncertainty of GHG emission factors on model outputs have to be taken into account while interpreting GHG emissions of the modelled scenarios. However, the overall conclusion that increasing milk yield in dairy farming could result in higher GHG emissions, if the whole system of milk and beef production is considered, remains.

Beef as a co-product of dairy cow production in Germany

In the model, DU was built to combine milk and beef production. The tight connection between milk and beef production can be observed in German development of milk and beef production in recent years. Milk yield per cow per year in Germany increased by approximately 2000 kg (4900 to 6600 kg milk/cow per year) from 1990 to 2009 (FAOSTAT, 2010). In the same period, the number of dairy cows in Germany decreased from approximately 6.3 to 4.2 million animals (Destatis, 2010), whereas total milk output remained constant. Owing to this decrease, gross domestic beef production in Germany declined by approximately 967 million kg in the same period (Destatis, 2010), which represents a 44% reduction of total beef production in Germany. This did not remarkably affect self-sufficiency of beef in Germany as beef demand has considerably decreased because of bovine spongiform encephalopathy (BSE) crises in 2001. However, as beef demand remained constant since 2002, self-sufficiency of beef decreased from 140% in 2002 to 117% in 2009 (Weiß and Kohlmüller, 2010).

Effect of market demand of milk and beef on model assumptions

The extent to which increasing milk yield per cow reduces or increases GHG emissions depends on the demand for milk and beef as well as the ratio of milk to beef output per dairy cow. The ratio of milk (excluding butter) to beef consumption (kg/kg) in Germany was 18 for the year 2007 (FAOSTAT, 2010). This means that milk consumption exceeded beef consumption by more than 18 times. The ratio of milk to beef output per year (kg/kg) for the modelled DU was 18 for one DU-6, 25 for one DU-8 and 44 for one DU-10 (Table 6). Thus, if total milk demand in Germany is satisfied by dairy cows yielding 8000 kg of milk/year, beef demand cannot be satisfied by co-products of dairy cow production. Therefore, suckler cows will be needed for beef production. The ratio of milk to beef consumption of a given country together with the ratio of milk to beef production (as co-product) from dairy cows are the most important factors in defining whether increasing milk yield per cow is a valid strategy to reduce total GHG emissions in that country.

Table 6 *Ratio of milk to beef demand for several countries (FAOSTAT, 2010) and ratio of milk to beef production for the modelled dairy cow production units*

Country	Ratio milk to beef demand (kg/kg)
Argentina	4
USA	6
Ireland	11
EU	14
Sweden	15
Netherlands	17
Germany	19
India	44
DU[a]	Ratio milk to beef production per year (kg/kg)
DU-6	18
DU-8	25
DU-10	44

[a] DU = dairy cow production unit differing in milk yield per cow per year (6000 kg (DU-6), 8000 kg (DU-8) and 10 000 kg (DU-10)).

Considering international trade and influence of future suppression of quota system in Europe on milk production of certain countries, it is also important to consider the ratio of milk to beef demand of other countries. The ratio of milk to beef production for modelled DU exceeds the ratio of milk to beef demand in many countries and in the EU, with the exception of Germany and India (Table 6). Thus, the reduction of beef production due to increasing milk yield per cow would result in a higher number of suckler cows if the ratio of milk to beef demand remains at the present level. If, along with an increasing milk yield per cow, there is a corresponding decrease in beef consumption (towards a higher ratio of milk to beef demand) and an increase in pork and poultry meat consumption, reductions in beef output would not have to be compensated for by an increasing number of suckler cows. Emissions per kg meat from pork (6.4 kg CO_{2eq}/kg meat) or poultry (4.6 kg CO_{2eq}/kg meat) production systems (Williams *et al.*, 2006) are assumed to be much lower than emissions per kg beef from suckler cow production (21.2 kg CO_{2eq}/kg meat, own calculations; 21.7 kg CO_{2eq}/kg meat, Beauchemin *et al.*, 2010). In this case, total GHG emissions (from milk and meat production) will be reduced as milk yield per cow is increased.

Furthermore, it has to be considered that the quality of beef derived from specialized suckler cow production could be higher than the quality of beef derived from co-products of dairy cow production and thus influence quality of beef offer. Offer and demand for high-quality beef was not analysed in this study and further research needs to consider this.

Allocation methods

Most studies calculating GHG emissions from dairy farming stop at the dairy farm gate (Lovett *et al.*, 2006; Hörtenhuber *et al.*, 2010), using different methods for allocating GHG emissions between milk and co-products. In our study, milk and beef production were combined defining PU and including suckler cow production in the model. Within Scenario 2 (constant milk and beef output), GHG emissions for the modelled PU were also allocated between milk and beef output using different methods of co-product handling, to determine emissions per kg milk and per kg beef. Results showed that emissions per kg beef were 4 to 18 times higher than emissions per kg milk, depending on milk yield per cow and allocation method.

Results showed that the method of handling co-products influences the amount of GHG emissions per kg of milk and per kg of beef produced. If only emissions per kg milk were considered, GHG emissions decreased with increasing milk yield per cow in both allocation methods used in this study. However, GHG emissions per kg beef produced increased considerably as milk yield per cow increased. Thus, calculations of GHG emissions that stop at the dairy farm gate are not always adequate to represent the whole impact of cattle production systems on GHG emissions.

Another approach to handle co-products of dairy farming that considers suckler cows is 'system expansion' (defined in Cederberg and Stadig, 2003). Using this method, suckler cow production is defined as an alternative way to replace co-product of dairy farming (beef from culled cows and surplus calves). However, in comparison with the approach in this study, the 'system expansion' method does not consider the fattening systems of surplus calves and does not account for differences in breed. In the 'system expansion' method, surplus calves from a dairy cow are replaced by calves from suckler cow production; however, it does not take into account that calves of dual-purpose breed show better fattening characteristics than calves of specialized dairy breeds. In the current model, the definition of PU included the dairy cow, replacement heifer and bull and heifer fattening from surplus dairy cow calves. Thus, differences derived from both level of milk production and breeds were taken into account.

Side effects of increasing milk yield per cow

Loss of fertility and higher probability of the appearance of diseases are mentioned as side effects of increasing milk yield per cow in dairy farming (Lucy, 2001; Dillon *et al.*, 2006). GHG emissions produced during the rearing phase of modelled replacement heifers contribute up to 20% of total GHG emissions from the modelled dairy farms. Thus, replacement rate plays an important role in total GHG emissions of dairy systems. Weiske *et al.* (2006) reported a reduction of GHG emissions per kg milk by up to 13% with a reduction of replacement rate from 40% to 30% for modelled dairy farms. However, if a constant beef production is assumed (Scenario 2), changing the assumed replacement rate of the 10 000 kg-yielding dairy cow from 40% to 30% did not reduce total GHG emissions. In this scenario, a reduction in replacement rate resulted in less beef from culled cows and thus a higher amount of beef to be replaced by suckler cows.

In this study, with increased milk yield per cow, the proportion of concentrates and soyabean meal in the ration fed to dairy cows increased, whereas the demand for grassland area decreased. This change in the diet has a side effect on GHG emissions, as demand for additional arable land may influence clearance of land elsewhere (Garnett, 2009). Cultivation of soyabean in South America is often assumed to be associated with the conversion of forest, pasture and shrub land to cropland. Dalgaard *et al.* (2008) reported 5.7 kg CO_{2eq}/kg soyabean meal if land use changes are included in the calculation of GHG emissions. Calculating GHG emissions with the emission factor of 5.7 kg CO_{2eq}/kg soyabean meal, total GHG emissions of Scenario 2 (constant milk and constant beef production) increased 25%, 31% and 32% for DU-6, 0.75 DU-8 including SU and 0.6 DU-10 including SU, respectively. This resulted in a higher increase of GHG emissions with increasing milk yield within Scenario 2.

As demand for grassland decreases with increasing milk yield per cow, the proportion of human-edible feed sources in the ration increases. Monogastric livestock systems are more efficient in terms of total feed conversion efficiency (kg cereals consumed/kg animal weight gain; Garnett, 2009). However, efficiencies of energy and protein on the basis of human-edible food produced per unit of human-edible feed consumed per animal are higher for ruminants than for monogastric animals (Gill *et al.*, 2010). In this study, concentrate intake per dairy cow increased with increasing milk yield from 11% to 25% and 37% of total DMI for the 6000, 8000 and 10 000 kg milk-yielding dairy cows, respectively. Thus, higher-yielding dairy cows had a higher input of human-edible food. Human-edible efficiency (output human-edible protein/dairy cow per input human-edible protein) was 1.05 for a dairy cow yielding 6000 kg milk per year, 0.68 for a dairy cow yielding 8000 kg milk per year and 0.55 for a dairy cow yielding 10 000 kg milk per year. Output included milk and beef/cow per year with a protein content of 190 g/kg beef, and 3.4%/kg milk input included protein content of concentrates feed per cow per year.

The introduction of suckler cow production increased GHG emissions in the present model estimations because of the high emission factors/kg beef produced. Again, it has to be mentioned that feed input for suckler cow production is mainly derived from non-human-edible sources (forage and hay). Furthermore, suckler cows can be farmed on less valuable land, with other ecosystem services such as conservation of biodiversity, water quality and aesthetic value.

Conclusion

In response to the original question in this paper 'Does increasing milk yield per cow reduce GHG emissions?', the answer would be yes, if GHG emissions are measured per kg milk yield and reduction in associated beef production is not accounted for. However, model outputs showed that this would not be the case if beef production is intended to be constant and milk yield per cow increases. Thus, the whole impact of increasing milk yield per cow in dairy farming on GHG emissions, and on other side effects, can only be observed by expanding the system boundaries from the dairy farm gate to the whole system to consider both milk and beef production. Regarding the modelled GHG efficiency, the ongoing specialization in both milk and beef production has to be questioned.

The extent to which total GHG emissions increase with increasing milk yield per cow also depends on the amount of beef that has to be compensated for and on the kind of meat (beef, pork or poultry) that compensates beef reduction as a co-product from dairy cows.

Further research is needed to determine how a change in the ratio of milk to beef demand and the demand for high-quality beef would influence model outputs.

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Paper II

Zehetmeier, M., Gandorfer, M., de Boer, I.J.M., Heißenhuber A. Economic Allocation and System Expansion Modelling GHG emissions in dairy farming. The impact of uncertainty. Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaus e.V. (GEWISOLA) 48, 397-406.[4]

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[4] The first author conducted the modelling and all statistical analysis. She analysed and discussed the results. She composed the tables and graphs, wrote the first complete draft of the paper and revised the paper.

ECONOMIC ALLOCATION AND SYSTEM EXPANSION MODELLING GHG EMISSIONS IN DAIRY FARMING. THE IMPACT OF UNCERTAINTY

M. Zehetmeier[1], M. Gandorfer[2], I.J.M. de Boer[3], A. Heißenhuber[1]

Abstract

In this study an existing deterministic model developed to calculate greenhouse gas (GHG) emissions of confinement dairy farm systems differing in milk yield (6 000, 8 000, 10 000 kg milk/cow per year) and breed (dual purpose, milk breed) was further developed. We incorporated uncertainty to account for epistemic uncertainty (e.g. emission factors for GHG modelling, GHG emissions from suckler cow production) and intrinsic variability (e.g. variability of production traits, such as calving interval, replacement rate and variability of prices). The developed stochastic model accounts for two different methods for handling co-products of dairy farming (beef from culled cows and surplus calves): economic allocation and system expansion. In case of economic allocation GHG emissions are allocated between milk and co-products according to their economic value. Within system expansion it is assumed that beef derived from culled cows and fattening of surplus calves replaces beef from suckler cow production. The avoided GHG emissions from suckler cows are credited to the dairy farm.

In consistent with other studies results showed that the choice of method for handling co-products of dairy cow production had the highest impact on mean values of model outcomes. The inclusion of uncertainty gave insight into robustness of deterministic model outcomes and identified factors that had the highest impact on variation of model outcomes. In case of economic allocation variation of emission factor for soybean meal and nitrous oxide emissions from nitrogen input into the soil had the highest impact on variation of GHG emissions outcomes (up to 92%).

In case of system expansion emission factor for beef derived from suckler cow production had the highest impact on variation of GHG emissions outcomes (up to 54%) resulting in even negative GHG emissions per kg milk. The method of system expansion is recommended if the consequences of changes or mitigation options in dairy cow production need to be evaluated.

Whereas the choice of method for co-product handling depends on the scope of GHG modelling in dairy farming the stochastic model approach gave insight into robustness and variation of model outcomes within each method for handling co-products. This is of special importance identifying cost-effective GHG mitigation options.

Keywords

Greenhouse gas emissions, uncertainty, dairy farming, milk yield, co-product handling

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Zusammenfassung

In dieser Studie wurde ein bestehendes deterministisches Modell zur Bilanzierung von Treibhausgas (THG)-Emissionen von Milchviehbetrieben unterschiedlicher Leistungsklassen (6 000, 8 000 und 10 000 kg Milch/Kuh und Jahr) und Milchviehrassen (Zweinutzung und Milchspezialrasse) weiter entwickelt. Unsicherheiten zahlreicher Modellkomponenten wurden in die Modellrechnungen integriert. Das stochastische Modell wurde für zwei unterschiedliche Methoden zur Bewertung von Koppelprodukten der Milchproduktion entwickelt (Altkuhfleisch und Kälber zur Mast). Dies sind: ökonomische Allokation und Systemerweiterung. Bei der ökonomischen Allokation erfolgt die Aufteilung der THG-Emissionen zwischen Milch und Koppelprodukten anhand des jeweiligen ökonomischen Wertes. Bei der Systemerweiterung wird angenommen, dass Rindfleisch, welches von Altkühen sowie der Ausmast von nicht zur Nachzucht benötigter Kälber stammt, nicht in der Mutterkuhhaltung erzeugt werden muss. Die dadurch eingesparten Emissionen werden der Milchviehhaltung gut geschrieben.

Wie auch in weiteren Studien der Literatur bestätigt, haben die Berechnungen gezeigt, dass die Wahl der Methode zur Bewertung von Koppelprodukten den höchsten Einfluss auf die resultierenden THG-Emissionen pro kg Milch hat.

Die Berücksichtigung von Unsicherheiten innerhalb der unterschiedlichen Methoden zur Bewertung von Koppelprodukten zeigt die Stabilität von Ergebnissen deterministischer Modelle auf und gibt einen Hinweis darauf, welche Faktoren am meisten zur Variabilität der resultierenden THG-Emissionen beitragen.

Im Falle der ökonomischen Allokation hatten die Emissionsfaktoren zur Vorhersage der THG-Emissionen von Sojaextraktionsschrot und Lachgas durch Stickstoffeintrag in den Boden den größten Einfluss auf die Variabilität der resultierenden THG-Emissionen (bis zu 92%).

Bei der Systemerweiterung hatte die Wahl des Emissionsfaktors für Rindfleisch aus der Mutterkuhhaltung den größten Einfluss auf die Variabilität der resultierenden THG-Emissionen der Milchproduktion (bis zu 54%). Dabei ergaben sich auch negative Emissionen pro kg Milch. Die Methode der Systemerweiterung wird vor allem für die Beurteilung von Strategien zur Vermeidung von THG-Emissionen in der Milchviehhaltung empfohlen.

Während die Wahl der Methode zur Beurteilung von Koppelprodukten vor allem von der Fragestellung der Modellierung von THG-Emissionen in der Milchviehhaltung abhängig ist, kann ein stochastisches Modell wichtige Informationen zur Robustheit und Variabilität von Modellergebnissen liefern. Dies ist vor allem bei der Suche nach kostengünstigen Möglichkeiten zur Reduktion von THG-Emissionen in der Tierhaltung von Bedeutung.

Schlüsselbegriffe

Treibhausgasbilanzierung, Unsicherheit, Milchviehhaltung, Milchleistung, Koppelprodukte

1 Introduction

Dairy cow production contributes to about 23 to 70% of total agricultural GHG emissions in different countries within the EU-27 (LESSCHEN ET AL., 2011). Thus, a growing interest can be observed in modelling GHG emissions from dairy cow production systems and identifying cost-effective GHG mitigation options.

As milk is the main output of dairy farms most studies express GHG emissions produced per kg milk delivered. However, beef can be considered as an important co-product of dairy farming (beef from culled cows and surplus calves sold to fattening systems) especially within dual purpose dairy cow production systems. To account for co-products from dairy farming different methods can be observed in literature (FLYSJÖ et al., 2011). Two main approaches can be distinguished: economic allocation and system expansion. In case of economic allocation GHG emissions are allocated between milk and co-products at the dairy farm gate according to their economic value. This approach is mainly used in the calculation of carbon footprints. It identifies GHG emissions at the dairy farm gate caused by milk production and allocates GHG emissions based on the value of milk and beef to the consumer. In case of system expansion allocation between milk and co-products is avoided by expanding the system and accounting for the alternative way of beef production (i.e. sucker cow production). It is assumed that the beef derived from culled cows and fattening of surplus calves replaces beef from suckler cow production. The avoided GHG emissions are credited to the dairy farm. The method of system expansion is recommended by the International Organisation for standardization (ISO, 2006). This approach is especially important if the consequences of changes or mitigation options in dairy cow production need to be evaluated (FLYSJÖ et al., 2011).

Recent determinist studies showed that the choice of method for handling co-products has a major impact on GHG emissions outcomes of dairy co-product systems (FLYSJÖ et al., 2011, ZEHETMEIER ET AL., 2012). Despite the impact of choice of method for co-product handling it has to be considered that assumptions and input data modelling GHG emissions from dairy cow production have known uncertainties. Many guidelines and scientific studies point out the importance of incorporating uncertainty in GHG and economic modelling (ISO, 2006; IPCC, 2006; PANNELL, 1997). The inclusion, the discussion and the reporting of model changes due to uncertainties can be important to identify robustness and variation of model outcomes and sensitive or important variables (PANNELL, 1997). It is a matter of special importance to investigate whether uncertainties of model inputs have an impact on conclusions to be drawn from the model or not.

To show the impact of uncertainty on GHG emission outcomes a deterministic model developed to calculate GHG emissions of confinement dairy farm systems differing in milk yield and breed (ZEHETMEIER et al., 2012) was further developed. A stochastic model was established that accounts for uncertainty in various components. Compared with deterministic models, stochastic models offer the advantage of predicting not just an outcome, but also the likelihood of this outcome. Thus, stochastic modelling and scenario analysis were undertaken to answer the following questions:

- does the inclusion of uncertainty influence the ranking of modelled dairy cow production systems in terms of GHG emissions? (6 000, 8 000, 10 000 kg milk/cow)
- which uncertainties have the highest impact on variation of GHG emission outcomes?

To show the impact of uncertainty within different methods for handling co-products uncertainty modelling was undertaken for economic allocation and system expansion approach.

2 Material and Methods

A whole system model calculating GHG emissions of confinement dairy cow production systems differing in milk yield and breed have been presented in detail in another paper (ZEHETMEIER et al., 2012). In the first part of this section a short summary of the existing model is given. Economic allocation and system expansion as methods for handling co-products were included in the existing model which is described in the second part. Finally, chosen parameters and methods for stochastic simulation are described.

2.1 Description of existing model

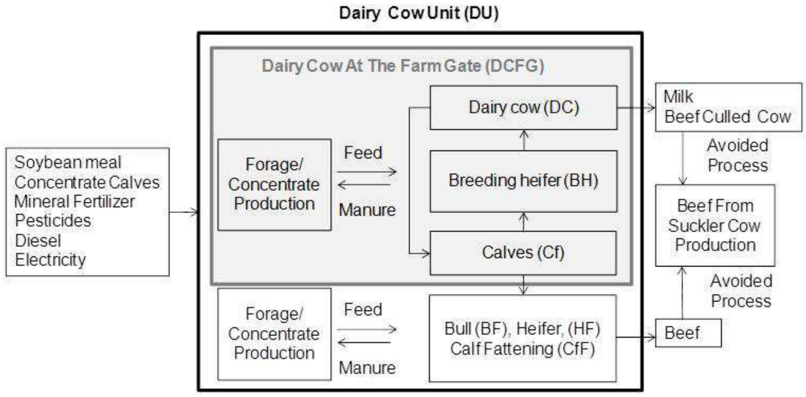
Livestock. The whole farm model incorporated dairy cows from different breeds and milk yield (6 000 and 8 000 kg milk/cow per year - dual purpose Fleckvieh (FV) breed; 10 000 kg milk/cow per year – Holstein-Friesian (H-F) breed). Representing a typical dairy farm calves and breeding heifers were combined with dairy cow production (Figure 1).

The amount of breeding heifers was equivalent to the rate of replacement to keep number of dairy cows constant. The number of calves born per year depended on calving interval and calf losses. Calves were assumed to be sold at a weight of 85 kg (FV cows) and 50 kg (H-F cows) representing typical German dairy farm production systems.

Production system and model inputs. A confinement production system with dairy cows, heifers and bulls being indoor all-year-round was assumed. Forage components were maize silage, grass silage and hay. Concentrates consisted of corn, winter wheat, barley, soybean meal, and concentrates for claves. Except soybean meal and concentrates for calves the production of all forage and concentrate components was incorporated into the model (Figure 1).

Global warming potential. Global warming potential (GWP) in the model was calculated considering all primary (occurring on farm e.g. during feed production, maintenance of animals and manure management) and secondary sources (occurring off-farm e.g. production of fertilizer, pesticides or diesel) of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions. Primary source emissions were mainly calculated according to guidelines and standard values from IPCC (2006) and Haenel (2010). To estimate CH_4 emissions from dairy cows we followed KIRCHGEßNER et al. (1995). Emission factors for the calculation of secondary source GHG emissions were taken from literature.

Figure 1: Illustration of system boundaries composition of modelled livestock production systems



2.2 Methods for handling co-products

One method to handle co-products from dairy cow production is to allocate GHG emissions between milk and co-products according to their economic value (economic allocation) (Equation 2).

$$(2)\ GWP_{\ EA}\left[\frac{kg\ CO_{2eq}}{kg\ milk}\right] = \frac{GWP_{Dairy\ cow\ at\ the\ farm\ gate}\ (kg\ CO_{2eq})}{milk\ delivered\ (kg)} * AF_{EA}$$

where GWP_{EA}= Global warming potential of milk production; EA= economic allocation; AF_{EA} = allocation factor for the economic allocation method (proportion of economic value of milk on total value of milk and beef output).

One option to avoid allocation between milk and co-products would be to expand the production system by defining an alternative way to produce the co-products of dairy farming (ISO, 2006). The method named `system expansion` (FLYSJÖ et al., 2011) was incorporated into the modelling defining suckler cow production as the alternative way to produce beef. To account for the whole potential of beef production of a dairy cow dairy units were defined (Figure 1). A dairy unit goes beyond the dairy farm gate and considers the fattening systems of surplus calves. Thus, amount of beef of a dairy unit was made up by beef from culled cows, bull, heifer and calf fattening (only H-F dairy cows) (Figure 1). One dairy unit of a

6 000 kg, 8 000 kg and 10 000 kg yielding dairy cow resulted in 322, 315 and 218 kg beef, respectively. Production system and calculation of GHG emissions for suckler cow production was taken from Zehetmeier et al. (2012). Suckler cows were assumed to be on pasture 185 days/year. One suckler unit resulted in 318 kg beef.

In the system expansion method, GHG emissions from suckler cow production were subtracted from GHG emissions of dairy cow production based on the potential amount of beef production (Equation 3).

$$(3)\ GWP_{SE}\left(kg\ CO_{2eq}/kg\ milk\right) = \frac{GWP_{Dairy\ unit}\left(kg\ CO_{2eq}\right) - \left(\frac{GWP_{Suckler\ unit}\ (kg\ CO_{2eq})}{b_{Suckler\ unit}\ (kg)} * b_{Dairy\ unit}(kg)\right)}{milk\ delivered\ (kg)}$$

where GWP_{SE}= Global warming potential of milk production using system expansion method; $GWP_{Dairy\ unit}$ = Global warming potential of one dairy unit (Figure 1); $GWP_{Suckler\ unit}$=Global warming potential of one suckler unit; $b_{Suckler\ unit}$ = amount of beef derived from one suckler unit; $b_{Dairy\ unit}$= amount of beef derived from one dairy unit.

2.3 Uncertainty modelling

Overview. A deterministic model (i.e. non-varying point estimate results - Kennedy et al., 1996) designed to simulate different yielding dairy cow and fattening production systems (Zehetmeier et al., 2012) was further developed to account for uncertainty. Probabilistic simulation was carried out for main model inputs (GHG modelling, production traits, economic parameter) using @RISK (Palisade Corporation software, Ithaca NY USA). In the course of applied Monte Carlo Simulations 5000 iterations were undertaken to estimate probability distribution of output values.

Parameters estimating GHG emissions. Greenhouse gas emissions derived from enteric fermentation of dairy cows (CH_{4ent}), nitrogen application into soil (N_2O) and soybean meal production (CO_{2eq}) were subject to uncertainty modelling. Sources of emissions included in the uncertainty modelling accounted for more than 70% of total GHG emissions reported in several studies (Zehetmeier et al., 2012; Kristensen et al., 2011). Furthermore, they are considered to have high uncertainty due to limited measurements (e.g. CH_{4ent} emissions from dairy cows), due to differences in geographical locations (e.g. N_2O emissions from nitrogen application into soil) or due to choices (e.g. incorporation of land use change calculating emission factor of soybean meal).

Uncertainty of CH_{4ent} emissions of dairy cows was included in this model using different equations from literature (Table 1) resulting in a wide range of predicted CH_{4ent} emissions.

Uncertainty of N_2O emission factor was included in the modelling assuming an uncertainty range of 0.003 - 0.03 kg N_2O–N/kg N (representing 95% confidence interval) for all nitrogen input into the soil (IPCC, 2006).

Soybean meal is of particular interest since it is an important feed providing high quality protein especially within high yielding dairy cow production systems. In 2010 EU-27 imported 34.5 Mio tonne of soybeans, soybean cake and soybean meal. Over 90% of imports to EU-27 countries were derived from Brazil (53%), Argentina (34%) and USA (7%) (EUROSTAT, 2011). Many studies discuss the contribution of soybean production especially in Brazil in terms of GHG emissions due to direct land use change (dLUC) (Flysjö et al., 2011a, Dalgaard et al., 2008) and indirect land use change (iLUC) (Arima et al., 2011). Emission factors chosen for soybean meal production (Table 1) represent different assumptions of soybean meal production. Minimum value includes emissions only from soybean meal production and transport to Europe while no land use change was assumed. A mixture of previous land use being converted to produce soybean meal was assumed for the calculation of most likely value. Maximum value represents a worst case as it is assumed that forest was converted to arable land for the production of soybean meal (Flysjö et al., 2012).

Triangle distribution function was used to describe probability distribution of CH_{4ent} and emission factors included in uncertainty modelling. Minimum, maximum and most likely values of this function are shown in Table 1.

Table 1: Values for uncertainty modelling of CH_{4ent} and emission factors

	Most Likely	**Miniumum**	**Maximum**
CH_4 ent ferm (kg CH_4) (6 000/8 000/10 000)*	128[1]/135[1]/138[1]	105[2]/116[2]/127[2]	140[3]/152[3]/157[3]
EF N_2O_{dir} N_{input} (kg N_2O-N/kg N)	0.01[4]	0.003[4]	0.03[4]
EF soybean meal (kg CO_{2eq}/kg)	3.1[6]	0.34[5]	10[6]

* kg milk/cow per year yielding dairy cow production systems; EF=emission factor; Sources: [1]Kirchgeßner et al. (1995); [2]Dammgen et al. (2009); [3]Jentsch et al. (2009); [4]IPCC (2006); [5]Dalgaard et al. (2008);[6]Flysjö et al. (2012)

Based on the study of Crosson et al. (2011) we included 15 values for GHG emissions of beef from suckler cow production using cumulative probability function. Emission factors varied from 15.6 to 37.5 kg CO_{2eq}/kg beef.

Production traits. Three different production traits of dairy cow production systems were investigated in terms of variability uncertainty (i.e. intrinsic variability): (1) yearly milk yield per dairy farm (kg milk/cow per year), (2) calving interval and (3) replacement rate. Data from LKV Bayern (2011) and LKV Weser Ems (2011) for a time period of 2004 to 2010 (LKV Bayern)/ 2009 (LKV Weser Ems) was used to identify variability within (variation of average yearly milk yield/ farm from one year to another) and between (variation of calving interval and replacement) dairy farms with equivalent milk yield/cow. Data included 19 070 dairy farms breeding FV cows and 3200 dairy farms breeding H-F dairy cows. To calculate year to year variation of average yearly milk yield/farm (kg milk/cow), milk yield/farm (kg milk/cow) for the observed time period was detrended (Lanoue, 2010). This was necessary to eliminate increase in milk yield due to progress in breeding. A weighted (farms size) linear regression model was used to estimate trends. Taking into account the influence of different farm sizes, standard deviation was standardized to a farm size of 35 (FV) and 48 (H-F) dairy cows.

Weighted (farm size) linear regression models were calculated consecutively with detrended milk yield as dependent variable and standard deviation of yearly milk output per farm, average calving interval and replacement rate per farm as independent variables. The method of quantile regression was used to calculate standard deviation of calving interval and longevity between different dairy farms as a function of detrended milk yield. Resulting production trait figures for different yielding dairy cow production systems are shown in Table 2. Normal distribution was assumed for all considered production traits.

Table 2: Mean and standard deviation (SD) of data input for stochastic modelling of production traits (milk output, calving interval and replacement rate)

System milk yield	**Milk yield (kg/cow/farm/yr)**		**Calving interval (days)**		**Replacement rate (%)**	
(kg milk/cow/yr)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
6000	6000	280	405	22	32.6	7.6
8000	8000	342	389	15	36.7	7.6
10000	10000	373	416	17	30.3	6.4

Economic parameters. Uncertainty of beef from culled cows and calf prices was incorporated into the modelling when calculating allocation factor of economic allocation method. No parametric distribution for prices was found. Thus, a nonparametric approach based on the empirical cumulative probability function using the RiskCumul function implemented in @RISK of prices over a period of 10 years (2000-2010) was chosen (ZMP, various volumes; AMI, 2011) (range is shown in Table 3). Greenhouse gas emission inputs parameters were assumed to be independently distributed. Statistically significant correlations between prices were modelled.

Table 3: Prices for beef from culled cows and calves

Dairy cow		**Calf entering bull fattening**		**Calf entering heifer fattening**	
FV	**HF**	**FV**	**HF**	**FV**	**HF**
(€/kg carcass weight)		(€/kg live weight*)	(€/calf**)	(€/kg live weight*)	(€/calf**)
2.2 (1.7-2.6)	1.7 (1.3-2.1)	4.7 (4.2-5.4)	113 (80-147)	3.2 (2.9-3.7)	48 (32-68)

FV= Fleckvieh; H-F= Holstein-Friesian; Live weight: *85kg/**50 kg; Sources: AMI, 2011; ZMP, various volumes, minimum and maximum value in parenthesis

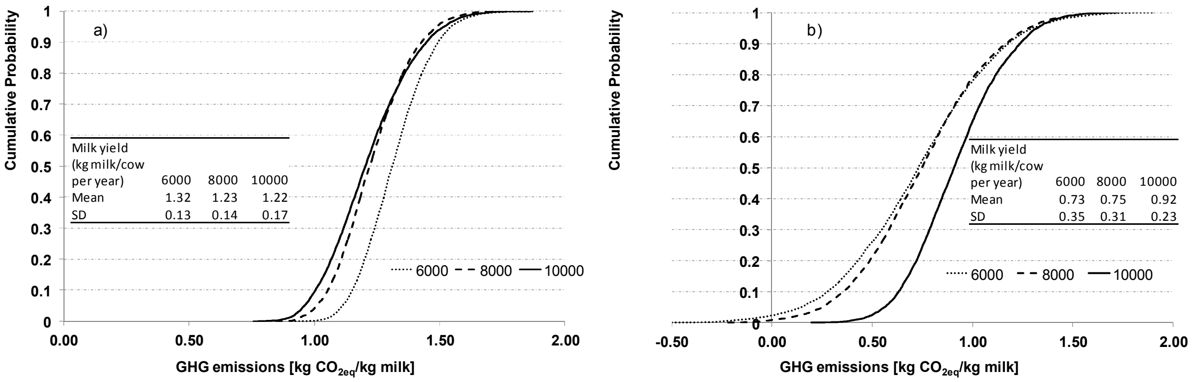
3. Results

3.1 Probabilistic simulation of all parameters

Probabilistic simulation was undertaken for all considered parameters simultaneously. Figure 2 shows cumulative probability of GHG emissions for both scenarios of handling co-products (economic allocation and system expansion). In case of economic allocation the 6 000 kg yielding dairy cow production system showed highest GHG emissions at each level of probability. Greenhouse gas emissions varied from about 1.1 to 2.4 kg CO_{2eq}/kg milk (Figure 2a). Probability that the 10 000 kg yielding dairy cow production system resulted in higher GHG emissions than the 8 000 kg yielding dairy cow production systems was 77% (Figure 2a).

The ranking of cumulative probability graphs changed if system boundary was expanded from the dairy farm gate to the whole system of milk and beef production (system expansion). Depending on the amount of beef as a co-product, modelled dairy cow production systems were credited with a certain amount of GHG emissions from suckler cow production (the alternative way producing the same amount of beef). In case of system expansion modelled production systems including 10 000 kg yielding dairy cows resulted in highest GHG emissions at each level of probability. Probability that dairy cow production system 6 000 had lower GHG emissions than dairy cow production system 8 000 was 60%. Total level of GHG emissions decreased considerably for all modelled dairy cow production systems. Greenhouse gas emissions ranged from negative values of minus -0.5 to 1.9 kg CO_{2eq}/kg milk for the 6 000 and from 0.2 to 1.7 kg CO_{2eq}/kg milk for the 10 000 yielding dairy cow production system.

Figure 2: Cumulative probability of GHG emissions considering uncertainty of GHG emission factors, production traits and prices.



a)

Milk yield (kg milk/cow per year)	6000	8000	10000
Mean	1.32	1.23	1.22
SD	0.13	0.14	0.17

b)

Milk yield (kg milk/cow per year)	6000	8000	10000
Mean	0.73	0.75	0.92
SD	0.35	0.31	0.23

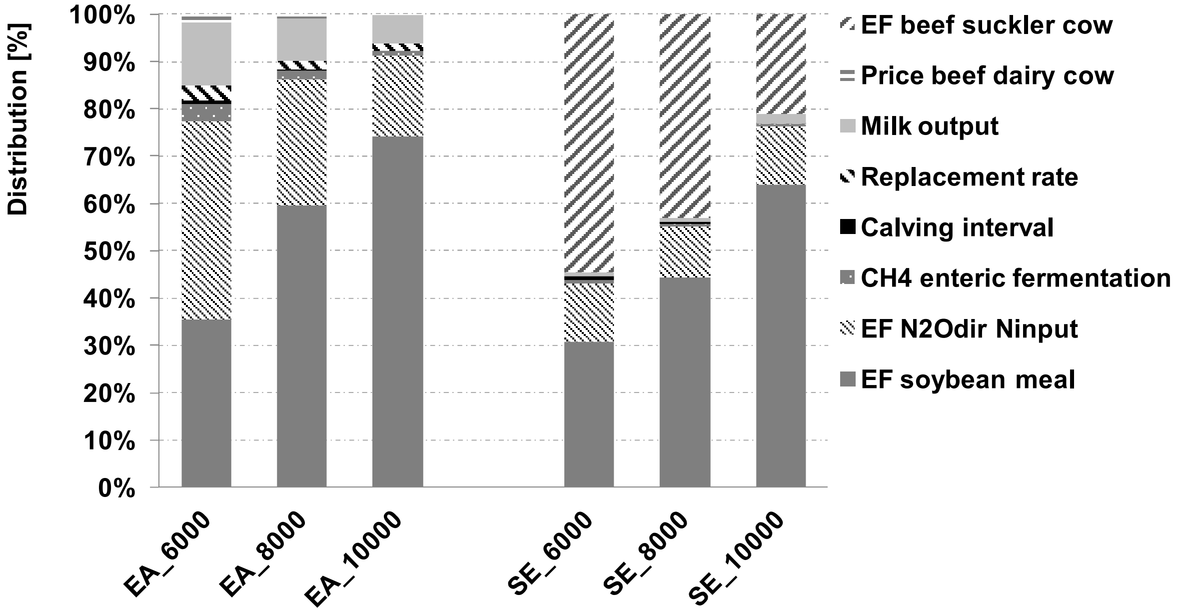
a) Economic Allocation, b) System expansion

3.2 Parameter influencing variation of GHG emission outcomes

Multivariate linear regression was undertaken calculating the impact of each input variable considered in the uncertainty modelling. In the case of uncorrelated input variables squared standardized regression coefficients sum up to r-squared value of the whole model (MURRAY AND CONNER, 2009) giving insight into the proportion of total variation of GHG emissions which can be explained by the variation of each variable (BORTZ AND WEBER, 2005). In case of economic allocation the impact of emission factors for soybean meal and direct N_2O emissions dominated total variance accounting for 79% for the 6 000 kg yielding dairy cow production system to 92% for the 10 000 kg yielding dairy cow production system (Figure 3). Furthermore, the variation of yearly milk output had an impact on variation of GHG emissions outcomes especially for the 6 000 kg yielding dairy cow production system (13%). The impact of replacement rate on total variance of GHG emissions ranged between 3-2%

In case of system expansion variation of emission factor for beef from suckler cow production had the highest impact on variation of GHG emission outcomes especially within dual purpose dairy cow production systems (54% for the 6 000 and 43% for the 8 000 yielding dairy cow production system). Impact of replacement rate could be negated (0.9 to 0.2%). Higher culling rates resulted in higher amount of beef from culled cows per year which reduced the amount of suckler cows needed for beef production. Thus, the effect of reduced GHG emissions due to lower amount of replacement heifers was reversed.

Figure 3: Parameters influencing variation of GHG emission outcomes



EA = economic allocation, SE=system expansion, EF=emission factor

4. Discussion and Conclusions

The main objective of this study was to incorporate uncertainty of main assumptions and parameters from a deterministic model modelling GHG emissions from different dairy cow production systems. Two different methods for handling co-products were used.

In consistence with other studies using deterministic model approaches (Flysjö et al., 2011; Zehetmeier et al., 2012) our study showed that the method for handling co-products had the highest impact on total value of GHG emissions. Mean values decreased up to 56% when system expansion was applied in comparison to economic allocation. Flysjö et al. (2011) discussed different methods for handling co-products comparing New Zealand and Swedish dairy cow production systems. Study results showed that GHG emissions per kg milk decreased 37% when system expansion was applied compared to allocating 100% of impacts to milk. However, in their study different allocation methods did not influence the ranking of modelled systems.

Due to the high uncertainty of emission factor for beef from suckler cow production standard deviation of GHG emissions were higher within system expansion in comparison to economic allocation. Considering uncertainty of emission factor for beef from suckler cow production even negative GHG emissions per kg milk were calculated for the dual purpose dairy cow production systems. This shows that if surplus calves from dairy cow production systems replace calves from suckler cow production systems GHG emissions from the dairy farm could be reversed. The finding that system expansion could result in negative GHG emissions emphasizes the recommendation that this method is not suitable to calculate e.g. carbon footprints of dairy farms. However, despite the high degree of uncertainties the method of system expansion gives insight if changes of GHG emissions at the dairy farm could be reversed by changes in other systems affected.

Stochastic models offer the advantage to give insight on the robustness and probability of model outcomes (Pannell, 1997). This is especially important in case of system expansion where changes of production systems are evaluated. In case of system expansion the stochastic model showed that dairy cow production system 6 000 has lower GHG emissions than dairy cow production system system 8 000 in only 60% of model runs. In contrary the increase in milk yield ongoing with a change in breed (8000 to 10000 kg milk/cow per year) resulted in higher GHG emission for the 10 000 kg yielding dairy cow production system at each stage of probability.

In case of economic allocation the main purpose of stochastic modelling was to identify factors which have an important impact on GHG emissions of milk production at the dairy farm. Stochastic models have advantage to give insight into the variation of GHG emissions outcomes and can identify most important factors. In our study regression analysis showed that uncertainty of soybean meal emission factor had the largest single impact on variation of total GHG emissions especially within high yielding dairy cow production systems. This is confirm with the study of FLYSJÖ et al. (2012) who showed that the inclusion of LUC to emission factor of soybean meal resulted in an increase of 12 up to 82% of total GHG emissions for investigated dairy cow production systems. Thus, the calculation of carbon footprints of dairy products is mostly influenced by the knowledge of production and origin of soybean meal. While the influence of dLUC e.g. from soybean meal production is already included in guidelines for carbon footprint calculations of dairy products as IDF (2010) the inclusion of iLUC in GHG modelling of dairy cow production systems is still to be discussed (FLYSJÖ et al., 2012). This should be focused in further research studies.

Uncertainty of some other parameters was not included in the modelling however being discussed in other studies: model assumption for GHG emissions from slurry storage (HINDRICHSEN et al., 2006) or carbon sequestration on grassland (SOUSSANA et al., 2010).

Whereas the choice of method for handling co-products depends on the scope of GHG modelling in dairy farming the stochastic model approach gave insight into robustness and variation of model outcomes within each method for co-product handling. This is of special importance identifying cost-effective GHG abatement options.

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Paper III

Zehetmeier, M., Gandorfer, M., Hoffmann, H., Müller, U.K., de Boer, I.J.M., Heißenhuber A. The impact of uncertainties and on predicted GHG emissions of dairy cow production systems. Journal of Cleaner production (in Press).[5]

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[5] The first author developed the approach of uncertainty classification. She conducted the modelling and all statistical analysis. She analysed and discussed the results. She composed the tables and graphs, wrote the first complete draft of the paper and revised the paper.

The impact of uncertainties on predicted GHG emissions of dairy cow production systems

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Abstract

Dairy farms produce significant greenhouse gas (GHG) emissions and are thereforea focal point for GHG-mitigation practices. To develop viable mitigation options, we need robust (insensitive to changes in model parameters and assumptions) predictions of GHG emissions. To this end, we developed a stochastic model to estimate the robustness of predictions based on input parameters (GHG emission factors and production traits) and their uncertainties.

In our study we explored how sensitive predictions of GHG emissions are to three factors: (1) system boundaries of the emission model (2) the uncertainty of input parameters due to quality of data or methodological choices (epistemic uncertainty) and (3) inherent variability in input parameters (variability uncertainty). To assess the effect of system boundaries, we compared two different boundaries: the “dairy farm gate” boundary (all GHG emissions are allocated to milk) and “system expansion”

(the model gives a GHG credit to beef derived from culled cows and bull, heifer and calf fattening of surplus dairy calves outside the farm). Results using the farm-gate boundary provide guidance to dairy farmers to reduce GHG emissions of milk production. The results using system expansion are important for defining GHG abatement policies for milk and beef production. We found that the choice of system boundary had the strongest impact on the level and variation of predicted GHG emissions. Model predictions were least robust for lower-yielding dairy cow production systems and when we used system expansion.

We also explored which GHG-abatement strategies have the most leverage by assessing the influence of each input parameter on model predictions. Predicted GHG emissions were least sensitive to variability-related uncertainty in production traits (i.e. replacement rate, calving interval). Lower-yielding production systems had the highest variation, indicating the highest potential for GHG mitigation of all production systems studied. Variation in predicted GHG emissions increased substantially when both epistemic and variability uncertainty in emission factors and variability uncertainty in production traits were included in the model.

If the system boundary was set at the farm gate, the emission factor of N_2O from nitrogen input into the soil had the highest impact on variation in predicted GHG emissions. This variation stems from uncertainties in predicting N_2O emissions (epistemic uncertainty) but also from inherent variability of N_2O emissions over time and space. The uncertainty of predicted GHG emissions can be reduced by increasing the precision in predicting N_2O emissions. However, this additional information does not reduce GHG emissions itself. Knowing site specific variability of N_2O emissions can help reduce GHG emissions by specific management (e.g. reduce soil compaction, adopted manure management, choice of suitable crops).

In case of system expansion, uncertainty in GHG emission credit for dairy beef contributed the most to increasing the variation in predicted GHG emissions.

The stochastic-model approach gave important insights into the robustness of model outcomes, which is crucial in the search for cost-effective GHG-abatement options. Despite the high degree of uncertainty when using system expansion, its results help identifying global GHG mitigation options of combined milk and beef production.

Keywords: GHG emissions, uncertainty, variability, milk yield, system boundary, beef

Highlights

We modelled variation of GHG emissions within different dairy cow production systems.

We used a stochastic-model approach to account for uncertainty and variability.

Production trait-variability contributed relatively little to variation in GHG emissions.

Predicted GHG emissions were highly sensitive to uncertainty in GHG emission credit for dairy beef.

Outcome probabilities were investigated for predicted GHG emissions of different dairy cow systems.

1. Introduction

In the search for greenhouse gas (GHG)-abatement options, agriculture has become a focal point as the livestock sector contributes greatly to its total GHG emissions (e.g. 10% of total European Union GHG emissions; Lesschen et al., 2011). In particular, milk and beef production emit high amounts of methane (CH_4) and nitrous oxide (N_2O). When trying to identify possible GHGabatement options three main points need to be considered: (1) models of GHG emissions have a high degree of uncertainty (Flysjö et al., 2011b) (2) dairy farms have high variability related uncertainty (De Cara et al., 2005; Moran et al, 2011), further increasing the uncertainty of model outcomes, and (3) changes in one system can affect emissions elsewhere due to GHG emissions leakage. Leakage occurs e.g. in dairy cow production when GHG emissions are reduced on a farm or in a country by reducing beef output but replacing the production shortfall with beef from suckler cow production or imports from other countries emitting greater GHG emissions/unit of output (Franks and Hadingham, 2012; Lee et al., 2004).

(1-2) Epistemic *uncertainties and variability-related uncertainty*

Deterministic models of GHG emissions and life cycle assessment (LCA) of dairy cow production systems are well-established in the literature (Crosson et al., 2011; de Vries and de Boer, 2010; O'Brien et al., 2011; Thomassen et al., 2008). Many guidelines and scientific studies point out the importance of incorporating uncertainty in GHG modelling (IPCC, 2006; ISO, 2006; Pannell, 1997). Stochastic models use these uncertainties to predict a range of outcomes and their likelihood. A stochastic model predicting GHG emissions of dairy cow production systems needs to distinguish the nature of uncertainty: epistemic uncertainty due to data quality or methodological choices, and variability-related uncertainty ("variability uncertainty") due to inherent variability (e.g. of production traits among dairy farms) in the systems or processes under consideration (Walker et al., 2003). Several studies explored the impact of epistemic uncertainty (e.g. the choice of GHG emission factors) on predicted GHG emissions in dairy cow production (Basset-Mens et al., 2009, Flysjö et al., 2011b; Gibbons et al., 2006; van Middelaar et al., 2013). Other studies explored the impact of variability uncertainty on predicted GHG emissions (Henriksson et al., 2011; Lovett et al., 2006; Thomassen et al., 2009). Considering both types of uncertainties is important for developing GHG-abatement options because they have fundamentally different causes and need to be addressed in different ways (Morgan and Henrion, 2006). Consideration of uncertainties provides information for policy makers and farmers on robustness (sensitivity to changes in parameters) (Mußhoff and Hirschauer, 2011) and variation of model outcomes (Pannell, 1997). Furthermore, consideration of uncertainties helps identify "variables with the most influence on predictions" (Pannell, 1997).

(3) Possible GHG emission leakage

Many deterministic model approaches (Capper et al., 2009; Zehetmeier et al., 2012) have shown that GHG emissions per kg of milk can be reduced by increasing milk yield per cow. However, high-yielding dairy cow production systems with pure milk-oriented breeds produce relatively less beef than less intensified (lower milk yield) and less specialised (dual-purpose breed) dairy cow systems (Zehetmeier et al., 2012). If less beef is provided from dairy cow production systems, this decrease would have to be compensated by increases in suckler cow production systems to maintain the same level of beef production. The link between dairy and beef production illustrates the importance of developing models that go beyond the farm gate to include links between different GHG generating-processes (Franks and Hadingham, 2012). Incorporate these links should improve the understanding of GHG emissions derived from milk and beef production. Hence, previous studies developed “system expansion” to handle co-products from dairy cow production systems (i.e. beef from culled cows and fattening of surplus calves) (Flysjö et al., 2012). System expansion accounts for the observation that GHG emissions of beef from culled dairy cows and fattened surplus dairy calves are lower than those of beef from suckler cow production systems (Nguyen et al., 2010).

The main objectives of this study were twofold:

(1) include epistemic uncertainty and variability uncertainty of main model inputs to identify those with the largest effect on variation of predicted GHG emissions

(2) quantify the robustness of model predictions in response to varying input assumptions, such as type of dairy cow production system and method to account for milk and beef output.

2. Material and Methods

This study is based on a deterministic model whose assumptions surrounding the livestock production systems and predictions of GHG emissions were described byZehetmeier et al. (2012). In the following sections we present the main assumptions of the stochastic model.

2.1. Description of main model components

2.1.1. Livestock production systems

The stochastic model incorporated three dairy cow production systems with different breeds and milk yields: 6,000 kg of milk/cow/year – dual-purpose Fleckvieh (6,000 kg

Fleckvieh-system); 8,000 kg of milk/cow/year – dual-purpose Fleckvieh (8,000 kg Fleckvieh-system); 10,000 kg of milk/cow/year – milk-oriented breed Holstein-Friesian (10,000 kg Holstein-Friesian–system).

Each system represents an average dairy cow of a typical dairy farm that is characterised plus replacement heifer from birth to age of first calving plus surplus calves until sold. The number of breeding heifers was assumed to equal to the number of cows sold to culling and lost to natural mortality (= replacement rate of the herd). The annual number of calves born was derived from calving intervals and calf mortality. Production of milk, beef and calves was based on a time period of one year for investigated dairy systems. Surplus dairy calves were assumed to be sold to bull and heifer fattening systems at a weight of 50 kg (milk-oriented Holstein-Friesian breed) or at a weight of 85 kg (dual-purpose Fleckvieh breed) representing German production systems (Brüggemann, 2011). Bull and female calves from different dairy breeds were assumed to differ in fattening characteristics such as daily live weight gain and carcass conformation. A higher fattening performance, live weight and carcass kill-out for Fleckvieh compared to Holstein-Friesian animals was assumed (Zehetmeier et al., 2012).

We assumed a feeding regime of total mixed ration fed indoors all year round for all production systems considered in the model. Feed components were maize silage, grass silage, hay, and concentrates. Total dry matter intake and the proportion of concentrates and forage in dairy cows ration were calculated in order to satisfy metabolisable energy and crude protein requirements and considering limitation on dry matter intake (Zehetmeier et al., 2012).

2.1.2 Prediction of GHG emissions

Model predictions included on-farm GHG emissions (e.g. from crop cultivation, keeping of animals, and manure management) and off-farm emissions (e.g. from production of synthetic fertilisers, pesticides, diesel, and purchased feed) (Zehetmeier et al., 2012). The model included the GHGs CH_4, N_2O and carbon dioxide (CO_2). Global warming potentials of 1, 25, and 298 were used to convert

CO_2, CH_4 and N_2O emissions into CO_2 equivalents (CO_{2eq}), respectively (IPCC, 2007).

2.1.3 Methods to handle co-products

We chose two methods to handle co-products from dairy cow production to show the impact of epistemic uncertainty and variability uncertainty on variation in predicted GHG emission intensity: "all GHGs to milk" and "system expansion" (Flysjö et al., 2011a). Both methods avoid the definition of an allocation factor to allocate GHG emissions between milk and beef, yet each arrives at a vastly different prediction of GHG emissions intensity expressed as kg CO_{2eq}/kg of milk.

For „all GHGs to milk" all GHG emissions from dairy cow production were allocated to milk. The system boundary is the dairy farm gate. As surplus calves were assumed to be sold to fattening systems beef output is confined to culled cows. This production system represents a specialised dairy farm. The "all GHGs to milk" provides a good metric for dairy farms to evaluate current and improved GHG emissions up to the dairy farm gate.

System expansion considers not only milk output but beef output from culled dairy cows and fattening of surplus dairy calves. Thus, system expansion goes beyond the system boundary of the dairy farm gate. In system expansion, also called the "avoided burden" method (Thomassen et al., 2008), beef from surplus dairy calves that were fattened in bull, heifer and calf fattening systems outside the farm gate was added to beef from culled dairy cows. Accordingly, GHG emissions occurring during the fattening of surplus dairy calves were added to GHG emissions of the dairy cow production system up to the farm gate. Dairy cow production systems received an avoided-burden GHG credit for beef output equal to the amount of GHGs that would have been emitted had the beef been produced in a sucklercow beef system (ISO, 2006). This GHG credit reduced the GHG emission intensity per kg of milk incurred by dairy cow production. Annual beef output was 322 kg/cow/year for the 6,000 kg Fleckvieh-system, 315 kg/cow/year for the 8,000 kg Fleckvieh-system and 218 kg/cow/year for the 10,000 kg Holstein-Friesian-system.

2.2 Classification of epistemic and variability uncertainties

We investigated three types of epistemic uncertainty (i.e. parameter uncertainty, model uncertainty and uncertainty due to methodological choices) and three types of variability uncertainty (i.e. temporal and spatial variability and variability within dairy cow production systems) (Table 1) (Huijbregts, 1998; Walker et al., 2003). Distinction between the nature of uncertainty i.e. epistemic uncertainty and variability uncertainty is important because they have fundamentally different causes and need to be addressed in different ways (Morgan and Henrion, 2006). Epistemic uncertainty is due to “imperfection of our knowledge, which may be reduced by more research and empirical efforts” (Walker et al., 2003). Variability uncertainty is due to the inherent variability of natural and human systems and thus natural heterogeneity of values (Walker et al., 2003); it may be reduced by disaggregation and points at possibilities for improving the system (Basset-Mens et al., 2009). Both types of uncertainty were included in the model to determine the robustness of predicted GHG emissions for different dairy cow production systems.

Model uncertainty: Model uncertainty arises from uncertainty due to simplifying assumptions implicit in mathematical expressions of relations between physical, biological or economic variables used to describe the production system (Walker et al., 2003). The prediction of emission factors for direct N_2O emissions from nitrogen (N) input into the soil (N_2O N_{input}) or CH_4 emissions from enteric fermentation (CH_{4ent}) based on measurements are examples of model uncertainty. *Parameter uncertainty.* “Empirical inaccuracy (inaccurate measurements), unrepresentativity (incomplete or outdated measurements) and lack of data (no measurements) are common sources of parameter uncertainty” (Huijbregts, 1998). In our model the lack of data on site specific N_2O N_{input} emissions is an example for parameter uncertainty (Table 1).

Uncertainty due to methodological *choices*. Examples of choices leading to uncertainty in LCA modelling are the choice of functional unit or, as in our case study, method to handle co-products which affects the GHG intensity expressed in CO_{2eq}/kg of milk (Huijbregts, 1998).

Spatial and temporal variability. Spatial and temporal variability refers to natural variability between different geographical sites (Bjorklund, 2002) and variability that occurs over time. Examination of spatial and temporal variability can help to identify the most favourable regions for milk production (Basset-Mens et al., 2009). In many cases, uncertainties in N_2O N_{input} reported in literature are influenced by spatial and temporal variability.

Variability uncertainty. Dairy cow production systems with similar milk yields and breeds can differ in production traits due to differences in farm management. The production traits chosen in our study (replacement rate and calving interval) are mentioned in the literature as important for comparing dairy cow production systems with different milk yields and breed (Knaus, 2009).

Table 1 Classification of uncertainty of main model inputs according to Huijbregts (1998) and Walker et al. (2003)

Sources of uncertainty	Epistemic uncertainty			Variability uncertainty	
Model parameter	Model uncertainty	Parameter uncertainty	Uncertainty due to choices	Temporal/Spatial variability	Variability between sources
Production traits					
Calving interval/ replacement rate					***X***
GHG emissions					
Emission factor nitrogen input into soil	***X***	***X***		***X***	
CH_4 enteric fermentation	***X***				
Emission factor beef from suckler cow production		***X***			
Methods to handle co-products[a]			***X***		

X: types of uncertainty considered in the model, [a] co-products in dairy farming (beef from culled cows and surplus calves sold to fattening systems)

2.3 Stochastic modelling using Monte Carlo simulations

To analyse the impact of epistemic uncertainty and variability uncertainty on predicted GHG emissions, we performed Monte Carlo simulations using @RISK (Palisade Corporation software, Ithaca NY USA) by varying parameters for GHG emissions factors and production traits (calving interval, replacement rate). For each dairy cow production system investigated, we ran 5,000 iterations simultaneously to obtain a probability distribution of predicted GHG emissions.

2.3.1 Parameters estimating GHG emissions

We modelled uncertainty in GHGs emitted by enteric fermentation of dairy cows (CH_{4ent}), N input into the soil (N_2O N_{input}), and suckler cow beef production (for system expansion) (Table 2). Overall, emission sources included in the stochastic model accounted for more than 70% of total GHG emissions reported in several studies (Kristensen et al., 2011; Zehetmeier et al., 2012). To account for the considerable uncertainty in CH_{4ent} emissions from the dairy cows investigated (the model used different equations from the literature (Table 2). Uncertainty in N_2O N_{input} was represented by using the uncertainty range reported by IPCC (2006). The uncertainty model used a triangle distribution to describe the probability distribution of CH_{4ent} and emission factor for N_2O N_{input} based on their minimum, maximum and most likely values (Table 2) following previous studies (Lovett et al., 2008). These GHG emission factors were assumed to be independent because they do not interact.

Emission factors for GHG emissions from suckler cow beef production were taken from Crosson et al. (2011), who summarised GHG emissions from beef production systems from different countries and based on different models. From Crosson et al. (2011) we included 15 values for GHG emissions of beef from suckler cow production and assumed a uniform distribution. Emission factors per kg beef varied from 15.6 to 37.5 kg CO_{2eq} (Table 2).

Table 2 Minimum, maximum, most likely values and shape of distribution for greenhouse gases emissions and emission factors (EF) considered in the uncertainty modelling

	Most Likely	Minimum	Maximum	Probabilistic distribution
CH_4 enteric fermentation (kg CH_4/dairy cow) (6,000/8,000/10,000)[a]	128[b]/135[b]/138[b]	105[c]/116[c]/127[c]	140[d]/152[d]/157[d]	Triangle
EF N_2O N_{input}[e] (kg N_2O-N/kg N)	0.01[f]	0.003[f]	0.03[f]	Triangle
EF beef from suckler cow production (kg CO_{2eq}/kg beef)		15.6[g]	37.5[g]	Uniform

[a]kg milk/cow/ year; sources of equations used to model CH_4 emissions: [b]Kirchgeßner et al. (1995); [c]Dämmgen et al. (2009); [d]Jentsch et al. (2009) ; [e]nitrogen input into the soil; [f]IPCC (2006);[g]Crosson et al. (2011)

2.3.2 Production traits

Our study focused on two traits of dairy cow production systems that are closely linked to milk yield per cow (Knaus, 2009; Roemer, 2011): replacement rate and calving interval. We used data from 19,070 dairy farms breeding Fleckvieh cows and 3,200 dairy farms breeding Holstein-Friesian cows for the time period 2004 to 2010 to identify variability in replacement rate and calving interval within dairy cow production systems of equal milk yield/cow/year and breed. Data were provided by LKV Bayern (unpublished data, 2004 to 2009) and LKV Weser Ems (unpublished data, 2004 to 2010). We fitted weighted linear regression models (weighted by farm size) with detrended milk yield/cow/farm as the dependent variable and replacement rate (%) per farm and average calving interval (days) as independent variables. We used quantile regression (Koenker, 2005) to calculate the standard deviation (SD) of replacement rate and calving interval for dairy cow production systems yielding 6,000, 8,000 and 10,000 kg of milk/cow/year. The resulting production trait values for these systems are shown in Table 3. We assumed that all production traits were normally distributed and we found no statistically significant correlations between production traits.

Table 3 Mean and standard deviation (SD) to generate a normal distribution for stochastic modelling of production traits (calving interval and replacement rate)

System milk yield (kg milk/cow/yr)	Calving interval (days)		Replacement rate (%)	
	Mean	SD	Mean	SD
6,000[a]	405	22	32.6	7.6
8,000[a]	389	15	36.7	7.6
10,000[b]	416	17	30.3	6.4

Yr=year, normal distribution; [a] evaluation of data for 19,070 Fleckvieh dairy farms from LKV Bayern (unpublished data, 2004 to 2009); [b]evaluation of data for 3,200 Holstein-Friesian dairy farms, from LKV Weser Ems (unpublished data, 2004 to 2010)

2.4 Impact of a single parameter on variation in predicted GHG emissions

We identified the impact of each parameter considered in the uncertainty modelling on variation in predicted GHG emissions within each modelled dairy cow production system (6,000 kg Fleckvieh-system, 8,000 kg Fleckvieh-system, 10,000 kg Holstein-Friesian-system). We used multivariate linear regression implemented in @Risk to calculate standardised regression coefficients. Standardised regression coefficients were used to identify variable importance of multiple regression models. The coefficients predict “the standard deviation change in the dependent variable when the independent variable is changed by one standard deviation, holding all other variables constant” (Murray and Conner, 2009). If the input variables are independent, then the sum of all squared standardized regression coefficients is equal to the r-squared value of the whole model (Murray and Conner, 2009). This relation provides insight into the contribution of each input variable to the total variation in predicted GHG emissions (Bortz and Weber, 2005). When interpreting regression coefficients it is important to keep in mind that coefficients reflect both the uncertainty of the input variables and the sensitivity of the model to this particular parameter (Basset-Mens et al., 2009).

3. Results

3.1 Variation of predicted GHG emissions

3.1.1 Variability uncertainty in production traits

For all GHG to milk, mean predicted GHG emissions per kg of milk for all dairy cow production systems decreased with increasing milk yield. For system expansion, predicted GHG emissions per kg of milk were considerably lower due to crediting beef output with emissions from suckler cow production. Furthermore, dual-purpose lower-yielding dairy cow production systems (6,000 and 8,000 kg Fleckvieh-system, higher beef output per t of milk) resulted in lower predicted GHG emissions compared to the higher-yielding milk-oriented Holstein-Friesian breed dairy cow production system (10,000 kg Holstein-Friesian-system, lower beef output per t of milk) (Table 4). These results can be attributed largely to the high GHG credits for avoided beef production from suckler cows. Including only variability uncertainty in production traits in Monte Carlo simulations, resulted in a relatively low SD of predicted GHG emissions (SD = 0.068 to 0.016) (Table 4). For both methods of handling co-products, the SD of GHG emissions per kg of milk decreased with increasing milk yield of dairy systems. The fact that higher-yielding systems have a lower variation in predicted GHG emissions can be attributed largely to lower variability uncertainty in production traits in the high-yielding production systems (Table 3).

3.1.2 Epistemic and variability uncertainties

When both epistemic and variability uncertainties were included in the modelling, then variation of predicted GHG emissions increased considerably due to the high uncertainty of epistemic uncertainty model inputs. We observed the highest variation in predicted GHG emissions under system expansion. This high variation was mainly caused by the highly uncertain emission factor for beef derived from suckler cow production. Uncertainty of emission factor for suckler cow beef was classified as parameter uncertainty, which means that there is a lack of knowledge on GHG emissions of the replaced suckler cow production system. The Fleckvieh-system yielding 6,000 kg of milk/cow/year had the highest variation in predicted GHG emissions (SD = 0.3 kg CO$_{2eq}$/kg of milk; Table 4). There is a high uncertainty in the credit for beef from suckler cow systems and relatively high beef output from the lowest yielding dairy cow system (ca. 55 and 22 kg of beef/t milk for the 6,000 kg Fleckvieh-system and the 10,000 kg Holstein-Friesian-system, respectively). Differences in mean predicted GHG emissions between models that consider only variability uncertainty and those that consider epistemic and variability uncertainties can be attributed to the skewed triangle distributions of the epistemic uncertainties.

Table 4 Mean, standard deviation (SD), coefficient of variation (CV) and confidence interval of greenhouse gas (GHG) emissions (in kg CO$_{2eq}$/kg milk) for the dairy cow production systems investigated via uncertainty modelling

Method to handle co-products		All GHGs to milk			System expansion		
		Dairy cow production system (kg milk/cow/ year)					
Indicator		6,000	8,000	10,000	6,000	8,000	10,000
Considering only variability of production traits							
Mean		1.366	1.136	0.923	0.241	0.243	0.465
(of which credit for beef output[a])					(1.406)	(1.102)	(0.880)
SD		0.068	0.051	0.035	0.051	0.030	0.016
CV		0.049	0.045	0.038	0.212	0.125	0.033
Confidence Interval (95%)	Lower Limit	1.255	1.053	0.867	0.154	0.194	0.440
	Upper Limit	1.478	1.220	0.980	0.322	0.293	0.487
Considering both epistemic uncertainty of GHG modelling and variability in production traits							
Mean		1.432	1.201	0.986	0.323	0.321	0.534
(of which credit for beef output[a])					(1.403)	(1.100)	(0.886)
SD		0.133	0.107	0.085	0.300	0.234	0.137
CV		0.093	0.089	0.086	0.929	0.731	0.257
Confidence Interval (95%)	Lower Limit	1.231	1.041	0.860	-0.237	-0.111	0.296
	Upper Limit	1.670	1.388	1.138	0.786	0.684	0.755

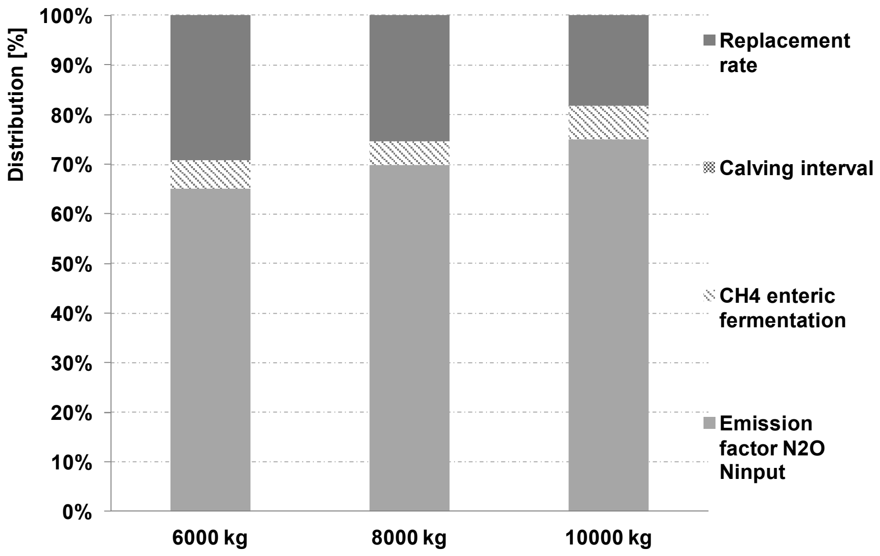
[a] value based on emission factor for suckler cow beef production

3.2. Impact on variation in predicted GHG emissions

For all GHGs to milk, the N_2O N_{input} contributed most to variation in predicted GHG emissions. 77% (10,000 kg Holstein-Friesian-system) to 65% (6,000 kg Fleckvieh-system) of variation in predicted GHG emissions were explained by uncertainty of this emission factor. Variability uncertainty in replacement rate was the second greatest contributor (Figure 1a). The effects of variability uncertainty in replacement rate were stronger in lower-yielding dairy cow production systems (30 %) (Figure 1). In contrast, variability in calving interval did not influence variation in predicted GHG emissions for all GHGs to milk because calves are sold to fattening systems outside the dairy farm gate and are thus only marginal included in GHG emission modelling.

For system expansion, uncertainty in the emission factor for beef from suckler cow production systems had the highest impact on variation in predicted GHG emission outcome (i.e. from 79% of total variation in predicted GHG emissions in the 6,000 kg Fleckvieh-system to 62% in the 10,000 kg Holstein-Friesian-system (Figure 1b). The second biggest contributor was N_2O N_{input}, which explained 18% to 35% of the total variation in predicted GHG emissions; Figure 1b). The combined contribution of the remaining factors was less than 5%, with variability uncertainty in calving interval explaining 2.5% (6,000 kg Fleckvieh-system) to 0.9 % (10,000 kg Holstein-Friesian-system). Impact of calving interval was higher for dual-purpose dairy cow production systems (Figure 1b) as surplus calves show better fattening characteristics resulting in a higher beef output/cow/year.

a)



b)

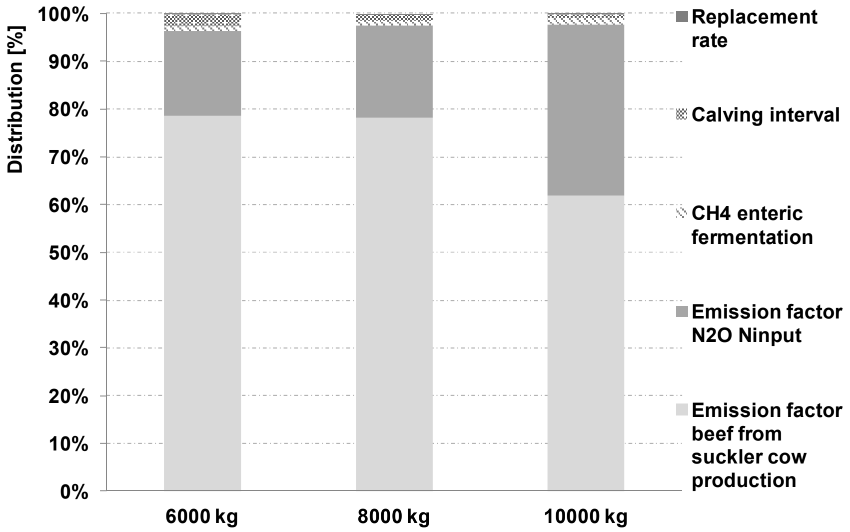


Figure 1 Parameters influencing variation in predicted greenhouse gas (GHG) emissions under a) “all GHGs to milk” b) and “system expansion” methods to handle co-products

3.3 Probability of predicted GHG emissions of dairy cow production systems

Cumulative distributions give insight into the probability of GHG emission outcomes as they display probabilities that emissions will be lower than a given amount. For all GHGs to milk lower-yielding systems resulted in higher GHG emissions per kg of milk at each level of probability. This indicates high probability that predicted GHG emissions of higher-yielding systems are lower compared to lower-yielding systems considering the system boundary of a typical dairy farm (dairy cow, heifers, selling of surplus calves).

For system expansion the model predicted a 49% probability that the 6,000 kg Fleckvieh-system generates lower GHG emissions per kg of milk than the 8,000 kg Fleckvieh-system (Figure 2). The probability that the 6,000 kg Fleckvieh-system has lower GHG emissions per kg of milk than the 10,000 kg Holstein-Friesian-system exceeds 91% (Figure 2). In contrast, the 10,000 kg Holstein-Friesian-system had higher GHG emissions per kg of milk than the 8,000 kg Fleckvieh-system at each stage of probability (first degree stochastic dominance) (Figure 2).

We found negative GHG emissions per kg of milk in 9% (8,000 kg Fleckvieh-system) and in 13% (6,000 kg Fleckvieh-system) of model iterations. In these cases, the avoided GHG emissions from suckler cow beef production were higher than the GHG emissions incurred by the dairy cow production system.

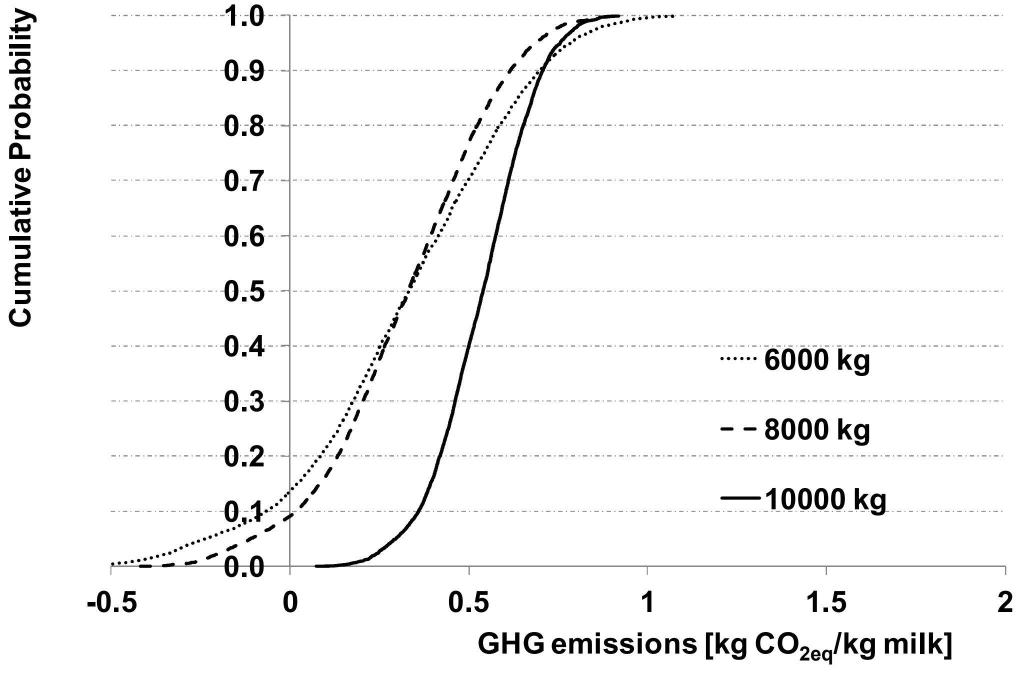


Figure 2 Cumulative probability of greenhouse gas (GHG) emissions for dairy cow production systems differing in milk yield and breed based on Monte Carlo simulation in @Risk; System expansion was used to handle co-products

4. Discussion

4.1 Methods to handle co-products

We applied two methods to investigate the variation of GHG emission outcomes within different dairy cow production systems, i.e. “all GHGs to milk” and “system expansion”. In both cases a comprehensive interpretation of results needs to consider the main model assumptions and system boundaries. The “all GHG to milk” method appears suitable for dairy farms to quantify GHG emissions and their variations at the farm level. Its results provide guidance for dairy farmers to reduce GHG emissions at the farm. As system expansion accounts for milk and beef production beyond the boundary of the dairy farm gate, its results are important for politicians and decision makers to evaluate GHG emissions of regional or global milk and beef production. Results are also important for defining GHGabatement policies for both food production systems.

Our study shows the stark contrast between predictions of a model allocating all GHG emissions to milk (all GHGs to milk) and one using system expansion. While the first method emphasises increasing milk yield as an abatement option on the dairy-farm level, the second indicates that any beneficial effects of increasing milk yield might be negated by GHG emission leakage due to increase in beef production from suckler cow systems. Franks and Hadingham (2012) emphasise that prediction of GHG emissions that are restricted to the dairy farm gate can lead farmers to adopt GHG mitigation options that inadvertently increase global GHG emissions despite lowering farm emissions. Our study showed that dairy cow production systems are such an example, because varying milk yield per cow affects beef production; hence, predicted GHG emissions of the two models differ. Flysjö et al. (2011a) also, found that these methods for handling co-products yield different results: GHG emissions per kg of milk dropped by ≤37% when system expansion was used compared to all GHGs to milk. Mean GHG emissions in our study decreased 46 to 77% for system expansion in comparison to all GHGs to milk (Table 4). System expansion assumes that beef from dairy cow production systems (culled cows, fattening of surplus calves) is needed on the market and will replace beef from suckler cows (Flysjö et al., 2011a; Zehetmeier et al., 2012). However, it could also be assumed that beef from dairy cow production replaces pork or poultry meat which would lead to lower credits for beef output increasing the net GHG emissions of lower-yielding dairy cow production systems (Flysjö et al., 2011a). Furthermore, we did not distinguish between different qualities of beef. Whether beef from culled cows can be considered equal to beef from suckler cow production should continue to be discussed.

4.2 Variation in predicted GHG emissions and identification of most important variables

We identified a relatively small impact of variability uncertainty in production traits on variation in predicted GHG emissions within the dairy cow production systems investigated. For all GHGs to milk, variability uncertainty in replacement rate showed an impact on variation in predicted GHG emission outcomes. Variability in number of replacement heifers caused comparatively high variations in GHG emission outcomes. The impact of replacement rate was higher for production systems with lower-yielding cows due to higher variability in replacement rate (Table 3). Thus, farmers, especially those with lower-yielding herds, have a certain potential to mitigate GHG emissions by increasing the longevity of dairy cows. This finding agrees with Garnsworthy (2004), who concluded that in the UK a decrease in the number of heifers needed for replacement could decrease CH_4 emissions by 11% per herd compared to 1995 levels.

The impact of replacement was small in case of system expansion since the impact on GHG emissions due to changing numbers of heifers was compensated by changes in beef output from culled cows (GHG emission credit for avoided suckler cow beef production). For system expansion, variability uncertainty in calving interval showed an impact on variation in predicted GHG emission outcomes. Calving interval affects the number of calves available for bull, heifer and calf fattening and thus beef output/cow/year. Lower calving intervals and thus more calves/cow/year can be an option to reduce GHG emissions considering both milk and beef production. The potential of improvement is again higher within lower-yielding dairy cow production systems as surplus calves of lower-yielding Fleckvieh systems were assumed to have better fattening characteristics resulting in a higher beef output/cow/year and due to higher variability uncertainty in calving interval.

Regardless of the method used to handle co-products, higher-yielding dairy cow production systems showed lower impact of production traits on variation in predicted GHG emissions and thus less potential for GHG mitigation. This may indicate that within higher-yielding dairy cow production systems more focus is given to management resulting in lower variability in production traits among farms. A more narrow focus on herd management might decrease variability in production traits among lower-yielding farms.

Considering both epistemic uncertainty and variability uncertainties variation in predicted GHG emissions increased for all dairy cow production system. The emission factor of N_2O from N_{input} had the highest impact for all GHGs to milk and the second highest impact for system expansion on variation in predicted GHG emissions. This result is consistent with Flysjö et al. (2011b) and Basset-Mens et al. (2009), who found that this emission factor was one of the highest contributors to uncertainty in GHG emissions from milk production. Uncertainty in the N_2O N_{input} emission factor in our study mainly stemmed from model uncertainty in finding a precise way to predict N_2O emissions but also from inherent variability of N_2O emissions over time and space. Model uncertainty of N_2O N_{input} emission factor could be reduced if the location of dairy farms was specified and measurements or models for single fields were available. One approach to identify field specific N_2O emission factors in Germany is discussed by Dechow and Freibauer (2001). Dechow and Freibauer (2011) emphasize that demand on amount and quality of data is high and thus not often available for more specified models. However, this additional information does not reduce GHG emissions itself.

Furthermore, variability uncertainty due to temporal and spatial variability within and between dairy farms would remain. There is a high range of N_2O emission factors caused by field differences (e.g. type of soil and climate) (Jungkunst et al., 2006). Knowing site specific variability of N_2O emissions can, however, help to reduce GHG emissions by specific management (e.g. reduce soil compaction, adopted manure management, choice of suitable crops) (Dechow and Freibauer, 2011; van Groenigen et al., 2008).

For system expansion, the high uncertainty in the emission factor for beef from suckler cow production explained 60 to 80% of the total variation in predicted GHG emissions and thus dominated uncertainty compared to all other input uncertainties. This high parameter uncertainty resulted from a lack of data about which suckler cow beef production system should be chosen to credit beef production from dairy cow production systems. Epistemic uncertainty in our model could be reduced if the origin and production system of suckler cow beef used to credit dairy cow beef were known, which requires knowing where beef would come from if it was not produced as a co-product from dairy cow production. These data are difficult to determine at a regional or international level.

It has to be considered that the contribution of single model parameters to variation in predicted GHG emissions depends strongly on the parameters included in uncertainty modelling. Epistemic uncertainty in emission factors for soybean meal due to direct land use change had a large impact on variation in predicted GHG emissions in other studies (Flysjö et al., 2012; Zehetmeier et al., 2012), but this was not included in our study. The type and amount of land use and land use changes due to changes in dairy and beef production will be the focus of further studies. Furthermore, feed conversion efficiency can be considered as an important source of variability uncertainty between dairy cows and farms (Henriksson et al., 2011) but was not investigated in this study.

4.3 Probability of predicted GHG emissions for dairy cow production systems

Our model showed high probability of occurrence that lower-yielding dairy cow production systems have higher GHG emission per kg of milk compared to higher-yielding systems when all GHGs were allocated to milk (10,000 kg Holstein-Friesian-system compared to 8,000 kg Fleckvieh-system; 8,000 kg Fleckvieh-system compared to 6,000 kg FV-system). This result is important for dairy farmers who want to decrease GHG emissions per kg of milk, e.g. if a carbon tax on GHG emissions were introduced.

For system expansion, the 10,000 kg Holstein-Friesian-system had higher predicted GHG emissions than the 8,000 kg FV-system and the 6,000 kg FV-systems, with a probability of 100 and 91%, respectively. Variation in predicted GHG emissions within the Fleckvieh systems was high. And switch from a 8,000 kg Fleckvieh-system to a

6,000 kg Fleckvieh-system has a roughly equal probability of increasing or decreasing GHG emissions. At regional and global levels, results of system expansion should help politicians and decision makers to find appropriate measures to mitigate GHG emissions from milk and beef production. This result also shows that GHG abatement-policies (e.g. carbon taxes, agri-environmental policies) need to consider both milk and beef production systems to avoid leakages. However, it is important to point out that the advantages of “system expansion” are countered by the high degree of variation it gives to results.

5. Conclusions

Comparing GHG emissions of dairy cow production systems and exploring their potential of GHG emission leakage is a three-step process. First, to identify “hot spots” (i.e. parameters that contribute most to GHG emissions), methods such as “all GHGs to milk” should be used to calculate GHG emissions based on the system boundary of the dairy farm gate (Moran et al., 2011). In the second step, system expansion can be used to ensure that production systems with lower farm-gate GHG emissions do not inadvertently increase overall GHG emissions due to shift of GHG emissions to other food production sectors or countries (GHG emission leakage). In the third step, stochastic models are particularly useful because they provide insight into the robustness of model predictions (Pannell, 1997). This study demonstrates the importance of taking into account epistemic and variability uncertainties and one possibility of GHG emission leakage (i.e. shift of GHG emissions from dairy beef production to suckler beef production systems).

However, differences in milk yield are likely to lead to leakage effects not only in beef production, but also e.g. in land use. Future studies should explore additional leakage effects and epistemic and variability uncertainties, e.g. of feed intake, cattle fattening systems and manure management.

There is a big interest in quantifying carbon footprints. However, our study shows that current LCA methods are not very precise because of large epistemic and variability uncertainties. The implementation of a single carbon footprint for different dairy cow production systems is problematic because of these uncertainties but also due to various other environmental impacts (e.g. biodiversity, nitrogen leaching).

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Paper IV

Zehetmeier, M., O'Brien, D., Hofmann, G., Dorfner, G., Heißenhuber A., Hoffmann, H. An assessment of variable importance when predicting greenhouse gas emissions, beef output and land use of dual purpose and specialized German dairy farms. (under Review).[6]

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[6] The first author prepared the data from the BZA-Milk database to conduct modelling of greenhouse gas emissions. She developed the conceptual approach of the paper and conducted all modelling and statistical analysis. She analysed and discussed the results. She developed the first complete draft of the paper.

An assessment of variable importance when predicting greenhouse gas emissions, beef output and land use of dual purpose and specialized German dairy farms

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Abstract

The goal of this study was to firstly compare GHG emissions, land use and beef output per kg of fat and protein corrected milk (FPCM) of dual purpose and specialized German dairy farms using a life cycle approach and secondly determine the relative importance of parameters explaining variability of GHG emissions, beef and land use outcomes. In total, 27 dairy farms from south Germany with dual purpose Fleckvieh cows (South-FV) and 26 dairy farms from west Germany with Holstein-Friesian cows (West-HF) both feeding total mixed rations were assessed. Modelling of GHG emissions was based on international LCA guidelines and included all emissions up to the moment milk is sold from the farm. Beef output was calculated as actual (beef from culled cows) and potential beef output (includes beef from culled cows and from fattening of surplus calves outside the farm). Stepwise multiple linear regression and dominance analysis was used to identify parameters that have the highest impact on variation of GHG emissions, beef output and land use. The results showed that South-FV dairy farms emitted greater GHG emissions/kg of FPCM ($P<0.01$) than higher yielding West-HF dairy farms. A wide range in GHG emissions within region was found from 0.90-1.25 kg CO_2-eq/kg of FPCM for South-FV German farms and 0.79-1.20 kg CO_2-eq/kg of FPCM for West-HF German farms. Average beef output/kg of FPCM of West-HF dairy farms was significantly lower compared to South-FV dairy farms. Outcomes of variable importance analysis showed that milk yield and replacement rate had a high impact on variation of GHG emissions and beef output of both dairy farm groups. A trade off between GHG emissions/kg of FPCM and beef output/kg FPCM was shown in the case of increasing milk yield and reducing replacement rate. However, the impact of replacement rate on potential beef output/kg of FPCM was sensitive to assumptions made to estimate potential beef output. No difference between the regions and breeds was found in case of land use/kg of FPCM. The analysis is a first approach identifying the parameters of commercial dairy farms that are key contributors to GHG emissions/kg of FPCM and are also highly variable between farms indicating a high potential to mitigate GHG emissions. It was also shown that it is important to identify those parameters that have a negative impact on beef output to avoid shifting GHG emissions between production systems.

Key words: GHG emissions, beef output, land use, variable importance, milk yield, replacement rate

1. Introduction

With approximately 530 thousand specialised dairy farms and a milk output of 152 million tonnes (European Commission, 2011; Gorn, 2012), milk production plays an important role in the whole European Union (EU-27). While achieving a viable income is the basic goal of most farmers, there is now an increasing focus on dairy farmers, by consumers and policy makers, to minimise the effects dairy farming has on the environment and in particular climate change. On average livestock production emits about 9% of total EU-27 GHG emissions. The contribution of dairy farming to total livestock GHG emissions of individual EU-27 nations ranges from 22% in Spain to 70% in Latvia (Lesschen et al., 2011). Efforts to reduce emissions from dairy farming have so far been limited due to “disagreements over the abatement potential, technical feasibility, and cost-effectiveness" of the policy instruments available (Cooper et al., 2013).

In addition, there is uncertainty on how to measure emission reductions due to system boundary complications which may lead to carbon leakage. Carbon leakage occurs when GHG emissions are reduced on a farm or in a country by reducing production but replacing the production shortfall with increased output from another farm or imports from other countries that emit greater GHG emissions/unit of output (Franks and Hadingham, 2012; Lee et al., 2004; Webb et al., 2013). In order to identify GHG mitigation potential on commercial farms it is important to investigate variability of emission sources between farms and to address the risk of carbon leakage attributed to single on-farm mitigation options. Most studies comparing GHG emissions of different dairy cow production systems are based on model approaches and sensitivity analysis of case studies or single research farms (Flysjö et al., 2011b; O'Brien et al., 2012; Zehetmeier et al., 2012). A major advantage of these studies is that they refer to detailed data from literature or measurements. However, the potential from these studies are limited as these experiments are expensive and limited to only small numbers for each region.

Furthermore, these studies do not give insight into variability of investigated outcomes between farms and identification of those parameters that have the highest impact on variability of investigated farm outcomes. Assessing the parameters that influence variability between GHG emissions of dairy farms is important to identify mitigation potential. For instance, if parameters that contribute to dairy farms GHG emissions have a low variability between farms there is little room for improvement. However, where a parameter significantly contributes to sensitivity of GHG emission outcomes and also shows a large variability between farms it has a high potential to mitigate GHG emissions (Figure 1). Parameters or variables that are high contributors to GHG emissions and show a high degree of variability are defined as "important parameters/variables" (Azen and Budescu, 2003).

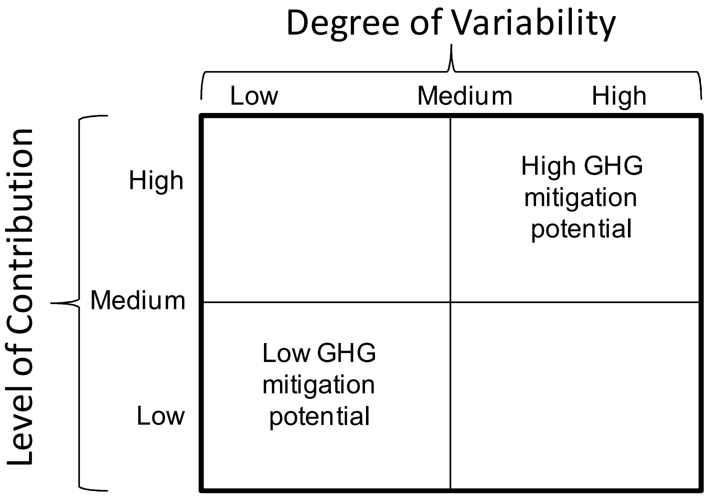

Figure 1: A matrix of variability of parameters versus contribution of parameters on greenhouse gas (GHG) emissions (Makinson et al., 2012; Heijungs, 1996)

Relatively few studies give insight into variability of emission sources and parameters between farms by modelling GHG emissions of commercial dairy farms due to the high amounts of data required (Cederberg and Flysjö, 2004; Christie et al., 2012; Haas et al., 2001; Thomassen et al., 2008; van der Werf et al., 2009). These studies mainly focus on inter-system comparison of different dairy farming systems and did not undergo intra-system comparison of single farms to give insight into variability between farms of one system apart from Christie et al. (2012). Studies which investigate GHG emission of commercial dairy farms can also be distinguished by the type of dairy farm systems that were compared. Cederberg and Flysjö (2004), Haas et al. (2001), Thomassen et al. (2008) and van der Werf et al. (2009) compare GHG emissions of conventional and organic dairy farms. Chrisitie et al. (2012) focused on a comparison of dairy farms from diverse geographical locations in Australia. However, none of these studies address the influence of the type or breed of cow on dairy production systems GHG emissions.

Previous modelling and case studies (Capper and Cady, 2012; Flysjö et al., 2011b; O’Brien et al., 2010) have reported that the breed or type of cow has an important affect on total farm GHG emissions due to differences in production traits (e.g. milk yield). Generally, the effect of dairy breeds on GHG emissions is assessed by comparing breeds specifically selected for milk production such as Holstein-Friesian (HF) and Jersey cows. One of the main reasons for this is the dominance of HF dairy cows in most developed countries (e.g. over 90% of total dairy cows are estimated to be HF breed in Canada, USA and UK; WHFF, 2011). However, in some European countries dual purpose breeds, such as Fleckvieh (FV) dairy cows still play an important role. The contribution of dual purpose FV dairy cows to national dairy cow populations is 80% in Austria and Serbia, 50% in Slovenia and Czech-Republic, 16% in France and Switzerland. In Germany about 30% of the dairy cow population are dual purpose FV breed mainly located in the south of Germany (ESF, 2013). The FV breed is mainly characterised by a lower milk yield per cow, a higher live weight per dairy cow and better fattening characteristics of surplus female and bull calves (Haiger and Knaus, 2010, Geuder et al., 2012).

The overall aim of this study was to investigate GHG emissions/kg of fat and protein corrected milk (FPCM) of commercial dairy farms from two regions in Germany as affected by breed using a life cycle approach. We further investigated beef output and land use/kg of FPCM. These are important indicators that need to be considered when comparing GHG emission of dairy farms as changes in beef output or land use of dairy farming could result in carbon leakage (Smith et al., 2013).

We specifically aimed to identify:

(i) the impact of different parameters on GHG emissions, beef output and land use

(ii) the relative importance of these parameters explaining variability of investigated farm outputs.

2. Material and Methods

2.1. BZA-Milk Database

Data from BZA (economic performance of milk production branch within a farm)-Milk network (Dorfner and Hofmann, 2012) were taken to calculate GHG emissions, potential beef output (beef from culled cows and fattening of surplus calves outside the dairy farm gate) and land use of commercial dairy farms. BZA-Milk is a farm accounting platform established to calculate economic, physical and management parameters of German dairy farms on a yearly basis. The BZA-Milk database was used to model GHG emissions from dairy farms as this database has several advantages:

- contrary to other farm accounting tools (e.g. European Commission, 2011) BZA-Milk provides several physical and supplementary data besides economic data which are reported by farm advisors e.g. production and fertility traits such as calving interval and replacement rate, feed intake of dairy cows, calf and heifer mortality, type and amount of mineral fertilizer application, yield of forage and concentrates produced on-farm and type of feed purchased
- inputs and outputs of other enterprises on the dairy farm that are not connected to milk production are excluded (e.g. production of cash crops).

2.2. Farm selection

We used the group of dairy farms out of the BZA-Milk database that are defined as high-performing-dairy farms. These farms have a better economic performance, and higher production trait performance compared to the average of farms reported in BZA-Milk. They are also expected to be the most competitive under future market conditions. Four groups of high-performing-dairy farms, representing south, west, north and east Germany are defined each year to compare economic and production trait performance of dairy production systems (Dorfner, 2013). The group of west and south high-performing-dairy farms was chosen for this study to represent two different dairy breeds. Holstein-Friesian is the dominant breed of west dairy farms (87% of farms) and FV is the most important breed for south dairy farms (57% of farms; Dorfner, 2013). Farms with breeds other than FV or HF were excluded from the study. Furthermore, farms that fed a total mixed ration (TMR) were only selected. This was to guarantee homogeneity in feeding regime. Cows were housed throughout the year in all the farms analysed. Grass and maize silage were the most important forage components. The choice of high-performing-dairy farm groups also provides certain homogeneity in terms of management ability of the farmer. Thus, the comparison of south and west high-performing-dairy farms stresses the effect of breed and region.

2.3. Farm description

After screening the high-performing-farms in the BZA database, a total of 27 dairy farms breeding dual purpose FV dairy cows from the state Bavaria in the south of Germany (South-FV) and 26 dairy farms breeding HF dairy cows from the state of Nordrhein-Westfalen in the west of Germany (West-HF) were available. The main characteristics of investigated dairy farms reported from BZA-Milk data base are summarized in Table 1. Average dairy cow herd size of analysed West-HF dairy farms was 73% higher compared to South-FV dairy farms reflecting structural differences of the two regions (Table 1). Milk yield per cow was approximately 1,000 kg higher for West-HF dairy farms reflecting the lower milk yield of dual purpose dairy farms. As selected farms belong to the group of high performing BZA-Milk dairy farms milk yield per cow was high relative to the average performance on-farm within the same region and with the same or similar breed of cow. Average milk yield of dairy farms participating in milk recording in 2010 was 8,800 kg of milk/cow per year in Nordrhein-Westfalen and 7,000 kg of milk/cow per year in Bavaria (ADR, 2012). The mean calving interval of West-HF dairy farms was 30 days longer compared to the FV dairy farms reflecting lower fertility of milk breed dairy cows (Rehak et al., 2012). Reported feed dry matter intake/cow/year was about 600 kg higher for the West-HF dairy farms compared to South-FV farms due to higher milk yield per cow.

Table 1: Farm characteristics for the group of investigated South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms (maximum and minimum in parentheses)

		South-FV				West-HF			
Item	Unit	Mean	(max-min)	SD	CV	Mean	(max-min)	SD	CV
Dairy cows	#	86	(145-49)	23	0.27	149	(457-67)	85	0.57
Milk yield	kg FPCM/cow per year	8559	(9840-7507)	655	0.07	9596	(10680-8186)	700	0.07
Milk fat	%	4.1	(4.49-3.94)	0.12	0.03	4.01	(4.27-3.62)	0.13	0.03
Milk protein	%	3.47	(3.60-3.30)	0.08	0.02	3.4	(3.50-3.30)	0.05	0.01
Replacement rate	%	29	(55-14)	8	0.28	27	(51-15)	9	0.33
Calving interval	days	380	(416-359)	13	0.03	410	(461-380)	19	0.04
Dairy cow losses	%	1.74	(5-0)	1.6	0.92	4.47	(15-1)	2.76	0.61
Calf losses	%	5.91	(16-0)	3.8	0.64	6.62	(20-0)	4.47	0.68
Age of first calving	Months	28	(31-26)	1.6	0.06	27	(31-25)	1.6	0.06
Feed intake dairy cow	kg DM/cow per year	7081	(8816-6153)	614	0.09	7686	(8700-7033)	459	0.06
Feed intake heifer	kg DM/heifer per year	6327	(8870-3671)	967	0.15	5843	(7545-4498)	804	0.14

FPCM=fat and protein corrected milk, DM=dry matter, SD=standard deviation, CV= coefficient of variation

On average, grass silage and maize silage contributed more than 80% of forage dry matter intake of dairy cows within both investigated farm groups (Table 2). The main concentrate feeds were compound concentrate mixes and straight concentrates of winter wheat, barley, rapeseed meal and soybean meal. The dairy farms analysed also fed hay, clover silage, brewer’s grain silage, sugar beet pulp silage, lucerne and concentrates as corn, dried beet pulp, oat or bean. However, the average contribution of these feeds to the total feed intake of cows or heifers was low because they were a small component of the diet or they were used by the minority of farms.

Table 2: Reported composition of feed ration for the group of investigated South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms (maximum and minimum in parentheses)

		South-FV				West-HF			
Item	Unit	Dairy Cow		Heifer		Dairy Cow		Heifer	
		Mean	(max-min)	Mean	(max-min)	Mean	(max-min)	Mean	(max-min)
Forage	% TDMI[a]	71	(85-59)	91	(98-65)	70	(80-57)	85	(98-64)
Grass silage	% FDMI[b]	35	(69-8)	49	(86-15)	38	(74-9)	61	(98-6)
Maize silage	% FDMI	51	(72-16)	35	(74-5)	50	(85-5)	31	(73-0)
Concentrate	% TDMI	29	(41-14)	9	(34-1)	30	(43-20)	15	(36-2)
Winter wheat	% CDMI[c]	7	(33-0)	4	(20-0)	9	(45-0)	7	(30-0)
Barley	% CDMI	20	(72-0)	18	(71-0)	3	(20-0)	5	(26-0)
Rapeseed meal	% CDMI	11	(33-0)	12	(43-0)	8	(41-0)	6	(24-0)
Soybean meal	% CDMI	10	(29-0)	6	(33-0)	7	(36-0)	5	(33-0)
Mixed Concentrate	% CDMI	24	(71-0)	10	(54-0)	60	(100-0)	47	(99-0)

[a]TDMI = Total dry matter intake [b] FDMI = Forage dry matter intake [C] CDMI = Concentrate dry matter intake.

Information on mineral fertilizer application of feeds produced on-farms were provided by BZA-Milk database for each farm. Input data for the most important home grown feeds are shown in Table 3. Apart from P fertilizer application on maize, the input of P and K fertilizer are close to zero for the most important feeds grown on the investigated farms. The availability of slurry on the farm with high amounts of P and K ensured sufficient supply of these minerals for the farm land. A high variance in N input/ha can be observed between the investigated farms. For 23 West-HF farms only data on costs of mineral fertilizer input/ha were provided by BZA-Milk database. Thus, the amount of mineral fertilizer input per ha was calculated based on the price of N (1.23 €/kg N) and P (1.05 €/kg P) and a N to P ratio of 1:0.5 for maize and 1:0 for other feed types (Hofmann, 2013).

Table 3: Mineral nitrogen fertilizer input per ha for the most important home grown feeds of the investigated South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms, (maximum and minimum in parentheses)

		South-FV				West-HF			
		Mean	(max-min)	SD	CV	Mean	(max-min)	SD	CV
GS	kg N/ha	129	(217-5)	68	0.52	134	(290-15)	57	0.42
MS	kg N/ha	100	(199-45)	39	0.39	70	(186-0)	45	0.64
WW	kg N/ha	139	(191-0)	44	0.32	144	(275-76)	67	0.47
Barley	kg N/ha	124	(242-0)	45	0.36	144	(275-76)	67	0.47

GS=grass silage, MS=maize silage, WW=winter wheat, SD=standard deviation, CV= coefficient of variation

2.4. Modelling

2.4.1. General assumptions

The BZA-Milk data for commercial farms was combined with literature estimates to calculate GHG emissions, beef output and land use of South-FV and West-HF dairy farms. Some assumptions and adaptations were necessary, for example if data was unavailable. The number of heifers was based on the replacement rate of the farm. Thus, GHG emissions and land use from heifer rearing was always included irrespective of whether heifers were reared on the farm or reared outside the dairy farm. The number of calves on the farm was based on the average caving interval and calf mortality. Furthermore, a fertility index of 0.5 was included in the calculation (Gerber et al., 2010). Thus, we assumed that 50% of cows culled a calf is provided by the cow that leaves the herd and also from the heifer replacing the cow (based on ADR, 2012 data). This accounts for the fact that number of calves born per year exceeded the number of dairy cows for the investigated dairy farms (Dorfner and Hofmann, 2012).

The amount of N excreted per animal was assumed to equal the amount of N from feed intake (calculated as the dietary dry matter intake and N content of the diet) minus the N output in milk or beef (Zehetmeier et al., 2012). We assumed that the amount of slurry kept on the farm was spread equally on dairy farm land. The amount of lime applied, crop residues removed and diesel use for home grown feed production as well as all assumptions for GHG and land use modelling of bought in feed was taken from FeedPrint model of Vellinga et al. (2012).

2.4.2. Modelling GHG emissions

Greenhouse gas emissions were calculated using a “cradle to farm gate” approach based on LCA guidelines (ISO, 2006). This includes CH_4, N_2O and CO_2 emissions from production and transport of farm inputs and processes on-farm up to the moment that the product leaves the dairy farm gate. Sources of GHG emissions were distinguished between on-farm GHG emissions occurring during feed production, maintenance of animals and manure management and GHG emissions occurring off-farm, for instance, those generated during production of fertilizer, pesticides or diesel. Global warming potentials of 1, 25, and 298 were used to convert CO_2, CH_4 and N_2O emissions into CO_2 equivalents (CO_2-eq), respectively (IPCC, 2007). The functional unit was defined as one kg of FPCM provided at the dairy farm gate (DLG, 2011). All GHG emissions at the dairy farm gate were allocated to milk. Co-products at the dairy farm gate (surplus calves and beef from culled cows) were not burdened with GHG emissions. Instead, differences in co-products between farms were accounted for through the introduction of an indicator trait “potential beef output” which is described in section 2.4.3 and similar to the approach of Flysjö et al. (2011a, b).

Emissions from the production of capital goods such as buildings and machinery are not accounted for following recommendations from the British Standards Institution (BSI, 2008). Land use plays an important role in climate change as it can be both a carbon source e.g. deforestation or land use change, and a carbon sink through land use change or cultivation of crops for bio-energy production (Smith et al., 2013). In this study land use was included as an indicator (see 2.4.4) to show differences between farms in land use efficiency. Carbon dioxide emissions from land use and land use change where not accounted for in this study due to lack of scientific consensus (Don et al., 2009; Flysjö et al., 2012; Soussana et al., 2010).

Equations and emission factors for modelling direct and indirect on-farm GHG emissions were taken from three main sources: IPCC (2006) guidelines, national GHG inventory of Germany (Haenel, 2010) and the FeedPrint model (Vellinga et al., 2012; Table A.1).

Methane emissions form enteric fermentation of dairy cows were calculated based on a detailed equation of Kirchgeßner et al. (1995) due to the importance of this emission source. Methane emissions from enteric fermentation of heifers and calves as well as CH_4 and N_2O emissions from manure management were calculated based on the equations from IPCC (2006) with country specific conversion and emission factors taken from Haenel et al. (2010).

Indirect N_2O emissions occur from volatilisation of NH_3 emissions and leaching of nitrogen. Ammonia emissions occur in the shed, during manure storage and mineral fertilizer and manure application on the field. Leaching of N depends on N input into the soil derived from mineral fertilizer, manure and crop residues. Assumptions to calculate NH_3 emissions and N leaching are shown in Table A.2.

The amount of N in crop residues depends on the harvested annual dry matter yield, the ratio of above and below ground residues and N content of above and below ground residues (IPCC, 2006). Assumptions for these parameters were taken from Vellinga et al. (2012).

Electricity required for milking-related activities was set at 0.056 kWh/kg of milk (Kraatz, 2009), whereas electricity consumption for all other animals was taken from KTBL (2008). We took the emission factor of 0.65 kg of CO_2-eq/kWh from UBA (2010) to convert electricity into CO_2 emissions. Emission factors from production of off-farm inputs such as mineral fertilizer, pesticides, diesel and bought in feed (Table A.3) were taken from the Vellinga et al. (2012) and Ecoinvent (2010).

Total GHG emissions of production and processing of on-farm and bought in feed were allocated between feed products and co-products using economic allocation. Allocation takes place both at the stage of cultivation (e.g. grain and straw) and at the processing stage (distinction between feed and food production e.g. oil from soybeans, sugar from sugar beet; Vellinga et al., 2012). Allocation factors of the most important feeds are shown in Table A.4.

2.4.3. Modelling potential beef output

Besides milk, surplus calves and beef from culled cows can be considered as important outputs from dairy farms. Surplus bull and female calves are typically fattened in specialised fattening systems for German farms, where they are slaughtered at around 18 to 20 months of age. Bull and female calves from different dairy breeds differ in fattening characteristics such as daily live weight gain and carcass conformation (Geuder et al., 2012). It was assumed that all bull calves from FV dairy farms are fattened in bull fattening systems while 50% of bull calves from HF dairy farms were assumed to be fattened in veal fattening systems (Zehetmeier et al., 2012). A higher fattening performance, live weight and carcass kill-out for FV compared to HF animals was assumed (Table 4). To assess beef output from dairy farms differing in breed we estimated potential beef output by adding the amount of beef derived at the end of fattening period from fattening of surplus calves outside the dairy farm gate to the amount of beef derived from culled cows. No fattening period was assumed for culled cows

Table 4: Live weight (LW) and carcass weight (CW) values per animal used to calculate beef output at the dairy farm gate (beef from culled cows) and potential beef output per farm (beef form culled cows and fattening of surplus calves in fattening systems outside the dairy farm gate) for South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms

	South-FV		West-HF	
	kg LW	kg CW	kg LW	kg CW
Beef inside dairy farm gate				
Culled cows	685	345	600	290
Beef outside the dairy farm gate				
Bull fattening	700	406	600	336
Heifer fattening	550	297	500	260
Calf fattening			180	97

Reference: Zehetmeier et al. (2012) derived from LKV Bayern (2012) and KTBL (2008)

2.4.4. Modelling land use

Total land use per dairy farm was defined as land required to produce feed for farm animals. Therefore, this included land needed to grow feed produced on-farm and the land outside the dairy farm gate required to produce bought in feed (off-farm). Land requirement on-farm was calculated using reported feed intakes of farm animals and information provided by BZA-Milk database on yield/hectare (ha) of home grown feeds produced on each farm. Yield in kg of dry matter/ha is defined as net yield. This means that all losses occurring on the field, during transportation to the farm and on the farm until the intake of the animals were subtracted. The high yield variance between the investigated dairy farms can be explained by differences in soil quality, climatic conditions but also a high variance of losses on the field due to differences in technical performance of the farmers involved (Köhler et al., 2009).

Crop yields to calculate off-farm land requirement was taken from Feedprint model (Vellinga et al., 2012). The amount of land needed to produce a kg of dry matter of feed for the most important feeds produced on and off-farm are shown in Table 5.

Table 5: Land use[a] in m²/kg dry matter (DM) for most important feed produced on-farm and off-farm for investigated South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms, (maximum and minimum in parentheses)

	On-farm (m^2/kg DM)		Off-farm[c] (m^2/kg DM)
	South-FV[b]	West-HF[b]	
Feed	Mean (max-min)	Mean (max-min)	
Grass silage	1.10 (1.83-0.87)	1.40 (1.82-1.19)	0.98
Maize silage	0.64 (0.96-0.52)	0.71 (0.88-0.58)	0.71
Winter wheat	1.24 (1.77-1.06)	1.38 (1.99-1.04)	1.28
Barley	1.36 (1.89-1.09)	1.32 (1.89-0.98)	1.52
Rape seed meal			1.25
Soybean meal			3.51
Compound dairy concentrate			0.76-1.99

[a]According to GHG modelling land requirement was allocated between feed and co-products using economic allocation (Vellinga et al., 2012); Source: [b]BZA-Milk database; [c]Vellinga et al. (2012)

2.5. Multiple linear regression and dominance analysis

Multiple linear regression and dominance analysis was undertaken to evaluate the effects of various parameters on model outputs of the South-FV and West-HF dairy farms. To identify directional contribution of model inputs (predictor variables) on model outputs (criterion variable e.g. GHG emissions) multiple linear regression (MLR) models were defined using the statistical programme R (R Development Core Team, 2006). The aim was to characterize the nature and degree of relationship between the criterion variable and the predictor variables (Azen and Budescu, 2003).

The number of variables within the multiple linear regression models was set at a maximum of four predictor variables to avoid over-fitting due to the low number of farms within investigated farm groups. Four predicator variables were chosen that were expected to explain the majority of the variation in emissions or land use or beef output. The choice was assessed by calculating the overall R² of the MLR model and testing goodness of model fit (Crawley, 2013). Estimated effects (beta coefficients) depend on the unit of the predictor variable and the unit of the outcome variable. Thus, coefficients belonging to different predictors cannot be compared but corresponding coefficients from the different MLR can be compared if they have matching units of predictor and outcome variable.

Another focus was to infer how much each of the predictor variables contributes to the variation of model outcomes. Thus, in a second step, the relative importance of predictor variables included in the MLR model is identified which makes a comparison of predictor variables within a MLR model possible. A “predictor’s importance reflects its contribution in the prediction of the criterion in the presence of a specific set of predictors” (Azen and Budescu, 2003). Variable importance combines the contribution a predictor variable has on the criterion variable and the degree of variability of predictor variables (Makinson et al., 2012; Figure 1).

Dominance analysis (Budescu, 1993) was used to calculate the importance of particular variables. In the case of “dominance analysis” “one predictor is more important than another if it is selected over another in all possible subset models where only one predictor of the pair is to be entered” (Azen and Budescu, 2003). Dominance analysis weights sum to the MLR model R², thus it is “possible to provide a meaningful decomposition of the total predicted variance in the criterion” variable (LeBreton et al., 2004). This is also true in the case of multicollinearity of predictor variables. Dominance analysis was implemented in this study using “relaimpo – lmg metrics” package of the statistical programme R (equation 1);

$$LMG(x_k) = \frac{1}{p} * \sum_{i=0}^{p-1} \left(\sum_{\substack{S \subseteq \{x_1,\dots,x_p\} \setminus \{x_k\} \\ n(S)=i}} \frac{seqR^2(\{x_k\} \mid S)}{\binom{p-1}{i}} \right) \tag{1}$$

where LMG (x_k) equals the average over model sizes i of average improvements in R² when adding regressor x_k to a model of size i without x_k, seqR² ({x_k}IS) equals = additional R² when adding xk to a model with the regressors in set S. A detailed description of the method and the package “relaimpo” is given by Groemping (2006) and Christensen (1992).

3. Results

3.1. Investigated farm indicators

The GHG emissions (expressed in kg of CO_2-eq), potential beef output and land use per kg of FPCM of the South-FV and West-HF dairy farms are shown in Table 6. The mean on-farm GHG emissions/kg of FPCM was 11% lower ($P<0.01$) for the West-HF dairy farms relative to the South-FV dairy farms which reflect the lower milk yield of South-FV dairy farms and thus more animals needed to produce the same amount of FPCM. However, the mean off-farm GHG emissions/kg of FPCM were greater for the West-HF dairy farms compared to South-FV dairy farms. Thus, including off-farm GHG emissions reduced the difference ($P<0.01$) to 7% between total (on and off-farm) GHG emissions/kg of FPCM of the South-FV dairy farms (1.06 ± 0.11 SD) compared to the West-HF dairy farms (0.98 ± 0.12 SD).

The difference in beef output from culled cows (beef at the dairy farm gate) per tonne of FPCM between South-FV and West-HF dairy farms was low, with South-FV dairy farms having a higher output of 4 kg of beef/tonne of FPCM. Including beef from fattening of surplus calves increased the mean total potential beef output/tonne of FPCM by 4-fold to 44 kg of beef/tonne of FPCM for South-FV. This was significantly higher ($P< 0.01$) compared to the mean of 23 kg of beef/tonne of FPCM for West-HF dairy farms (Table 6). The difference can be explained by a higher amount of beef output from fattening of surplus dual purpose breed calves divided by a lower amount of FPCM.

In the case of total land use/kg of FPCM there was no statistical significant difference between the investigated groups of dairy farms (Table 6). On average, on-farm land accounted for 74% of total land use for South-FV dairy farms and 65% for West-HF dairy farms. However, a larger range of on-farm land use was observed for West-HF dairy farms (0.14-1.02 m^2/kg of FPCM) relative to South-FV dairy farms (0.56-1.14 m^2/kg of FPCM). The average proportion of total land use that was arable land was 61% for South-FV dairy farms and 52% for West-HF dairy farms. Thus, on average less than 50% of total land use was derived from grassland.

Table 6: Greenhouse gas (GHG) emissions (expressed as kg of CO_2-equivalent [eq]), potential beef output and land use per unit of FPCM (fat and protein corrected milk) for investigated South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms

Item	Unit	South-FV			West-H-F		
		Mean	(max-min)	SD	Mean	(max-min)	SD
GHG on-farm	kg CO_2-eq/kg of FPCM	0.88^{**}	(1.06-0.73)	0.09	0.78^{**}	(0.96-0.62)	0.09
GHG off-farm	kg CO_2-eq/kg of FPCM	0.18	(0.25-0.14)	0.03	0.20	(0.35-0.13)	0.05
GHG Total	kg CO_2-eq/kg of FPCM	1.06^{**}	(1.25-0.90)	0.10	0.98^{**}	(1.20-0.79)	0.12
Beef culled cows within dairy farm gate	kg beef/tonne of FPCM	11^{**}	(21-6)	3	7^{**}	(13-3)	3
Beef fattening outside the farm gate	kg beef/tonne of FPCM	33^{**}	(39-28)	4	17^{**}	(21-12)	2
Total	kg beef/tonne of FPCM	44^{**}	(53-36)	5	23^{**}	(27-19)	2
Land use on-farm	m²/kg of FPCM	0.80^{*}	(1.14-0.56)	0.17	0.68^{*}	(1.02-0.14)	0.21
Land use off-farm	m²/kg of FPCM	0.28^{*}	(0.45-0.13)	0.08	0.37^{*}	(0.78-0.17)	0.16
Total	m²/kg of FPCM	1.08	(1.45-0.84)	0.16	1.05	(1.36-0.81)	0.15

*p<0.05; **p<0.01

The contribution of individual GHG emission sources to total GHG emissions per farm is shown in Table 7. The average GHG profiles were similar for both farm groups and showed that CH_4 emission from enteric fermentation was the main source of GHG accounting for 50% of GHG emissions/kg of FPCM for South-FV dairy farms and 47% of GHG emissions/kg of FPCM for West-HF dairy farms. Direct CH_4 and N_2O emissions from manure storage was the next most important source of GHG emissions generating 15% of GHG emissions/kg of FPCM for South-FV and West-HF dairy farms. The remaining source of GHG emissions for both dairy farms groups was mainly direct N_2O emissions from the soil due to N input from mineral fertilizer and manure application. This source accounted for 16% of GHG emissions/kg of FPCM for South-FV dairy farms and for West-HF dairy farms.

Table 7: Contribution analysis (source percentage of greenhouse gas emissions) for investigated South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms

Item	South-FV				West-HF			
	Mean	max	min	SD	Mean	max	min	SD
Enteric fermentation	0.50	0.55	0.45	0.02	0.47	0.53	0.40	0.03
Manure management (housing, storage, spreading)	0.15	0.17	0.13	0.01	0.15	0.19	0.12	0.01
N_2O from NH_3 re-deposition	0.02	0.02	0.02	0.00	0.02	0.02	0.02	0.00
Electricity animal husbandry	0.03	0.04	0.03	0.00	0.04	0.04	0.03	0.00
Feed produced on farm								
N mineral application	0.05	0.09	0.01	0.01	0.04	0.08	0.01	0.01
Crop residues	0.02	0.03	0.02	0.00	0.02	0.03	0.00	0.01
Mineral fertilizer production	0.05	0.10	0.01	0.02	0.04	0.09	0.01	0.02
Machinery and feed processing	0.04	0.06	0.03	0.01	0.03	0.04	0.01	0.01
Lime application and production	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00
Pesticides	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Organic manure application	0.09	0.11	0.07	0.01	0.10	0.13	0.03	0.03
Bought in Feed								
N mineral application	0.01	0.01	0.00	0.00	0.01	0.04	0.01	0.01
Crop residues	0.01	0.01	0.00	0.00	0.01	0.02	0.00	0.00
Mineral fertilizer production	0.01	0.02	0.00	0.00	0.02	0.05	0.01	0.01
Machinery and feed processing	0.00	0.03	0.00	0.00	0.02	0.16	0.00	0.04
Lime application and production	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Pesticides	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Organic manure application	0.01	0.01	0.00	0.00	0.01	0.06	0.00	0.01

SD=standard deviation, max=maximum, min=minimum

3.2. Multiple linear regressions

Multiple linear regression models were estimated per kg of FPCM to predict GHG emissions, potential beef output and land use for both groups of dairy farms (Table 8). The analysis showed that GHG emissions/kg of FPCM could be predicted quite well using dry matter intake/cow, N fertilizer application/ha, replacement rate and milk yield/cow as predictor variables. The adjusted coefficient of multiple determination, R^2, for the estimated regression models was 0.743 for South-FV and 0.616 for West-HF. Assuming that all other variables are kept constant a single decrease in mineral N input/ha, dry matter intake/cow, replacement rate and an increase in milk yield resulted in a decrease in GHG emissions/kg of FPCM within MLR models of both dairy farm groups.

The independent variable of dry matter intake/cow was included in the MLR model as data showed a high variation of dry matter intake/cow between dairy farms with a similar milk yield. No strong correlation between milk yield and dry matter intake/cow was identified in the data. This could be explained mainly by differences in feed intake efficiency/cow and differences in energy content per kg of dry matter. Due to differences in feed efficiency (kg of FPCM/kg of dry matter intake) the MLR revealed a positive relationship between dry matter intake/cow and GHG emissions/kg of FPCM.

The MLR models showed that improving the replacement rate by 10% resulted in a similar decrease in GHG emissions for South–FV and West–HF dairy farms (0.07 kg of CO_2-eq/kg of FPCM). The regression coefficient for milk yield showed that increasing FPCM yield by a tonne per cow reduced GHG emissions by 0.14 kg of CO_2-eq/kg of FPCM for South-FV dairy farm, but the reduction for the same increase in milk yield per cow was 0.10 CO_2-eq/kg of FPCM for West-HF dairy farms.

Multiple linear regression models predicting potential beef output per farm determined a high R^2 of 0.994 for South-FV and West-HF dairy farms (Table 8). All chosen predictor variables were significant at the 1% level. As FPCM yield increased by a tonne/cow beef output decreased by 4.96 kg beef/tonne of FPCM for South-FV dairy farms. The decrease in beef output per tonne of FPCM was lower at 2.48 kg of beef for the same milk yield increase for West-HF dairy farms.

A negative relationship between calving interval and beef output/tonne of FPCM was found in both MLR models. A decrease in calving interval resulted in a higher number of calves. Thus, more surplus calves were available for fattening and beef production. A higher regression coefficient for calving interval was found for South-FV dairy farms compared to West-HF dairy farms, because the beef output of FV calves was higher than HF calves. There was a positive relationship between replacement rate and beef output/tonne of FPCM. The MLR models of both dairy farm groups showed that increasing the replacement rate by 10% resulted in an increase of 2.45 kg of beef/tonne of FPCM for South-FV dairy farms and 1.40 kg of beef/tonne of FPCM for West-HF dairy farms (Table 8).

The MLR models for land use/kg of FPCM also determined a high R^2 of 0.797 for South-FV dairy farms and 0.782 for West-HF dairy farms (Table 8). The models showed that if all other variables are kept constant increasing the yield of feed production and FPCM yield and reducing the replacement rate and dry matter intake per cow resulted in a decrease of land use/kg of FPCM within both investigated dairy farm groups.

Table 8: Multiple linear regression models for greenhouse gas emissions (kg CO_2-eq/kg FPCM), potential beef output (kg potential beef/kg FPCM) and land use (m²/kg FPCM) of investigated dairy South-Fleckvieh (FV) and West-Holstein-Friesian (HF) dairy farms

		South-FV				West-HF			
	Unit	R^2	B	SEb	Pr(>|t|)	R^2	B	SEb	Pr(>|t|)
Milk intensity	kg CO_2-eq/kg of FPCM	0.743				0.616			
Intercept			1.11E+00	2.28E-01	***		6.13E-01	7.80E-01	*
Nitrogen fertiliser	kg N/ha		9.06E-04	5.37E-04			1.23E-03	5.69E-04	*
Dry matter intake	kg DM/cow		1.10E-04	2.35E-05	***		1.22E-04	3.19E-05	**
Replacement rate	%		6.70E-03	1.30E-03	***		6.95E-03	1.67E-03	***
Milk yield	kg FPCM/cow		-1.36E-04	1.77E-05	***		-9.76E-05	2.22E-05	***
Beef intensity	kg beef/kg of FPCM	0.994				0.994			
Intercept			1.20E-01	2.22E-03	***		6.86E-02	9.86E-04	***
Calving interval	days		-9.73E-05	5.41E-06	***		-5.44E-05	1.81E-06	***
Cow and calf mortality	%		-4.66E-04	1.46E-05	***		-2.69E-04	7.55E-06	***
Replacement rate	%		2.45E-04	8.57E-06	***		1.40E-04	3.86E-06	***
Milk yield	kg of FPCM/cow		-4.96E-06	1.10E-07	***		-2.48E-06	5.33E-08	***
Land intensity	m²/kg of FPCM	0.797				0.782			
Intercept			2.22E+00	2.33E-01	***		1.91E+00	2.89E-01	***
Yield feed production	kg DM/ha		-1.13E-04	1.36E-06	***		-1.20E-04	1.52E-05	***
Dry matter intake	kg DM/cow		1.20E-04	2.43E-05	***		1.40E-04	3.16E-05	***
Replacement rate	%		6.55E-03	1.75E-03	**		7.51E-03	1.62E-03	***
Milk yield	Kg of FPCM/cow		-1.43E-04	2.39E-05	***		-1.29E-04	2.19E-05	***

b is the unstandardized coefficient, SE b is the standard error of b, R² is the adjusted coefficient of determination, significant codes: *** p<0.001; ** p<0.01; * p<0.05; '.' p<0.1, FPCM = fat and protein corrected milk, DM=dry matter

3.3. Dominance Analysis

The relative importance of variables predicting GHG emissions/kg of FPCM is illustrated in Figure 2. Milk yield/cow showed the highest contribution within regression model of South-FV dairy farms, accounting for 55% of the variance in GHG emissions/kg of FPCM and the second highest contribution within regression model of West-HF dairy farms (30%). Replacement rate was the second highest contributor accounting to the variance in GHG emissions of South-FV dairy (25%) and the highest contributor, accounting for 31% of variance in GHG emissions of West-HF dairy farms. The contribution of N fertilizer input/ha (18%) and dry matter intake/cow (21%) was higher for the West-HF dairy farm group compared to South-FV dairy farms. Nitrogen fertilizer contributed only marginally (3%) to variance for the South-FV dairy farms indicating the variable had the lowest potential to influence GHG emissions/kg of FPCM for that dairy farm group.

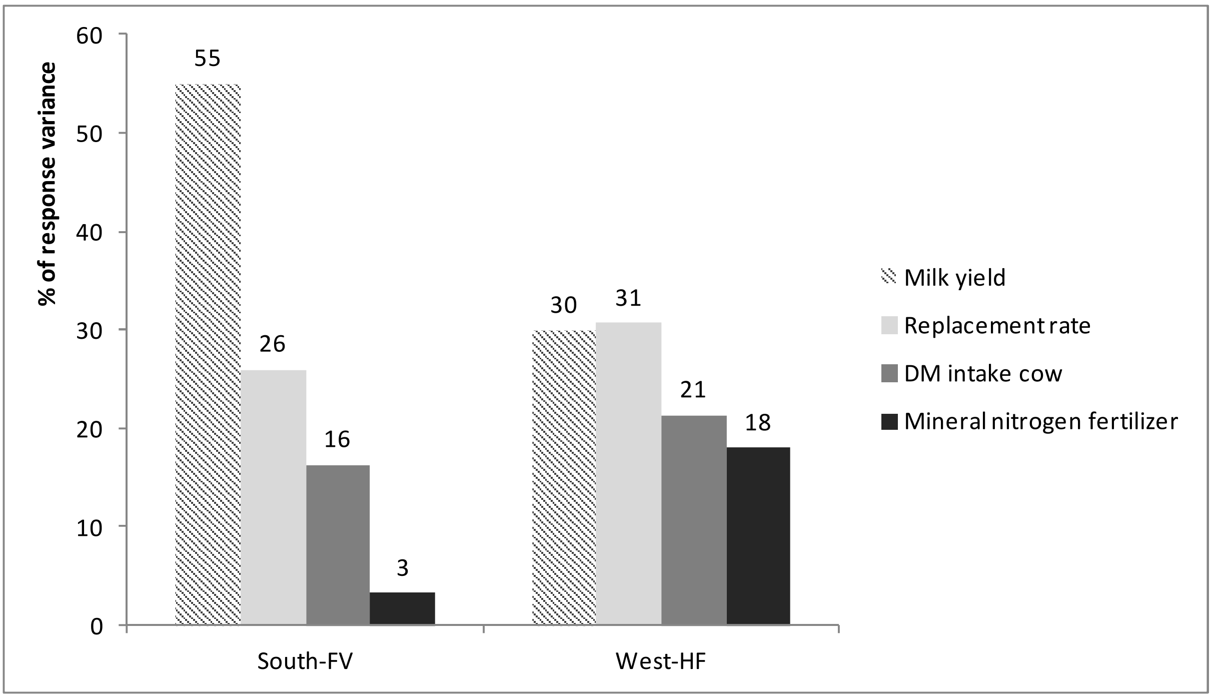

Figure 2: Linear regression with variance decomposition indicating the percent of variance in GHG emissions per kg of fat and protein corrected milk yield accounted for by predictor variables.

DM = dry matter. South-FV = dairy farms with Fleckvieh (FV) breed in the south of Germany. West-HF = dairy farms with Holstein-Friesian (HF) breed in the west of Germany.

Decomposition of R² for MLR models of potential beef output/kg of FPCM is illustrated in Figure 3. The order of most important predictors in the case of South-FV dairy farms were milk yield (46%), cow and calf mortality (27%), replacement rate (15%) and calving interval (12%). The relative importance of milk yield (33%) and replacement rate (28%) was similar within the group of West-HF dairy farms, followed by cow and calf mortality (20%) and calving interval (19%).

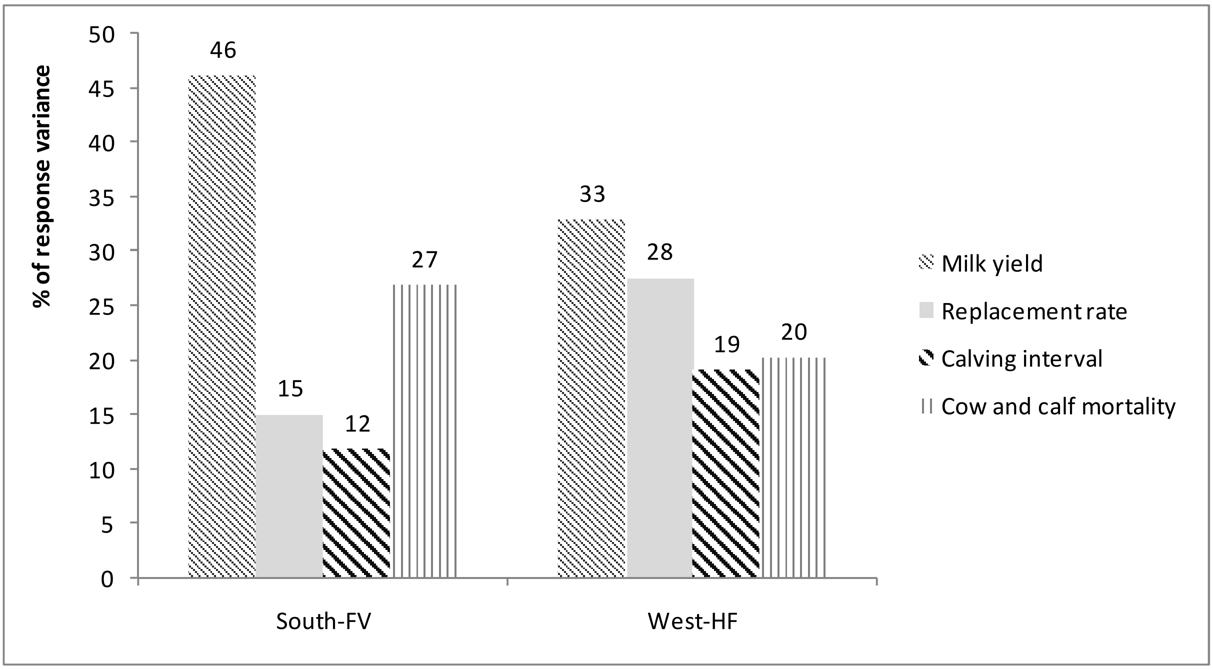

Figure 3: Linear regression with variance decomposition indicating the percent of variance in potential beef output per kg of fat and protein corrected milk yield accounted for by predictor variables.

South-FV = dairy farms with Fleckvieh breed in the south of Germany, West-HF = dairy farms with Holstein-Friesian breed in the west of Germany

Net crop yield (kg of dry matter/ha) was the main contributor to variance of land use per kg of FPCM, accounting for 58% of variance of South-FV dairy farm and 55% for West-HF dairy farms (Figure 4). The relative importance of milk yield was similar for the MLR models of both dairy farm groups. Dry matter intake/cow and replacement rate had a relative low impact on variance of land use/kg of FPCM within both dairy farm groups.

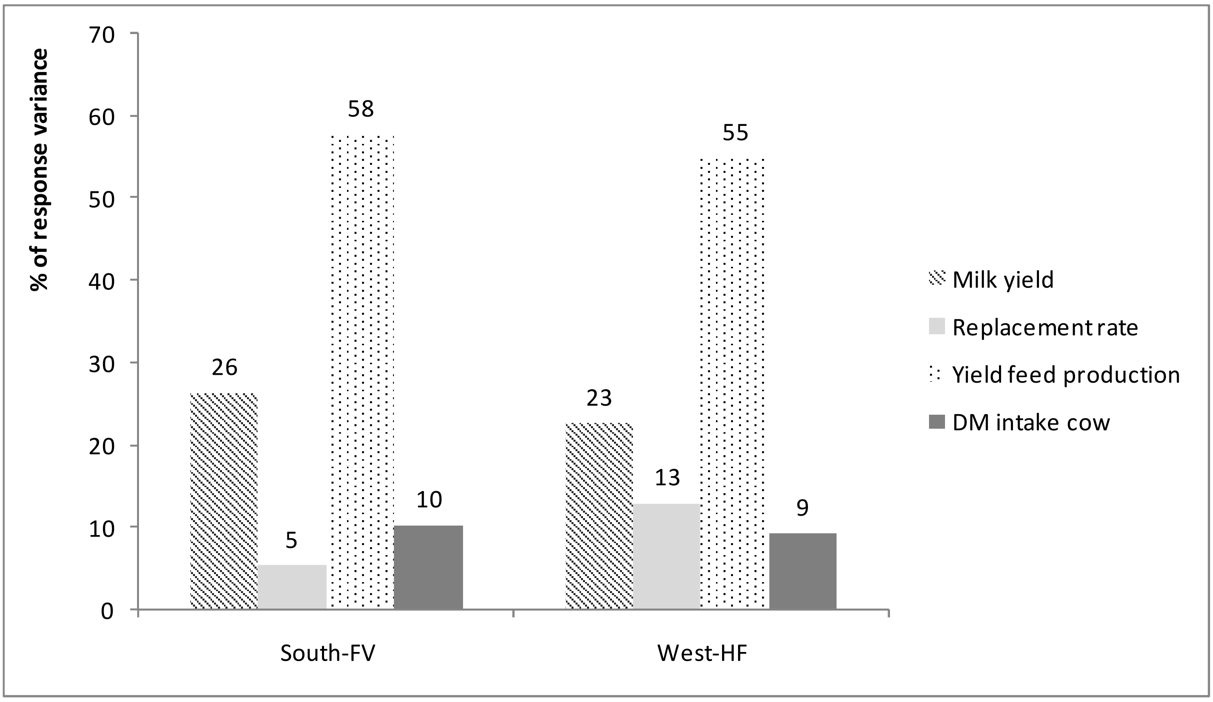

Figure 4: Linear regression with variance decomposition indicating the percent of variance in land use per kg of fat and protein corrected milk yield accounted for by predictor variables.

DM = dry matter, South-FV = farms with Fleckvieh breed in the south of Germany, West-HF= farms with Holstein-Friesian breed in the west of Germany

4. Discussion

4.1. Comparison of South German Fleckvieh and West German Holstein-Friesian dairy farms

The assessments of GHG emissions, potential beef output and land use of South-FV and West-HF dairy production systems demonstrated intra and inter farm variability. By choosing only high performing dairy farms and farms with a similar housing and feeding regime a homogenous group of farms differing only in dairy cow breed was targeted. However, comparing the results of analysed FV and HF dairy farm groups in this study it has to be considered that the FV and HF farms were located in different regions of Germany.

4.1.1. Inter farm production system variability

Most studies evaluating GHG emission of commercial dairy farms have examined the effect of production mode, for instance organic versus conventional, intensive versus extensive (van der Werf et al., 2009). Mean GHG emission outcomes of previous studies were 1.40 kg CO_2-eq/kg of FPCM for Dutch dairy farms (Thomassen et al., 2008), 0.90-1.04 kg CO_2-eq/kg of milk for Swedish dairy farms and 1.04 kg CO_2-eq/kg of milk for French dairy farms (van der Werf et al., 2009). Outputs from this study fit within this range of reported study outcomes. However, comparison between modelling studies are questionable due to differences in GHG modelling approaches.

Only few studies can be found in the literature evaluating GHG emissions of dairy cow production systems with different breeds e.g. Capper and Cady (2012) and O'Brien et al. (2010). However, none of those studies investigated commercial dairy farms or dual purpose dairy cows. Zehetmeier et al. (2012) compared FV and HF dairy production systems in a model approach and showed that FV systems emitted higher total (on and off) GHG emissions/kg of milk. The results of this study supported this finding, but in contrast to Zehetmeier et al. (2012) the South-FV dairy system emitted slightly lower off-farm GHG emissions/kg of FPCM. This was because the South-FV dairy system imported less feed relative to West-HF dairy system. However, the FPCM yield and the productive efficiency (resource use per unit of milk) of the West-HF dairy system was greater than the South-FV dairy system. Thus, similar to previous reports (e.g. Capper et al., 2009) this resulted in lower enteric CH_4 emission and manure management emissions for the HF dairy system, which led to the West-HF system generating a significantly lower on-farm and total GHG emissions/kg of FPCM compared to the South-FV dairy system.

The difference between GHG emission outcomes of FV and HF dairy production systems was slightly higher in the study of Zehetmeier et al. (2012) due to a greater difference in milk yield between breeds. This also explained in part the higher GHG emission estimates in Zehetmeier et al. (2012) of 1.13 kg CO_2-eq/kg of milk for South-FV dairy production systems. The difference in productive efficiency, specifically feed efficiency of dairy cows between Zehetmeier et al. (2012) and the commercial farms assessed in this study explained the higher level of GHG emissions from commercial dairy farms. The lower feed efficiency of the investigated farms in this study caused greater GHG emission from feed production and increased CH_4 emission form enteric fermentation and manure management emissions, because feed intake is a key determinant of these emission sources (O'Brien et al., 2012). The difference in feed efficiency was because the model approach of Zehetmeier et al. (2012) optimized dry matter intake to fulfil animal requirement but this was rarely achieved on investigated commercial farms.

The beef from culled cows and from fattening of progeny on or off-farm was considered in this study by estimating the potential beef output and showed that South-FV dairy farms produced twice as much as beef as the West-HF dairy farms. Assuming suckler beef compensated for the lower beef output of the West-HF dairy farms result in an average increase in GHG emissions of up to 0.3 kg CO_2-eq/kg of FPCM. Thus, emissions from West-HF dairy farms would be higher compared to South-FV dairy farms when suckler beef emissions are included. This result agrees with the model approach of Zehetmeier et al. (2012). Nevertheless, it has to be considered that the emission factor of suckler beef is highly dependent on the production system (Nguyen et al., 2010; Crosson et al., 2011). In addition, it could also be assumed that the lower beef output of the HF dairy systems could be compensated by a different meat (e.g. pork or chicken) with a lower GHG emissions/kg of meat than meat from a dairy farm (Flysjö et al., 2011a).

Assessing potential beef output is one of several approaches to evaluate GHG emissions from co-products at the dairy farm gate. The most common method is to apply arbitrary factors based on e.g. economic value or protein content (Flysö et al., 2011b) to allocate GHG emissions between milk and meat co-products. However, it is impossible to determine “true” or “correct” allocation factors. An unfortunate by-product of this contention has been the scant attention paid to establish criteria for choosing a particular, albeit arbitrary, allocation schemes from among a variety of alternatives (Flysö et al., 2011b; IDF, 2010; Kristensen et al., 2011; Verrecchia, 1982). Thus, we used the additional indicator of potential beef output to account for differences in co-products of dairy systems. This improves traceability of GHG emission outcomes because trade-offs between GHG emissions/kg of FPCM and beef output/kg of FPCM can be identified. For instance, farms with a low amount of potential beef output/kg of FPCM might contribute to carbon leakage assuming the shortfall in the quantity of beef is supplied by increased suckler beef production (Flysjö et al., 2011a, Schmidt and Dalgaard, 2012).

This study showed no difference in land use/kg of FPCM between different dairy cow production systems. This result is contrary to the fact that the proportion of feed intake used for maintenance is higher with lower yielding dairy cow, which reduces feed efficiency (Capper et al., 2009). However, in our study the higher net crop yields of the South-FV dairy farms relative to West-HF dairy farms (Table 5) compensated for the lower feed efficiency of the South-FV farm.

Differences in the area and type of land use between farms were not evaluated in this study. However, including direct land use change or indirect land use change (Flysjö et al., 2012) can affect GHG emissions of dairy production systems (Schmidt and Dalgaard, 2012). For instance, if farms reduce land use/kg of FPCM the released land could be used as a carbon sink through a number of ways including forestry, bio-energy production or grassland (Berlin and Uhlin, 2004). A change in type of land use (e.g. ploughing of grassland to produce maize silage) can also result in a release of GHG emissions (Vellinga and Hofing, 2012). A further detailed study of differences in overall land use and type of land use per farm could provide further insight into GHG mitigation potential of investigated farms.

4.1.2. Intra-farm production system variability

Van der Werf et al. (2009) points out that the “contribution of production mode to overall inter-farm variability of impacts was minor relative to inter-farm variability within each of two production modes examined” (van der Werf et al., 2009). Even though our results showed a significant difference at the 1% level in mean GHG emissions between FV and HF dairy farms we also found that the intra-farm variability in GHG emissions was greater between the upper and lower 10% of dairy farms within each production mode, ranging from 0.3 kg of CO_2-eq/kg of FPCM for South-FV dairy farms to 0.4 kg of CO_2-eq/kg of FPCM for West-HF dairy farms. The evaluation of the variance of farm GHG emissions showed milk yield and replacement rate explained the majority of variability between farms. This agrees in part with Christie et al. (2012) who showed that milk yield per cow explained 70% of the variance in GHG emissions/kg of milk of 41 Australian dairy farms. It also partially supports the finding of Casey and Holden (2005) that 87% of the variance in GHG emissions/kg of milk of Irish dairy farms was explained by milk yield/cow. However, compared to our analysis the contribution of milk yield/cow to the variance of GHG emissions/kg of FPCM was greater for Christie et al. (2012) and Casey and Holden (2005). This was mainly due to lower average milk yield of these studies, which ranged from 5,260-6,270 kg milk/cow per year. Furthermore, in contrast to the current study the impact of replacement rate on GHG emission was not reported in these studies.

The relationship between milk yield and GHG emissions has also been reported by Gerber et al. (2011). The study showed that increasing milk yield from 2,000 to 5,000 kg of FPCM/cow per year causes a large reduction in GHG emissions but moves towards a plateau from 6,000 kg of FPCM/cow per year onwards (Figure 5). The GHG emission results of this study were at a lower level compared to that of Gerber et al. (2011) at the same milk yield/cow, which was partly due to differences in farm management but also variation in modelling GHG emissions. As a result, contrary to Gerber et al. (2011) the regression analysis of dairy farms showed that increasing FPCM yield/cow caused a further minor decrease in GHG emissions/kg of milk. For lower yielding South-FV dairy production system increasing milk yield by a tonne/cow caused a greater marginal reduction in GHG emissions than increasing the milk yield of the higher yielding HF dairy production system by the same quantity. This indicates that the farms are operating near the plateau level where similar outcomes of GHG emissions/kg of FPCM can be reached above a certain level of milk yield/cow (Figure 5).

Therefore, considering the average improvement of milk yield/cow in Germany in the last 20 years of 100 kg milk/cow per year (ADR, 2012) the potential to reduce GHG emission by further increasing milk yield/cow is limited. This phenomenon is also observed in economics and described by Pannell (2006). Pannell (2006) observed flat payoff functions investigating optimum input level of farms. At a high input level a further increase in input does not result in a considerable improvement of output. However, research and development in search of new technologies might shift the output function to a lower level and thus result in a higher benefit of improved output. For instance, this could be high yielding dairy production systems with low emission manure management systems (e.g. anaerobic digestion) or a lower rate of replacement of cows. Another option may be to modify the feeding regime of high performance indoor dairy system to include grazed grass (partial mixed rations), which some reports indicate mitigates GHG emissions (Meul et al., 2012; Rotz et al., 2009).

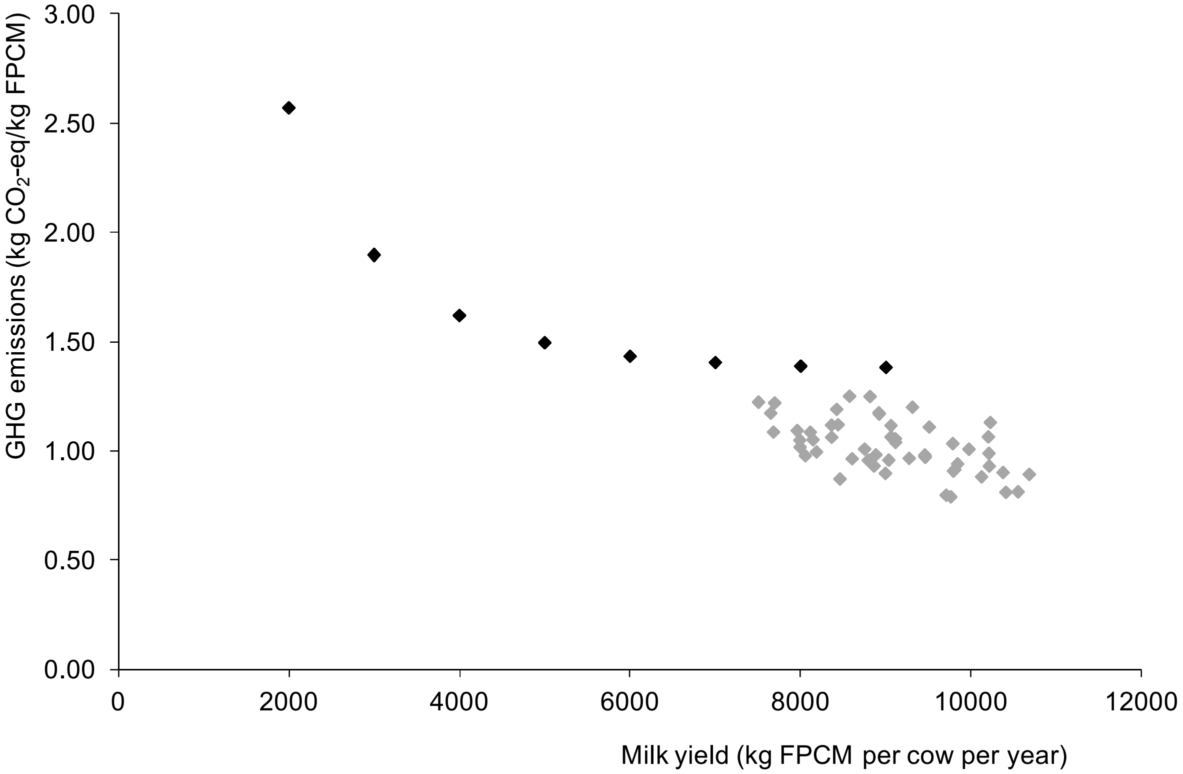

Figure 5: Relationship between fat and protein corrected milk (FPCM) yield/cow and GHG emissions (kg CO_2-eq/kg FPCM). Black squares: data derived from Gerber et al. (2011). Grey squares: own study results

Results of this study also showed that milk yield together with replacement rate explained a high proportion of variance in GHG emission outcomes. Milk yield and replacement rate are also important indicators of profitability for confinement dairy farms (Roemer, 2011). Nonetheless, Lucy (2001) points out that to achieve low replacement rates in high yielding dairy herds requires “better feeding, healthier cows, and better reproductive management” (Lucy, 2001) and optimal husbandry conditions. This is becoming more challenging given the continuing increase in milk yield per cow within confinement production systems. Roemer (2011) introduced the indicator of milk yield per day of life as a joint indicator of milk yield, replacement rate and age of first calving. The indicator is calculated by dividing milk produced over the lifetime of a dairy cow by its final age in days. Figure 6 shows that around 50% for South-FV and about 40% for West-HF of the variance of GHG emissions could be explained by the indicator milk yield/day of life. This emphasizes that the interaction of production traits need to be considered in the search for GHG mitigation options (O’Brien et al., 2010), especially within high yielding dairy cow production systems where the additional benefit from increasing milk yields is limited.

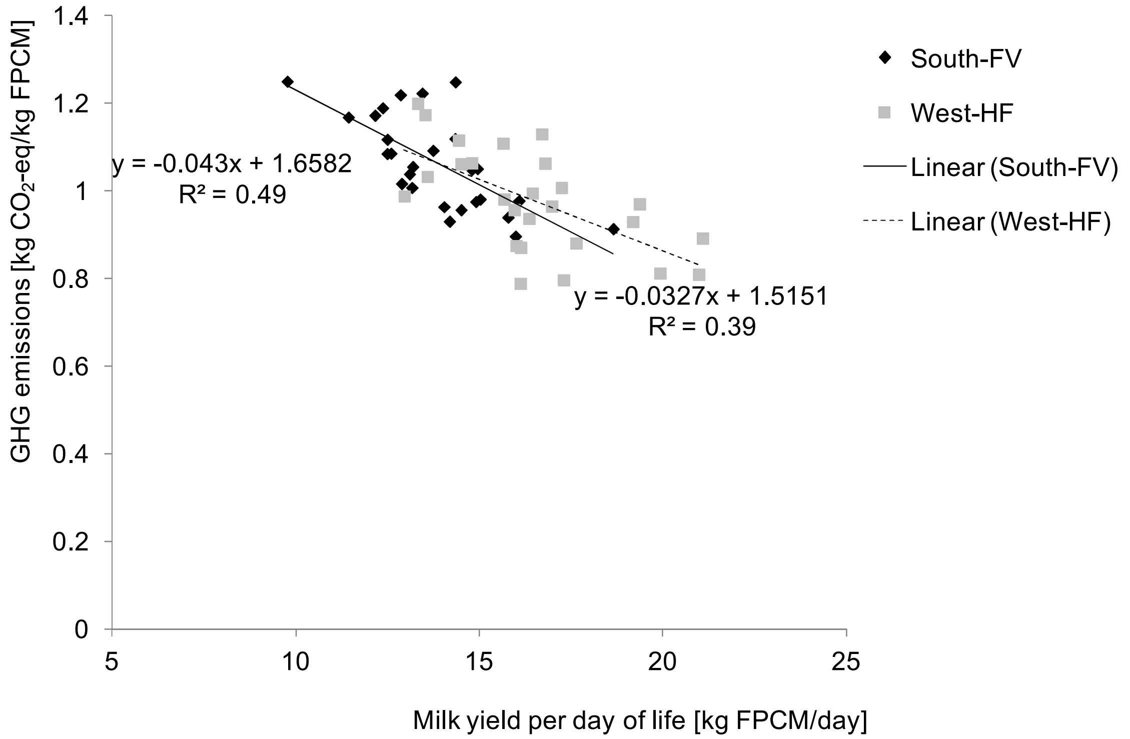

Figure 6: Greenhouse gas (GHG) per kg of fat and protein corrected milk (FPCM) as a function of milk yield per day of life (milk yield per cow per life divided by days of life from birth to culling)

Although, MLR models showed increasing milk yield/cow and reducing replacement rates resulted in lower GHG emissions/kg of FPCM, the analysis demonstrated there was a trade-off with potential beef output/kg of FPCM. However, the impact of replacement rate on potential beef output/kg FPCM in our study was highly sensitive to assumptions made to calculate potential beef output. A higher replacement rate provided more beef from culled cows and thus resulted in an increase in beef output. Replacement rate also affects the number of calves born and provided for fattening systems. A higher replacement rate means less female calves are available for heifer fattening. However, due to the fertility index included in the modelling, a higher replacement rate also means more cases of two calves born per cow place (one from culled cow, one from heifer replacing the culled cow). Results of dominance analysis in this study were highly sensitive to the assumption of fertility index. Sensitivity analysis showed that if fertility index was reduced to 0.25 (50% reduction), variable importance of replacement rate (contribution to variance decomposition) for beef output/kg of FPCM decreased from 15 to 7% for South-FV dairy farms and from 28 to 11% for West-HF dairy farms.

Further possibilities do exist to increase potential beef output/kg of FPCM from dairy farms which were not investigated in this study. This includes the production of calves from heifers entering fattening system, higher weights of fattening bulls and heifers, reducing the proportion of calves send to calf fattening systems or the use of sexed semen.

4.2. Modelling limitations

The use of commercial farm data in modelling GHG emissions from dairy farms provides the advantage that the variability between farms within a homogenous production system can be explored. However, the interpretation of the results of this study are limited to farms using a similar feeding regime and operating within similar environmental constraints. For instance, contribution analysis of GHG emissions and variability of production traits could be different for dissimilar dairy cow production systems such as grazing systems.

The evaluation of the environmental impact of dairy farms is often compromised as the data required to assess environmental impacts is often not available or is of low quality. Thus, it has to be considered that the outcomes from these studies are dependent on the number of farms, the quality and availability of data and model assumptions. Firstly, the BZA-Milk database is not an investigation of environmental impact, but the evaluation of economic performance and production traits of dairy production systems. Thus, model assumption had to be undertaken because of inadequate data and to ensure comparability of farms (e.g. manure storage systems).

It has to be considered that the results of contribution analysis and dominance analysis in this study highly depend on parameters included in GHG modelling and investigated dairy farm parameters. As stated in the introduction only those variables that are significant contributors to total GHG emissions and are variable can be identified as important variables. Thus, it has to be considered that there might be other important variables which were not identified in our study as their variability was not investigated on the farms e.g. variance of CH_4 emission from enteric fermentation due to difference in animal genetics (Reynolds et al., 2011) or variance of feed GHG emissions due to data sensitivity (van Middelaar et al., 2013).

No data on differences in management of manure storage and the method of application of manure to field was available from the farms investigated in this study. However, previous reports indicate that GHG emissions from manure storage could yield up to 20% of total GHG emissions/kg of FPCM. Popp et al. (2010) reported that variance in manure management practices of farms indicates an opportunity to influence the GHG emissions of farms. Thus, data collection on manure management would improve the evaluation of the dairy farms in this study and should be included in BZA-Milk.

Information about differences in soil quality and carbon sequestration through changes in soil organic matter during on-farm feed production was not available for the investigated dairy farms. Hörtenhuber et al. (2010), Kuestermann et al. (2008) and Sousanna et al. (2010) point out that differences in soil management practices and type of land has an impact on soil carbon sequestration and should be included in GHG modelling. However, recent studies such as Powlson et al. (2011) emphasize the limitations of carbon sequestration for climate change mitigation as the quantity of carbon stored in soil is finite, the process is reversible and there may be trade-offs through changes in the fluxes of other GHG such as N_2O. Thus, more research is needed to explore possibilities to include differences in soil carbon sequestration.

Possible options to mitigate GHG emissions also need to be compared in respect of their cost effectiveness. Although, production costs were not included in this analysis, previous reports indicate that the most important parameters explaining variation in GHG emissions/kg of FPCM in this study have a positive effect on economic performance of dairy farms (i.e. milk yield, replacement rate) (Dorfner and Hofmann, 2012; McCarthy et al., 2007; Roemer, 2011). However, without advisory support these options may not be easily implemented on-farm given that these strategies require maximizing genetic gain as well as optimizing animal nutrition. Nonetheless, it has to be considered that “the failure of livestock producers to carry out farm-management changes that would generate emissions reductions at a net profit may indicate attitudinal and social barriers to changing farming practices” (Cooper et al., 2013). These barriers need to be identified to implement GHG abatement options in dairy farming.

5. Conclusions

Data from a farm accounting tool with a special focus on production traits were used to model GHG emissions, beef output and land use of high performing dual purpose South-FV and specialized West-HF dairy farms. Even though GHG emissions/kg of FPCM was significantly lower for West-HF dairy farms, variation between farm groups was low compared to within group variation. This indicates a higher potential to improve GHG emissions/kg of FPCM within investigated production systems compared to changing production modes. Milk yield and replacement rate were identified as the most important variables explaining variation of GHG emissions. However, if the milk yield/cow of dairy farms is already in the upper range, to mitigate GHG of high performing farms the focus should be on an optimal combination of milk yield and replacement rate rather than solely focusing on increasing milk yield/cow.

Potential beef output and land use per kg of FPCM were calculated for each farm to evaluate the risk of possible carbon leakage. South-FV dairy farms showed considerable higher potential beef output compared to West-HF dairy farms. Within investigated groups an opposite effect of milk yield and replacement rate on GHG emissions/kg of FPCM and beef output/tonne of FPCM was observed, particularly in the case of South-FV dairy farms. Trade-offs between GHG emissions, potential beef output and land use per kg of milk indicate the potential for carbon leakage. Therefore, in the search for GHG mitigation options, effective strategies that do not have an undesirable impact on key indicators e.g. feed efficiency, nitrogen use efficiency or potential beef output should be prioritised.

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Appendices

Table A.1: Summary of emission factors and equations to quantify on-farm greenhouse gas (GHG) emissions

GHG	Source	Emission factor/equation	Unit	Reference
Direct on-farm				
CH_4	Enteric fermentation			
	Dairy cow	(63+79*CF[a]+10*NfE[b]+26*CP[c]-212*EE[d])	g CH4/d	Kirchgeßner et al. (1995)
	Calves up to 125 kg	0.02*gross energy intake	MJ CH_4/MJ	Haenel (2010)
	Other cattle	0.065* gross energy intake	MJ CH_4/MJ	Haenel (2010)
	Manure storage			
	Dairy cow	0.24*(VS[e]*MCF[f])	m³ CH_4/kg VS	Haenel (2010)
	Other cattle	0.18*(VS[e]*MCF[f])	m³ CH_4/kg VS	Haenel (2010)
N_2O	Manure storage	0.005*(N excreted+N in straw)	kg N_2O-N/kg N	Haenel (2010)
	Nitrogen input into the soil			
	Manure (Fertilizer) application	0.01*N in manure (fertilizer)	kg N_2O-N/kg N	IPCC (2006)
	Crop residues	0.01*N in crop residues	kg N_2O-N/kg N	IPCC (2006)
CO_2	Lime application	0.44*$CaCO_3$	kg CO_2/kg $CaCO_3$	IPCC (2006)
	Machinery	30-80[g]	kg CO_2/hour	Vellinga et al. (2012)
Indirect on-farm				
N_2O	Leaching	0.0075*N input into the soil *N fraction leached	kg N_2O-N/kg N	IPCC (2006)
	Volatilisation	0.01*NH_3-N volatilised	kg N_2O-N/kg NH_3-N	IPCC (2006)

[a] CF = Crude fibre intake; [b] NfE = intake of N-free extract; [c] CP' = intake of crude protein; [d] EE' = intake of ether extract; [e] VS = amount of volatile solids excreted; [f] MCF = CH_4 conversion factor, 0.1 kg/kg C for slurry, 0.02 kg/kg C for farm yard manure; [g]: includes direct fuel use and indirect emissions related to the production and maintenance of machinery, value differs among feed due to differences in type of machinery, machinery work and diesel use

Table A.2: Emission factors (EF) to calculate ammonia (NH_3) emissions from volatilisation and nitrogen (N) losses from leaching

Livestock class and source	EF	Unit
Volatilisation		
Housing		
Dairy cow, slurry	12	kg NH_3-N/place/year
Heifer, slurry	2.5	kg NH_3-N/place/year
Calf, farm yard manure	7	% of N excreted
Manure storage		
Slurry	8	% of N content in slurry
FYM[a]	25	% of N content in FYM[a]
Mineral fertilizer applied	10	% of N applied
Manure applied	20	% of N applied
Leaching	30	% of N applied

[a] FYM = farm yard manure

Table A.3: Emission factors for mineral fertilizer, lime and pesticide production in g CO_2-eq/kg of fertilizer or pesticide

N production[a]	5852
P production[b]	1910
K production[b]	360
Lime production[b]	43
Pesticides[b]	7340

[a] Vellinga et al. (2012), average value of different mineral nitrogen fertilizer types for West Europe.
[b] Ecoinvent (2010)

Table A.4: Economic allocation of greenhouse gas emissions and land use between feed and by-products of feed cultivation and processing (% allocated to feed)

	Cultivation (%)	Processing (%)
Winter Wheat	79	100
Barely	75	100
Rapeseed meal	100	24.1
Soybean meal	100	36
Corn	100	100
Brewers grain	100	0
Sugar beet molasses	100	4.3
Malt germs	75	0
Maize gluten	100	5.8
Wheat bran	79	6.8