Mitig Adapt Strateg Glob Change (2012) 17:337–355
DOI 10.1007/s11027-011-9329-3

ORIGINAL ARTICLE

Greenhouse gas mitigation and offset options for suckler cow farms: an economic comparison for the Swiss case

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Received: 3 July 2011 / Accepted: 10 October 2011 /
Published online: 26 October 2011

Abstract We assessed the economic suitability of 4 greenhouse gas (GHG) mitigation options and one GHG offset option for an improvement of the GHG balance of a representative Swiss suckler cow farm housing 35 Livestock units and cultivating 25 ha grassland. GHG emissions per kilogram meat in the economic optimum differ between the production systems and range from 18 to 21.9 kg CO_2-eq./kg meat. Only GHG offset by agroforestry systems showed the potential to significantly reduce these emissions. Depending on the production system agroforestry systems could reduce net GHG emissions by 66% to 7.3 kg CO_2-eq./kg meat in the most intensive system and by 100% in the most extensive system. In this calculation a carbon sequestration rate of 8 t CO_2/ha/year was assumed. The potential of a combination of the addition of lipids to the diet, a cover of the slurry tank and the application of nitrification inhibitors only had the potential to reduce GHG emissions by 12% thereby marginal abatement costs are increasing much faster than for agroforestry systems. A reduction of the GHG emissions to 7.5 kg CO_2-eq./kg meat—possible with agroforestry only—raised costs between 0.03 CHF/kg meat and 0.38 CHF/kg meat depending on the production system and the state of the system before the reduction. If GHG emissions were reduced maximally average costs ranged between 0.37 CHF/kg meat, if agroforestry had the potential to reduce net GHG emissions to 0 kg CO_2-eq., to 1.17 CHF/kg meat if also other options had to be applied.

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Keywords Abatement costs · Agroforestry · Greenhouse gas mitigation · Greenhouse gas offset · Meat · Simulation · Suckler farming · Whole-farm model

1 Introduction

The contribution of agriculture to climate-relevant emissions has emerged as a major concern for scientists, policy makers and the public. Methane (CH_4) and nitrous oxide (N_2O) constitute crucial non-CO_2 greenhouse gases (GHG). From a global perspective livestock is responsible for around 80% of agricultural and 18% of total GHG emissions (FAO 2006). Moreover 60% of nitrous oxide and about 50% of methane are associated with agricultural activities such as keeping livestock (here in particular from enteric fermentation) and soil cultivation (IPCC 2007). Pressure from policy and consumers to reduce these emissions are increasing worldwide. For example in Australia Government is discussing the implementation of a tax on GHG emissions (Nelson et al. 2011). Even if agriculture is not addressed within these schemes it offers farmers the possibility to trade emission certificates as a new source of income. On the other hand, large retailers in France label their products with a carbon footprint giving consumers the possibility to choose the most climate-friendly product (Cousin 2009).

Strategies to cope with the challenge of mitigating GHG emissions from agriculture can occur through (1) changes in plant and livestock production, (2) changes in the intensity of production activities, and (3) adoption of specific technologies (cf. UNFCCC 2008). While the last group comprises, e.g., slurry additives and coverage of slurry tanks, the first group involves enhanced grazing and agroforestry.

In Switzerland in particular suckler farming is of increasing importance. This development is caused by a rising consumer demand for meat produced by animal-friendly livestock husbandry. In order to reduce the environmental loads from suckler farming, strategies to mitigate climate relevant emissions have to be considered.

Both the high degree of heterogeneity in farming practices and the transboundary character of GHG emissions make it challenging to assess mitigation potentials. Therefore, assessment of mitigation strategies necessitates an analysis at a more disaggregated level (e.g. at the farm level) (Crosson et al. 2011). In addition, the implications of agricultural production imply links between GHG, the nitrogen cycle and other environmental factors. Thus, a holistic view of the agricultural production process is required in order to evaluate different mitigation strategies (Schils et al. 2005; Stewart et al. 2009).

Different studies assess and compare greenhouse gas emissions from different suckler cow farming systems using life cycle analysis approaches (e.g. Beauchemin et al. 2010; Casey and Holden 2006; Foley et al. 2011). However these models do not consider economic rationalities (i.e. farmers' responses) and thus cannot estimate the costs associated with a reduction of GHG emissions. Veysset et al. (2010) present a modeling framework that assesses both, economic performance as well as GHG balance of French suckler cow farms. They show that the production system has an impact as well on the farm GHG balance as on the economic performance. Meyer-Aurich (2005) calculates marginal GHG abatement costs for a cropping farm in Germany, showing that marginal abatement costs at the farm level can help to approach optimal abatement strategies. For the dairy sector different models already exist that have proven to be suitable tools to explicitly assess the economic performance of mitigation options (for a review on such models see Schils et al. 2005).

In this article, we investigate the opportunities of low GHG emitting suckler cow production systems in Switzerland. Moreover, we quantify the marginal and average abatement costs for different mitigation strategies in grassland-based suckler farms. In our analysis, we consider 4 mitigation strategies: (1) switching to alternative production systems, (2) lipid fodder supplements, (3) the coverage of slurry tanks, (4) adding nitrification inhibitors to slurry, and one offset strategy: the use of agroforestry for GHG offset.

To assess the options mentioned above, an integrated bio-economic model, which links the agricultural production process to environmental factors, is applied at a representative Swiss suckler cow farm. In this model, marginal abatement costs are calculated. In addition, we investigate the impact of the reduction of GHG emissions on the price of meat, which is relevant from the consumers' and farmers' perspective. Our study provides information for farmers and policy makers about the suitability of the assessed option. To reach this goal we aim to answer the following three research questions: 1) What is the potential of the different options to improve GHG-balance of the farm? 2) What is the (economically) optimal combination of the different mitigation options? 3) What are the supplemental costs (e.g. for consumers) for carbon improved meat?

The remainder of this paper is organised as follows: Section 2 presents the methodological framework of the employed bio-economic model and an overview of the here considered mitigation and offset strategies. Results and discussions are presented in Section 3, while Section 4 concludes our analysis.

2 Data and methods

Our *Integrated Suckler Cow Optimisation* model (INTSCOPT) was designed to evaluate different GHG mitigation options as well as the biophysical and economic potential of agroforestry. This model was constructed to allow quantification of all direct and indirect gaseous emissions from suckler cow farms to assess mitigation and offset options.

INTSCOPT is based on linear programming (LP), since this approach has proven to be a suitable method for considering both economic and environmental constraints, especially in the case of farming systems (Janssen and Van Ittersum 2007). The structure of INTSCOPT takes the form of a standard LP model, as described in Table 1. We apply our model to a single existing, exemplary farm. This farm is located in the Swiss highlands on an elevation of 800 m.a.s.l. It is characterized by a total farm area of 25 ha, and has a maximum housing capacity of 35 livestock units (LU), what is a representative size for Swiss suckler cow farms. Land use activities are grassland based, i.e. no crop production is considered because soil and climate conditions are not suitable. Thus all feed concentrates are assumed to be purchased on the market.

The goal function underlying this model is the maximization of total (i.e. farm-level) gross margins for the farmer. Gross margins are taken as goal function because our analysis focuses on a short time horizon, and farmers can thus not adjust overhead and fix costs, but focus on the adjustment of direct, assignable (i.e. variable) costs of their activities. The objective function is measured in monetary units (Z) and is defined as follows:

$$Max\ Z = \sum returns - \sum assignable\ cost - \sum mitigation\ costs + \sum subsidies, s.t.\ constraints \quad (1)$$

In the maximization process the model has the ability to optimize the number of animals as well as land-use, i.e. the choice of grasslands of different intensities and agroforestry. Since the diet is calculated endogenously also the choice of the amount of concentrate feed

Table 1 General structure of the INTSCOPT model showing its constraints and activities. Constraints marked with (*PEP*) are part of the ecological cross compliance, a precondition to receive subsidies in Switzerland. All other constraints are either modelling the limitations the farmer is facing because of the size of his farm or the agronomic production capacity of the farm. Thereby *a* is an agronomic parameter specific for each activity and constraint combination and *Z* the farm-level gross margin. Also part of the optimization process is the calculation of total greenhouse gas emissions *E*, whereas *e* is the emission parameter

Activities → Constraints ↓	Cows	Calves	Feed forage	Feed concen-trates	Feed lipids	Grassland intensive	Grassland extensive	Agroforest intensive	Agroforest extensive		Remarks
Animal production											
Stable size	a	a								≤35	Limit due to size of the stable house
Herd structure	a	-a								=0	See chapter 2.1
Diet	a	a	-a	-a	-a					=0	See chapter 2.1
Forage production			a			-a	-a	-a	-a	=0	
Agronomic constraints											
Total farm area						1	1	1	1	=25	
Extensive grassland (PEP)							1		1	≥1.75	
Nutrient balance (PEP)	a	a				−1.1*a		−1.1*a		≤0	See chapter 2.2
Nutrient balance (Agronomy)	a	a				-a		-a		≥0	See chapter 2.2
GHG-Emissions	e	e		e	e	e	e	-e	-e	< E	See chapter 2.3
Objective function	+CHF/ Head	+CHF/ Head	-CHF/ ton	-CHF/ ton	-CHF/ ton	-CHF/ ha	-CHF/ ha	-CHF/ ha	-CHF/ ha	=Z	

or lipids in the diet is part of the optimization process. Also part of the optimization process is the implementation of the assessed GHG-mitigation measures.

Equation 1 shows that farm-level gross margins are maximized subject to specific constraints. An overview over these constraints is given in Table 1. They address for instance, the farm size (i.e. the used area has to be equal to the total farm size), the production of forages (i.e. forages are produced on the farm), but also address cross compliance restrictions that have to be fulfilled to receive general direct payments. For grassland based suckler farms the most important cross compliance restrictions are that at least 7% of the total farm area has to be cultivated with extensive grassland, and the nutrient balance of the farm has to be balanced.[1]

To optimise both profit and GHG emissions, an iterative procedure described by de Wit et al. (1988) has been chosen. The procedure consists of a number of optimisations of the total gross margin, whereas the GHG emissions are lowered in every optimisation round by 2.5 t CO_2-eq.[2] while keeping the animal husbandry system and the amount of meat production constant. Afterwards, the model is applied to 1) calculate the total (i.e. farm-level) gross margins of different production systems, 2) assess the environmental and economic performance of different GHG mitigation and offset options in an integrated approach and 3) to estimate marginal and average abatement costs.

In the following sections, the crucial parts of the model, including the calculation of the emission factors, are described. At the end of this section, a summary table on key-variables and assumptions (i.e. on prices, costs, direct payments, grassland yields, etc.) used in the model is presented (Table 5).

2.1 Animal production systems and farm structure

Table 2 shows the characteristics of the three considered suckler cow production systems.

For the optimisation of the feed mix, the year is split into two periods: winter and summer. Whereas in winter, hay and silage of different qualities are available, during the summer, fodder from pastures also is part of the feed mix. In both periods, forage can be supplemented by concentrates and fat. Determining the composition of the feed mix is part of the optimisation process. The daily energy requirement for every animal is calculated according to its weight and its needs (production, growth) in every period. These constraints are complemented by upper and lower limits of daily dry matter intake calculated on the basis of the animal's weight. To guarantee the availability of crude protein in the feed mix, an upper and lower bound is defined, depending on the energy intake. The calculations of the feed requirements and the composition of the different feeds are based on data provided by Arrigo et al. (1994).

The model assumes that the animals are kept in free-stall housing in which the number of stalls is flexible according to the age of the animals. Animals older than 15 months are kept in cubicles, whereas younger cattle are kept on deep litter. It is assumed that a change between the housing systems does not require much effort. Therefore, the only building constraint in INTSCOPT is the total number of LU, which in this case is 35 (cf. Table 2).

[1] See El Benni and Lehmann (2010) for an overview on Swiss agricultural policy as well as cross compliance restrictions.

[2] To make the results comparable between the different production systems it was necessary to reduce GHG-emissions by identical absolute values. Reduction steps of 2.5 t CO_2–eq. were chosen as a compromise between high accuracy of the results and required time for computation.

Table 2 Characteristic parameters of beef production in the three production systems presented in this study: Angus, Charolais and Galloway

Production parameter	Production system		
	Angus	Charolais	Galloway
Weight of the cow [kg]	625	800	525
Calves per year [1/year]	1	1	1
Weight of calf at birth [kg]	36	45	27
Age at slaughtering day [months]	10	15	25
Average growth per day [g/day]	1100	1133	700
Live weight at slaughter (LW) [kg]	364	550	482
Carcass weight (CW) [kg]	205	310	270
Milk production [kg/year]	2500	3000	2000
Max. number of Livestock Units [LU]	35	35	35
Max. number of cows	35	26	18

2.2 Nutrient balance and N-cycle

The outcome of the model is restricted by two different nutrient balances. The first balance ensures that the modelled farm fulfils the cross compliance requirements (*Proof of Ecological Performance* (PEP), see El Benni and Lehmann (2010) for details), which represents a criteria that must be met to receive direct payments in Switzerland. In order to fulfil the PEP the amount of nutrients spread may not exceed 110% of the nutrient demand of crops and grassland. The calculation of this nutrient balance in the model was done according to the official calculation criteria (for details see *Suisse-Bilanz*, Amaudruz et al. 2003).

Because GHG and nitrogen emissions are linked, a second refined balance was calculated for nitrogen. This second nitrogen balance integrates the different compartments of the farm nitrogen cycle. The amount of artificial fertilizer that is purchased is calculated as the difference between the demand for nitrogen by the grassland to reach yields as high as specified for the different intensity levels and the nitrogen available in manure. The available nitrogen in manure is calculated as the amount of nitrogen in the feedstuff—including both, roughage and concentrate feedstuff—minus the amount of nitrogen lost by selling animals, gaseous emissions and emissions through leakage. The different parts of the cycle are calculated according to the methods presented in Table 3.

2.3 Calculation of GHG emissions

In our model, we account for all GHG emissions on a farm, including indirect nitrous oxide emissions associated with N losses and selected pre-chain emissions from imported products. GHG emitted after the products, i.e. meat and timber, have left the farm are not considered. On-farm emissions are calculated applying the IPCC methodology (Houghton et al. 1997; IPCC 2000). Because emission levels are climate- and management-specific (Crosson et al. 2011), these methodologies have been adapted to Swiss conditions. The various on-farm emissions, their sources and the underlying methods are described in

Table 3 Description of the different compartments of the nitrogen cycle as modelled in INTSCOPT as well as the underlying methods. The amount of nitrogen flowing through the different compartments is influenced by the here shown factors

Compartement of the N-cycle	Source of nitrogen	Influencing factors for the different N-flows considered in INTSCOPT	References for the methods to assess each compartment of N-cycle
System inflow			
Fertiliser		Type of fertiliser/nutrient content	
Concentrate		Type of concentrate	Arrigo et al. 1994
Biological N Fixation		Land-use intensity	Schmid et al. 2000
System outflow			
Meat N-content	Animal	Amount of meat produced	Arrigo et al. 1994
NH_3	Manure	Housing system, manure storage and spread, pasture management, manure storage	Reidy and Menzi 2005
	Land use	Type of fertiliser or manure, manure management	
NO_3	Land use		Houghton et al. 1997
N_2O	Manure	Housing system, type of manure, manure storage	Schmid et al. 2000; Schmid et al. 2001
	Land use	Crop residues, NH_3 loss	
NO_x	Manure and fertiliser	Amount of N in manure and fertiliser	Schmid et al. 2000

Table 4. To compare the different emissions with each other, methane and nitrous oxide are converted into CO_2 equivalents following IPCC (2007).

Pre-chain emissions are emissions associated with the buying, i.e. importation into the farm system, of production factors such as concentrate feedstuff and artificial fertiliser. Note that pre-chain emissions for the consumption of electricity on the farm as well as for the construction of buildings and machinery are not considered since this study focuses only on short term optimization hence changes in buildings and machinery are not part of the optimization process. Vergé et al. (2007) show for the Canadian dairy sector that the neglected indirect GHG emissions account only for 5.1% of total GHG emissions. Since use of electricity in the here considered beef production is lower than in dairy production, we assume that our framework covers at least 95% of total GHG-emissions.

2.4 Selected mitigation and offset strategies for agricultural GHG emissions

Compilations of mitigation and offset strategies for agriculture are provided by, e.g. Martin et al. (2010), Wright and Klieve (2011), and UNFCCC (2008). With a focus on grassland-based suckler farming, this section addresses the mitigation practices and their relative reduction potentials, which are included in this assessment: They have been chosen since they do not require large investments as for example anaerobic digestion, or separation of slurry do. In addition their impact has been proven outside a laboratory environment (Veysset et al. 2010; Martin et al. 2010; Amon et al. 2006; Weiske et al. 2001) and these mitigation options are feasible for use in practice as also are agroforestry systems (Eichhorn et al. 2006).

Table 4 Factors influencing greenhouse gas emissions as considered in INTSCOPT as well as references for the underlying greenhouse gas calculation methods

Greenhouse Gas	Source of greenhouse gas	Factors influencing the emission of the different greenhouse gases	References for methods applied to model the emission of each greenhouse gas
CH_4	Enteric fermentation	Animal-specific methane rate, feed mix, lipid supplementation	Houghton et al. 1997; Minonzio et al. 1998
	Manure	Amount of different manures, feed mix, housing system, pasture management	
N_2O	Manure	Amount of different types of manure, manure management	Houghton et al. 1997
	Land-use	Fertiliser, N-fixation, harvest residues,	Schmid et al. 2000, 2001
	Indirect	Loss of N in different compounds	Schmid et al. 2000, see Table 4
CO_2	Tractor/Machinery	Land-use intensity	Houghton et al. 1997; Gazzarin and Albisser Vögeli 2010
Pre-chain emissions	Production and transport of concentrate feedstuff	Composition of the animal's diet	Van der Werf et al. 2005; Bernesson 2004; Williams et al. 2006
	Production and transport of artificial fertiliser	Land-use intensity, available on-farm manure	Williams et al. 2006

2.4.1 Different animal production systems

The animal production system has a major effect on the emission of GHG. Veysset et al. (2010) assessed differences of up to 10% in emitted GHG among grazing suckler farming, depending on the production system. We consider three common Swiss production systems in our analysis named after breeds that are suitable for the respective systems: Angus, Charolais and Galloway. The productivity per LU for Angus and Charolais is quite high because after 10 and 15 months (Boessinger et al. 2009; Mutterkuh 2011), respectively, the optimal live weight for slaughter must be attained. While the Angus and Charolais systems need to be managed rather intensively, the Galloway system can be applied on marginal sites using low-nutrient feed mixes (Mutterkuh 2011). For a detailed description of the different systems see Table 2.

2.4.2 Lipid supplements

Whereas different strategies, e.g. defaunating agents, or ionophores, did not yet provide convincing results in the decrease of methane production in ruminant's digestion, supplementation of lipids to the diet leads to a significant decrease of methane emissions (Wright and Klieve 2011) without decrease in performance (Grainger and Beauchemin 2011). Lipids reduce methane emissions through decreased organic matter fermentation, activity of methanogens and protozoal, and hydrogenation of fatty acids for lipids rich in unsaturated fatty acids (Johnson and Johnson 1995). However, the measured efficiency

Table 5 Summary of economic model parameters including prices for farm products, production factors, machinery, and mitigation options based on prices in the year 2009. In the lower part a description of the yields and carbon sequestration rates of the different land-use activities is given. Data mainly origins from publication for extension services in Switzerland

Parameter in INTSCOPT	Amount	Unit	Reference for data
Returns			
Meat Calve	10.3	CHF/kg CW	Boessinger et al. 2009
Meat Cow	7.9	CHF/kg CW	
Subsidies			
Grassland intensive	1040	CHF/ha	Swiss Federal Council 1998
Grassland mid-intensive	1040	CHF/ha	
Grassland extensive	1740	CHF/ha	
Cows	1130	CHF/LU	
Costs			
Young cow	450	CHF/cow/year	Boessinger et al. 2009
General costs husbandry	180	CHF/cow	
Concentrate feedstuff	700	CHF/t	
Fertilizer Urea	636	CHF/t	Schoch 2009
Fertilizer Ammonium Nitrate	385	CHF/t	
Fertilizer Triple Super Phosphate	680	CHF/t	
FertilizerPotash	640	CHF/t	
Machinery			
Hay conservation	106	CHF/ha/Cut	Gazzarin and Albisser Vögeli 2010
Silage conservation	497	CHF/ha/Cut	
Slurry spreading	2	CHF/m^3	
Manure spreading	18.6	CHF/t	
Mitigation measure			
Lipids	266	CHF/t	Price for sunflower oil (SwissOlio 2007)
Nitrification inhibitor	0.65	CHF/kg N	Landi Jungfrau 2008
Slurry tank cover	2.06	CHF/m^3slurry	Peter 2008
Agroforestry	0	CHF/ha	Discounted value of wood is as high as investments into plantation
Yields			
Grassland intensive	12.2	t/ha	Dütschler-Herrmann et al. 2006
Grasslandmid-intensive	8.54	t/ha	
Grassland extensive	2.44	t/ha	
Grassland intensive Agroforestry	7.32	t/ha	Dütschler-Herrmann et al. 2006; Kern 2006
Grasslandmid-intensive Agroforestry	5.124	t/ha	
Grassland extensive Agroforestry	1.464	t/ha	
Age of trees at harvest	20	years	Palma et al. 2007
Carbon sequetsration Agroforestry	8	t CO_2/ha	Palma et al. 2007

varies broadly, as Beauchemin et al. (2010) showed in a recent review. On average, a 1% increase of lipids in the feed mix leads to an emission reduction of 5.6%. Martin et al. (2010) indicated an average emission reduction of 4.8% per 1% increase of lipids in the dry matter. In the context of lipid supplements, however, it is important that the level of lipids must not exceed 6% of total dry matter content or else a depression of fodder intake may occur. Based on these two review studies, our analysis assumes a 5% reduction in emissions per 1% lipid supplementation and a maximum of 6% lipids of total dry matter in the diet.

2.4.3 Slurry tank coverage

Covering slurry tanks can reduce methane, nitrous oxide and ammonia emissions. However, depending on the type of slurry coverage and the temperature, the rate of reduction varies. Covering slurry with a wooden lid leads to a reduction in methane emissions of 14% (winter) and 17% (summer), and a reduction in ammonia emissions of 28% (winter) and 54% (summer) (Amon et al. 2006). Based on this study, we assume in our model 15%, 35%, and 50% reductions in methane, nitrous oxide, and ammonia emissions, respectively, if slurry tanks are covered.

2.4.4 Nitrification inhibitors

Mineralisation of soil organic matter results in the release of ammonium (NH_4^+) or ammonia (NH_3) (Firestone and Davidson 1989). In the process of nitrification, ammonium is oxidised via nitrite (NO_2^-) to nitrate (NO_3^-). Nitrate easily can be leached into the groundwater, causing eutrophication, and both nitrite and nitrate can be denitrified to nitrous oxide (McNeill and Unkovich 2007). The application of nitrification inhibitors (NI) (e.g. 3,4-dimethylpyrazole phosphate (DMPP)) lowers the nitrification rate by reducing the activity of *Nitrosomonas* bacteria (Zerulla et al. 2001). Weiske et al. (2001) showed a 49% reduction of nitrous oxide emissions when they applied DMPP on fertilised sites. A similar result of 48% (spring) and 61% (autumn) reduction in nitrous oxide emissions was demonstrated by Merino et al. (2005), who applied 1 kg of DMPP per hectare on slurry. Based on these and other studies, we assume a reduction potential of 50% for direct nitrous oxide emissions from pastures through the application of nitrification inhibitors.

2.4.5 The agroforestry system

Agroforestry systems contain a combination of a woody permanent crop with a crop or with grassland on the same area. Such systems result in diversified agricultural production, increased soil fertility, reduced nitrogen losses, improved landscape scenery, and enhanced biodiversity (Jose 2009; SAFE 2005). Compared to monocropping, one advantage of agroforestry is the ability to sequester carbon through storage in the permanent crop's wood or through the enrichment of organic matter in the soils (Palma et al. 2007). However, similar to other land use systems, the potential for carbon sequestration under agroforestry depends on multiple factors, e.g., the carbon content in existing biomass, the turnover of trees and the environmental conditions (Jose 2009). Thus, even at the small scale, the level of carbon sequestration varies. Palma et al. (2007) revealed a sequestration potential of 2.1 tC/ha/y to 3 tC/ha/y (equals 6.4 t CO_2/ha/y to 9.6 t CO_2/ha/y) for agroforestry systems based on fast-growing hybrid poplars. Based on these results, a sequestration potential of 2.5 tC/ha/y (equals 8 t CO_2/ha/y) is assumed in our analysis (Table 5). This can be seen as a rather conservative value. Arevalo et al. (2011) found 10 year old (monoculture) poplar plantations in Canada to sequester 8 tC/ha in average per year considering also carbon sequestration in the soil. In order to analyze the senstivity of our results to the assumption on sequestration potentials, we additionally considered the lower and upper tails of sequestration potentials (i.e. 6.4 t CO_2/ha/y and 9.6 t CO_2/ha/y) reported by Palma et al. (2007).

2.5 Land-use

All land-use activities in our model are grassland-based. These activities differ only in the intensity of the pasture and the presence or absence of trees (i.e. agroforestry). According to Boessinger et al. (2010), three different grassland intensities are considered in INTSCOPT: intensive, mid-intensive, and extensive (Table 5). For any grassland type, the model can establish an agroforestry system. Because of the increasing competition for sunlight and other resources, the yield of grassland under trees is reduced by 40% (Kern 2006).

3 Results

In our simulation highest total gross margin was achieved with the production system based on the Charolais or Angus breed (Table 6). Because of the low amount of meat produced per year in the Galloway system, its total gross margin was 14% lower than in the other systems.

Depending on the production system, GHG emissions per kilogram of meat ranged between 18 kg CO_2-eq./kg CW (Carcass Weight) for the Charolais system and 21.9 kg CO_2-eq./kg CW for the Galloway system. These values were comparable to those reported by other studies, such as Casey and Holden (2006) and Foley et al. (2011), which reported emissions of 20 kg CO_2-eq./kg CW and 15.7 kg CO_2-eq./kg CW to 23.1 kg CO_2-eq./kg CW, respectively for Irish beef production. However, the values reported in INTSCOPT were lower than emissions shown by Veysset et al. (2010) for Charolais based suckler cow systems in France (26.6–30.5 kg CO_2-eq./kg CW).

3.1 Mitigation options within the different production systems

Results for the Charolais and Galloway systems are indicated in Fig. 1. Both covering the slurry tank and adding lipids to the feed mix had a rather low impact and fast increasing

Table 6 Model output for the different production systems in the initial state, when they are in the economic optimum: Greenhouse gas emissions in total (GHG_{tot}), per kilogram of meat produced (GHG_{prod}), relative sources of the different greenhouse gases as well as total meat production and gross margins

Description of Output parameter	Unit	Production system		
		Angus	Charolais	Galloway
GHG balance				
GHG_{tot}	t CO_2-eq.	175	176	134
GHG_{prod}	kg CO_2-eq./kg CW	19.4	18	21.9
GHG sources				
CH_4 digestion	%	53	53	55
CH_4 manure	%	5	5	6
N_2O	%	37	35	36
CO_2 machinery	%	1	1	2
CO_2 inputs	%	4	6	2
Agricultural Production				
Meat production	kg CW	9050	9800	6113
Gross margin	kCHF	138	138	119

marginal abatement costs. The addition of fat to the cow's feed increased its net energy concentration, which might cause fattening problems. Due to the combination of this limitation and the cow's large contribution to total methane emissions, the impact of lipids was limited to a maximum reduction potential of 2% and 3% in the Galloway and the Charolais systems, respectively. Charolais cows required a higher energy concentration in the feed; thus a higher amount of lipids in the diet was tolerable and therefore the addition of fat had a higher potential for GHG reduction in the Charolais system than in the Galloway system. These results were consistent with a study by del Prado et al. (2010), which reported for dairy cows, which need fodder with higher energy concentration than suckler cows, a reduction potential of about 10% per kilogram of milk when lipids were added to the feed.

The curve progression for the marginal abatement costs of covering the slurry tank looked very similar to that of adding lipids to the diet (Fig. 1). The potential was limited to a decrease of 2% and 4% in the case of the Galloway and the Charolais systems. High abatement cost of the cover resulted from the small contribution of the slurry tank to total GHG emissions and the high cost for the construction of the cover .

Nitrous oxide emissions constituted about 50% of total emissions and our analysis indicated that nitrification inhibitors (NI) could reduce these emissions significantly. In comparison to the mitigation methods of adding lipids and covering the slurry tank, the marginal costs of applying NIs were relatively low (Fig. 1). The NI method of mitigation produced associated costs that were favourable in comparison to the lipid and cover options also because it reduced the need for expensive artificial nitrogen fertiliser.

With the application of a combination of all mitigation options, GHG emissions could be reduced by 12%. These results were similar to those of other studies. For example, Hartmann et al. (2009) reported a mitigation potential of 5% and 2% with the addition of lipids and the slurry tank cover, respectively.

The above presented analyses focussed on technical mitigation options. In a subsequent step, the option to offset GHG emissions with on-farm agroforestry was taken into account. In the Galloway system, the establishment of an agroforestry system could reduce net GHG emissions to zero. In the case of the Charolais and the Angus systems, carbon sequestration in an agroforestry system had the potential to reduce emissions by 66% and 60%, respectively. In combination with other mitigation options in these systems, respective

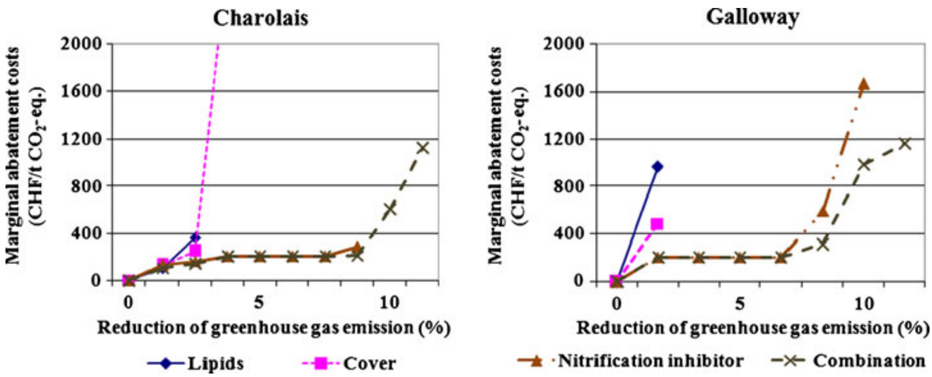

Fig. 1 Marginal abatement costs of different mitigation options for the Charolais (similar to Angus) and the Galloway systems. Marginal abatement costs are shown for the supplementation of lipids to the fodder (*Lipids*), for a cover on the slurry tank (*Cover*), for the application of nitrification inhibitor in manure management (*Nitrification inhibitor*) and for a combination of these three options (*Combination*)

reductions of 77% and 70% could be reached. Agroforestry had a greater potential for the Galloway system because in the initial state land was managed low-intensively in this system. Hence, land was available to compensate for the smaller forage production caused by the enlarged agroforestry area. In the other systems, land use in the initial state of the system was relatively intensive, thus, the potential to intensify land use was lower. Compared to the other mitigation options, agroforestry was relatively inexpensive (in terms of costs per mitigated/sequestered ton of CO_2-eq.). In all systems, a 50% reduction of GHG emissions was possible at marginal abatement costs of less than 57 CHF/t CO_2-eq.

In all systems average reduction costs per kilogram of meat were lower for the on-farm offset than for the other mitigation options considered (Table 7). Agroforestry was least expensive in the Galloway system since enough land was available for intensive use to compensate loss in fodder production due to expanded agroforestry.

With the application of all mitigation options (including agroforestry) within the production system, GHG emissions could be reduced to 5 kg CO_2-eq./kg CW or lower. Because agroforestry had the lowest marginal abatement costs compared to the other options, it was applied predominantly, while the other options were applied secondarily. In the Galloway system agroforestry potentially could reduce emissions to zero. A reduction of the emissions to 5 kg CO_2-eq./kg CW in this system cost only 0.11 CHF/kg CW. In contrast, in the Angus and the Charolais system, agroforestry alone could reduce emissions only to a level of 7.76 kg CO_2-eq./kg CW and 6.12 kg CO_2-eq./kg CW, respectively. For this reduction a significant share of the farm area has to be covered by agroforests (Table 8). Reductions cost 0.37 CHF/kg CW for the Angus system and 0.32 CHF/kg CW for the Charolais system. To reduce emissions further to 5 kg CO_2-eq./kg CW, other options to mitigate GHG must be applied, e.g., supplementing lipids in the diet and utilising NIs. These additional mitigation strategies significantly increased reduction costs to 0.5 CHF/kg CW and 1.14 CHF/kg CW for the Charolais and Angus systems, respectively.

Reduction costs depend on economic and ecological considerations. Average reduction cost per kilogram meat as well as the potential of the agroforest to offset GHG emissions were highly dependent on the assumed rate of carbon sequestration as indicated by a sensitivity analysis (Fig. 2). So in the case of the Angus system costs for the offset of 50%

Table 7 Average additional costs per kilogram of meat (CHF/kg carcass weight) for the reduction of greenhouse gas emissions per kilogram meat for the different production systems applying either a combination of mitigation options (*Mitigation w/o agroforestry*) or a combination of mitigation and offset options (*Mitigation and agroforestry*). The values underlined in a grey colour specify the emissions level of the different systems in the economic optimum, i.e. the emission level that is reachable without extra costs. Every cell beyond the grey shaded means a reduction in greenhouse gas emissions applying one of the different options. *n.a.* means not available, i.e. there is no convergence to a solution for these emission levels

Emissions per kilogram of meat [kg CO2-eq./kg CW]		**Production system**					
		Angus		**Charolais**		**Galloway**	
		Mitigation w/o agroforestry	**Mitigation and agroforestry**	**Mitigation w/o agroforestry**	**Mitigation and agroforestry**	**Mitigation w/o agroforestry**	**Mitigation and agroforestry**
22.5	Reduction of emissions	0	0	0	0	**0**	**0**
20		**0**	**0**	0	0	0.44	0
17.5		0.53	0	**0.08**	**0**	na	0
15		na	0.01	na	0	na	0.01
10		na	0.24	na	0.11	na	0.02
7.5		na	0.38	na	0.24	na	0.03
5		na	1.14	na	0.5	na	0.11
2.5		na	na	na	na	na	0.25
0		na	na	na	na	na	0.37

Table 8 Land-use in the different production systems if the systems are in their economic optimum (*Initially*) and if the systems are optimised with respect to their greenhouse gas emissions (*GHG-offset*)

Main land-use activity	Sub-land-use activity	Angus		Charolais		Galloway	
		Initially	GHG offset	Initially	GHG offset	Initially	GHG offset
Intensive grassland	Monoculture	15.09	15.41	21.6	14.2	15.12	9.12
	Agroforestry	0	7.84	0	9.05	0	11.71
Mid-intensive grassland	Monoculture	8.16	0	0	0	0.85	0
	Agroforestry	0	0	0	0	0	0
Extensive grassland	Monoculture	1.75	0	3.4	0	9.03	0
	Agroforestry	0	1.75	0	1.75	0	4.17

of GHG emissions were 21% higher if sequestration rate was at the lower than at the upper level as stated by Palma et al. (2007). It is therefore necessary that they are calculated independently for every country and farming system.

4 Discussion

We used an integrated bio-economic model to analyze the economic and environmental performance of 3 different suckler cow production systems in Swiss agriculture, with a particular focus on the mitigation of GHG emissions considering four mitigation and one offset strategies. Results confirm other studies (e.g. Casey and Holden 2006 and Crosson et al. 2011), which found, that the production system has a large impact on the emission level in the economic optimum. Mitigation options assessed in this study showed a limited possibility to mitigate GHG since they provoke fast increasing marginal abatement costs. The most efficient way to reduce GHG emissions is a combination of mitigation and offset options since marginal abatement costs are always lower than if mitigation options were implemented only. Above all, this combination showed a potential for the production system with the highest emissions per kilogram of

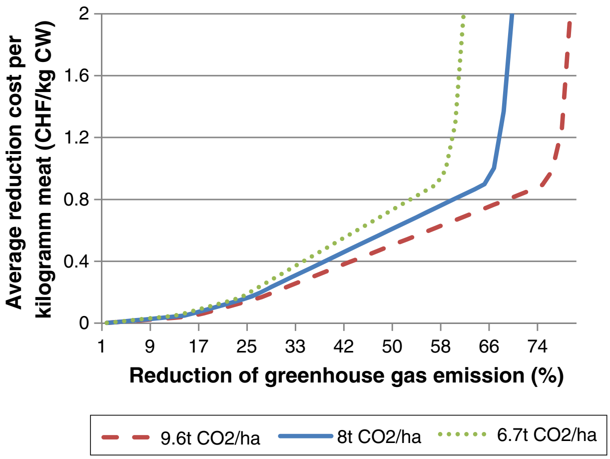

Fig. 2 Impact of the rate of carbon sequestration of the agroforestry systems on the average reduction costs per kilogram of meat. Sensitivity analysis was conducted at the example of the Angus production system. Maximum amount of greenhouse gas offset is 61%, 69% and 79% for sequestration rates of 6.4 t CO_2/ha/y (lower level stated by Palma et al. 2007), 8 t CO_2/ha/y (default level in this study) and 9.6 t CO_2/ha/y (upper level stated by Palma et al. (2007), respectively

meat in the economic optimum—the Galloway system—since in this system average additional costs are lowest and also a reduction of net greenhouse gas emissions to zero is possible. However the large agroforestry area needed might hinder farmers to maximize GHG offset and might limit its implementation on an area that can offset only a smaller share of GHG-emissions.

In our opinion agroforestry is especially suitable for extensive production systems not only in Switzerland but all around the world. The costs raised by the agroforestry systems are mainly opportunity costs of decreasing production and a loss in subsidies, i.e. parameters that depend on the local conditions. Farmers that receive lower prices for their products therefore will also face lower monetary losses by the implementation of agroforestry systems. It could therefore also be an opportunity for large scale beef farms, for instance in Australia, that could trade emission certificates when improving their carbon balance.

The use of LP as method for the simulation of decision making provides some caveats. LP is based on the neoclassical economic theory. In this theory, economic agents are profit optimizers. Combined with limited resources, represented by model restrictions, these normative model approaches incorporate the fundamental economic problem: making the best out of limited resources (Buysse et al. 2007). Of course, decision making is, other than the goal function of an LP, multidimensional considering different types of utilities (Edward-Jones 2006), e.g. farmers might be conservative regarding the use of specific methods if they strongly deviate from current practices (Karrer and Tikir 2010). Considering only monetary profit as a utility will neglect additional constraints farmers are facing. Therefore results of such a simulation must be considered as a type of best case solution. In order to overcome these drawbacks, linear programming methods can be augmented, for instance, by considering farmers' income risks (e.g. Finger et al. 2010) and integrating decision rules based on survey data (Möhring et al. 2010).

The accuracy of model results can be wrong if the model is based on an unsuitable design or false data. The results of such models therefore should be validated properly (Zander et al. 2008). For this purpose we compared some of the intermediate results with real farm data. For the amount of GHG emission as well as the efficiency of the assessed mitigation options this was not possible due to a lack of real data. The calculation of the emission is based on a widely accepted methodology (e.g. Vergé et al. 2007). The input parameters needed for calculation of emissions however inherent large uncertainty (Rypdal and Winiwarter 2001; Schmid et al. 2000). Parts of this uncertainty we tried to address by a comparison of our results with them of other studies as well as with a sensitivity analysis (Fig. 2). In further research this uncertainty should be assessed more in depth as for example done by Foley et al. (2011).

We are also aware that carbon fluxes in grasslands vary due to climatic and management conditions (Zeeman et al. 2010). Due to the long time period of 20 years considered in our empirical analysis and the assumption of constant grassland management, we assume that this variability is only of minor relevance for our analysis. Additionally a study of Ford-Robertson et al. (1999) suggests that a conversion of pastures to agroforestry systems does not lead to decreasing net soil carbon stocks of each year in the transition period. However, uncertainties arising from this issue should be addressed in future analyses.

Our analysis was conducted at the farm-level using an existing farm structure that in its size is representative for Swiss suckler cow breeding farms. Stewart et al. (2009) found that heterogeneity in farm structure will lead to different numerical results across farms. Thus, the site-specific, spatially explicit analysis of mitigation options should be addressed in further research. In addition, technical uncertainties arising from specific mitigation options and agroforestry should be empirically addressed in further research.

Our results show that reductions of greenhouse gas emissions per kilogram of meat are not free of costs. Thus, consumers would have to pay for these reductions. Studies on consumers' willingness to pay for emission reductions, for instance by using alternative electricity and fuel production techniques (Roe et al. 2001; Nomura and Akaib 2004) have shown that there is a positive willingness to pay for such environmental service. Different studies also show that consumers are ready to pay in addition for food with a lower carbon footprint or they at least choose products with a better carbon balance if the products else are identical (Bolwig and Gibbon 2009; Vanclay et al. 2010). Such willingness to pay is expected to be rather high in Switzerland, because the Swiss population has a high demand for environmentally friendly, low emission agriculture (Haller 2011). In addition, we think that the reduction of emissions from meat production, or even an emission-neutral meat production, is a large opportunity for producers because this could be used to label their products and could thus be used for further product differentiation. As shown in Table 5, subsidies in form of general and ecological direct payments as well as the associated cross compliance requirements play an important role in Swiss agricultural production. The reduction of emissions from animal production could thus also be fostered by integrating greenhouse gas emission restrictions in the cross compliance restrictions or by introducing additional ecological direct payments for low- or zero-emission animal production.

5 Conclusion

In our assessment of the economic suitability of mitigation and offset strategies to reduce GHG emissions for common suckler farming systems in Switzerland, only the agroforestry system, with its carbon sequestration potential, leads to significant GHG emission reductions at reasonable costs.

Other mitigation options considered in our study do not have the potential to reduce GHG emissions on a large scale. They neither have the potential to reduce a large share of GHG emissions, nor are they inexpensive enough to make implementation possible.

Additional production costs for carbon improved meat will be in a moderate range making it marketable. This is even more the case as the farmers' animal production costs represent only a part of the price the consumer pays for meat in the shop.

Consumers are becoming more and more sensitive to climate change and are modifying their behaviour accordingly when buying meat in the grocery store (Vanclay et al. 2010). For farms to benefit from this consumer trend, the emissions of the whole value chain must be assessed and optimised. For the agricultural link of the value chain, agroforestry is a way to contribute to GHG mitigation and to adapt to this future consumer trend.

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