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Environmental consequences of pig production scenarios using biomass from rotational grass-clover leys as feed

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ABSTRACT

Production of pork based on monoculture cereal-based cropping systems causes substantial environmental pressures and feed-food competition. This study evaluated the environmental consequences of five different scenarios involving inclusion of rotational grass-clover leys and incorporation of grass-clover biomass in pig diets: (1) a conventional reference scenario without grass-clover biomass; (2) a conventional scenario with replacement of feed with grass-clover silage in a total mixed ration, i.e., with grass-clover biomass replacing other feed; (3) an organic scenario using grass-clover silage for enrichment purposes only; (4) an organic scenario using grass-clover silage for enrichment purposes and additional grass-clover leys for green manuring; and (5) an organic scenario using grass-clover silage and pasture to replace feed. The functional unit was 1 kg of pork slaughter weight and the system boundary was from cradle to farm gate. We used life cycle assessment, the introductory carbon balance method and human edible feed conversion efficiency to assess the performance of the pig production system. Introducing grass-clover biomass as a total mixed ration in conventional pig diets, reduced the climate impact (-17%), eutrophication (-7.1%), marine eutrophication (-15%), energy use (-13%), and feed-food competition (-20%) per kg of pork meat, while acidification (+2.7%) and land use (+1.5%) were slightly increased compared with the reference. The lower climate impact (without considering soil carbon change) was attributable to reduced fertilizer and diesel needs due to pre-crop effects. Overall, feeding grass-clover biomass decreased several environmental impact categories, feed-food competition and improved cereal-based cropping systems by the introduction of grass-clover leys.

1. Introduction

The climate impact of meat is considerably higher than that of plant-based protein sources (Clune et al., 2017; Poore and Nemecek, 2018). However, there is substantial potential to reduce the climate impact of meat through improvements in the production system (Pexas et al., 2020). Production of meat from monogastric animals results in considerably lower emissions of greenhouse gases (GHG) per kg of meat produced than production of meat from ruminants, due to substantially lower emissions of methane (CH_4) from enteric fermentation and greater feed conversion efficiency

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(Gerber et al., 2013). However, production of monogastric animals is associated with a number of sustainability challenges. These include: feed-food competition (van Zanten et al., 2016), as the diet of monogastric animals is dominated by feedstuffs that are suitable for direct human consumption (Mottet et al., 2017); a risk of point-source pollution from manure (Pexas et al., 2020); and animal welfare challenges, including animals often being reared in barren environments with little stimuli (Brunberg et al., 2016). In addition, as the diets in current monogastric production systems are commonly exclusively based on annual crops, cropping systems on pig, poultry, and arable farms providing feedstuffs for monogastric animals are often monocultures (Karlsson et al., 2022), relying on considerable amounts of fertilizers and pesticides and leading to soil carbon losses (Tripathi et al., 2020).

Several of these challenges can be alleviated by introducing rotational grass-clover leys (GCL) in such cropping systems and using the grass-clover biomass (GCB) in the diet of monogastric animals. Under the climate conditions in northern European, perennial crops such as GCL have great potential to supply biomass and protein (Manevski et al., 2018). Rotational GCL are also important for increased soil fertility and biodiversity, and can be grown on soils of insufficient quality to produce valuable feed resources. Perennial grasses, clover (*Trifolium pratense*), and other forage legumes also help to increase the carbon content in soils, lower the risk of nitrogen (N) and phosphorus (P) losses from the field, and reduce the need for pesticides (Röös et al., 2020). Leguminous crops in GCL also add N to cropping systems and hence reduce the need for mineral fertilizers.

Previous research has shown that GCB can replace 20% of the dietary crude protein content in the diet of fattening pigs (Friman et al., 2021). The corresponding figure on a dry matter (DM) basis is also around 20% (Bellof et al., 1998; Carlson et al., 1999; Bikker and Binnendijk, 2012; Wüstholz et al., 2017; Presto Åkerfeldt et al., 2018). For pregnant sows, an even higher level of GCB can be included in the diet (Jakobsen et al., 2015). Using GCB in pig diets reduces feed-food competition, because it can replace ingredients in the pig diet that humans can use as food (Ertl et al., 2016). Feeding GCB to pigs is also a way of providing the animals with extended feeding time and environmental enrichment, which improves animal welfare (Olsen, 2001; Kallabis and Kaufmann, 2012; Holinger et al., 2018; Presto Åkerfeldt et al., 2019). However, the way in which GCB is incorporated into a pig production system determines the extent to which it can replace other feeds, improve animal welfare, and improve overall environmental performance. For example, GCB can be fed as: (1) pasture or silage *in addition* to a complete, nutritionally balanced diet (as is common practice in current organic production), hence providing enrichment only and not replacing other feed ingredients; or (2) in a total mixed ration (TMR), where it is included as a feed ingredient and mixed with other feedstuffs such as cereal grain, providing some enrichment (through longer feeding times) and reducing feed-food competition (Friman et al., 2021).

The aim of this study was to investigate the environmental performance of different scenarios involving incorporation of GCB into conventional and organic pig production systems. We investigated differences between the scenarios in terms of their climate impact, eutrophication and acidification potential, cropland use, and energy use from a lifecycle perspective per kg of meat produced, and also in terms of their contribution to animal welfare improvements and feed-food competition. Finally, we modeled potential soil carbon sequestration following introduction of GCL in cropping systems to provide feed for the pigs.

2. Materials and methods

2.1. Description of scenarios

2.1.1. Overview

We studied five theoretical pig farming scenarios. Each scenario is based on a virtual farm of 100 ha. A virtual pig farm is a pig production enterprise that produces its own feed together with other crops for sale but also complements its pig feed requirements by sourcing from neighboring farms following a similar crop rotation. Here, however, cropping wise we only account for the production of feed to the pigs. As a starting point and reference, we considered a conventional scenario not including GCB in diets, reflecting typical pig production in Sweden today (Conv_Ref). This was compared with four systems using GCB in different ways: a conventional scenario in which GCB was fed as a TMR, replacing part of the feed (Conv_TMR); an organic scenario that used GCB only as enrichment (Org_Enrich); an organic scenario that used GCB as enrichment and for green manuring (Org_Enrich_GM); and an organic scenario in which GCB was fed as forage on pasture during the outdoor season and as a TMR for the rest of the year (Org_TMR_Pas).

As the main aim was to investigate the effects of inclusion of GCB in pig diets, we assumed that all feed (except smaller amounts of potato (*Solanum tuberosum*) protein, feather meal, amino acids, and premixes) was produced on the farm. We also assumed that all pig diets used local ingredients, thereby avoiding having to account for direct and indirect land use change from imported ingredients such as soybean (*Glycine max*). Although soybean is a common feed ingredient in Swedish pig production, some farms rely entirely on feed grown on the farm itself or on neighboring farms, making this a realistic assumption. We assumed that the farms were all located in south-west Sweden (Västra Götaland) and that the soil type was sandy loam, with a topsoil depth of 0.20 m (Johnsson et al., 2019). Diets for sows, piglets, and fattening pigs were formulated for the five scenarios by an experienced pig production advisor, using EvaPig® (2021). Similar feed ingredients were used as a basis for each pig category in the different scenarios, with the exception that GCB partly replaced the ingredients in some of the scenarios using GCB. All diets were balanced according to the nutritional needs of the pigs.

In more detail, the five scenarios were:

1. *Conv_Ref:* Average conventional pig farm in Sweden as described in Zira et al. (2021), but based on local feed. The production system was integrated pig production, i.e., both piglets and fattening pigs were produced on the same farm. All pigs were kept in indoor housing without any outdoor access. Straw was provided to all pigs daily (as regulations require that all pigs should be supplied with sufficient amounts of materials to root in, examine, and chew (SJVFS 2019:20; Jordbruksverket, 2019), but no GCB was fed to the pigs in this system. Dry sows were kept in groups in loose housing pens with deep straw bedding until one week prior to farrowing, when they were transferred to individual loose-house farrowing pens (6 m^2 per sow and litter), where they were kept until the piglets were weaned (32 days after farrowing). Weaned piglets from different litters were mixed in groups of 30 after weaning. When the piglets reached 10 weeks of age they were moved to fattening pig pens, where they were kept until they were slaughtered at six months of age.

2. *Conv_TMR*: Same scenario as Conv_Ref, but with GCB mixed into the feed as a feed ingredient, replacing parts of the feed ration and fed as TMR. Substitution with GCB was made on a crude protein basis, with GCB replacing 30% of crude protein in dry sow diets, 5% in piglet diets, and 20% in fattening pig diets. Lactating sows did not receive any GCB, because of their high energy demands.

3. *Org_Enrich*: Average organic pig farm in Sweden with integrated production. Straw was provided to all pigs daily according to organic production regulations and all pigs received GCB for additional enrichment purposes, as silage all year round. Thus, pigs received an additional amount of enrichment material compared with the Conv_Ref and Conv_TMR scenarios. Dry sows were kept in groups in loose housing pens with access to outdoor concrete areas, while lactating sows were housed in individual loose housing farrowing pens from one week prior to farrowing and with their piglets until two weeks after farrowing. Two weeks after farrowing, several sows with their piglets were housed together in multi-family pens, with loose housing and deep straw bedding. Weaning occurred six weeks after farrowing. The piglets were then housed in groups and later as fattening pigs housed in loose housing pens with straw bedding and access to an outdoor concrete area. The fattening pigs had access to a larger area than in the conventional scenarios, in accordance with organic production regulations (EC, 2008).

4. *Org_Enrich_GM*: Same as Org_Enrich, except that this system had a greater area of farmland cropped with GCL than Org_Enrich. The extra GCL was used for green manuring and 20% of farmland was used for GCL, as is common practice in organic farming.

5. *Org_TMR_Pas*: Same as Org_Enrich, but with GCB included as a feed ingredient in pig diets, replacing parts of the feed ration and fed as TMR during winter and via access to fresh pasture during summer. The GCB inclusion level (crude protein basis) was 30% in dry sow diets, 5% in piglet diets, and 20% in fattening pig diets. Lactating sows were provided with GCB as enrichment, but not as a feed ingredient to replace parts of the diet, due to the high energy demand of these animals. We assumed a mobile hut system was used to reduce the risk of soil damage by pigs as well and leaching of nutrients. Intake of fresh pasture during summer was assumed to correspond to the same inclusion levels as with the TMR (Salomon et al., 2009), i.e., all GCB fed to pigs was assumed to replace other feed, except the GCB supplied to lactating sows as enrichment.

2.1.2. Scenario characteristics

The production characteristics for all pig classes (sows, piglets, and fattening pigs) in each scenario, and herd size and annual herd structure on the 100-ha farms, are shown in Table 1.

2.1.3. Pig diets

Table 2 shows the composition of the diets fed to different groups of pigs in the five pig production scenarios.

2.1.4. Crop production

Crops were assumed to be grown in rotation in all scenarios. In Conv_Ref, a seven-year rotation was assumed: (i) oats (*Avena sativa*), (ii) winter wheat (*Triticum durum*), (iii) barley (*Hordeum vulgare*), (iv) rapeseed (*Brassica napus*), (v) winter wheat, (vi) faba beans (*Vicia faba*) or peas (*Pisum sativum*), and (vii) winter wheat. In Conv_TMR, an eight-year rotation was assumed: (i) barley, (ii) grass-clover ley, (iii) grass-clover ley, (iv) rapeseed, (v) winter wheat, (vi) faba beans and peas (separate fields), (vii) oats, and (viii) winter wheat. In Org_Enrich, Org_Enrich_GM, and Org_TMR_Pas, a seven-year rotation was assumed: (i) barley, (ii) grass-clover ley, (iii) grass-clover ley, (iv) rapeseed, (v) winter wheat, (vi) faba beans and (vii) oats and peas (separate fields). These crop rotations represent well-designed conventional and organic crop rotations suitable for the region in which the production was assumed to take place (south-west Sweden).

Crop yields in the different scenarios are shown in Table S1 in the supplementary material. The difference between Conv_Ref and Conv_TMR is because of assumed increases in soil fertility due to pre-crop effects in the crop rotation (Cederberg and Flysjö, 2004a; Jordbruksverket, 2021). The pre-crop effects were assumed to be the same in the three organic scenarios, because the crop rotation was the same. The quantities of crops produced on a 100-ha farm are shown in Table 3 and the area of land used to produce these crops in Fig. 1. In Org_TMR_Pas, the only scenario with grazing, we assumed that 0.15 hectare of grass clover per year was required per sow for grazing, and 0.025 hectare per fattening pig (Jordbruksverket, 2015). The assumed N application rates per hectare (manure and mineral fertilizers and accounting

Table 1
Production characteristics in the five pig production scenarios.

	1. Conv_Ref	2. Conv_TMR	3. Org_Enrich/ 4. Org_Enrich GM	5. Org_TMR_Pas
Number of litters per sow and year	2.2[a]	2.2[a]	2.1[b]	2.1[b]
Live-born piglets per sow and year	27.5[a]	27.5[a]	24.2[b]	24.2[b]
Weaning age (days)	32[a]	32[a]	42[b]	42[b]
Mortality piglets (% of total born)	18[c]	18[c]	21[c]	21[c]
Culled sows (%)	50[c]	50[c]	40[c]	40[c]
Mean sow weight (kg)	240[c]	240[c]	240[c]	240[c]
Weight at movement to fattening pig section (kg)	35[b]	35[b]	38[b]	38[b]
Mortality in fattening pigs (% of total number of fattening pigs)	1.7[a]	1.7[a]	2.0[d]	2.0[d]
Fattening pig live weight at slaughter (kg)	120[a]	120[a]	120[b]	120[b]
Sows per year, including replacement gilts	62	61	40	41
Living piglets per year	1705	1678	1100	1128
Fattening pigs per year	1645	1618	1062	1089

[a] Gardochdjurhälsan (2020).
[b] Pig expert, personal communication, 21 January 2022.
[c] Zira et al. (2021).
[d] Pig expert, personal communication, 23 August 2022.

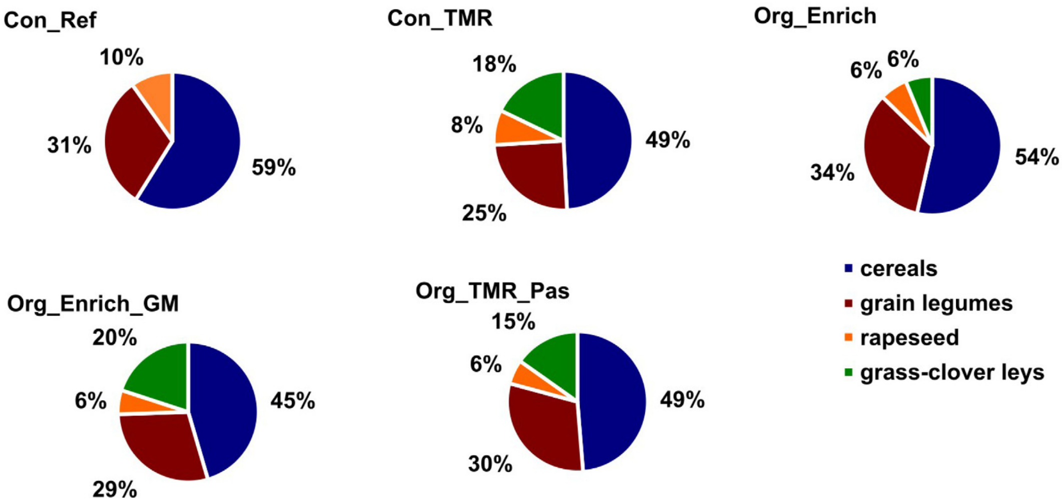

Fig. 1. Proportions of land on a 100-ha farm used for cereals, legumes, rapeseed, and silage in the different scenarios.

for pre-crop effects) (Cederberg and Flysjö, 2004a; Jordbruksverket, 2021) are shown in Table S2 in the supplementary material. Manure supplied 57 kg N per hectare in Conv_Ref, 75 kg N per hectare in Conv_TMR, 50 kg N per hectare in Org_Enrich/Org_Enrich_GM, and 47 kg N per hectare in Org_TMR_Pas. The remaining N requirement was assumed to be covered by N fixation (4 kg N per hectare for Conv_Ref and 33 kg N per hectare for organic scenarios) (Wivstad et al., 2009) and by bought-in fertilizer (ammonia nitrate in the conventional scenario and organic meat meal-vinasse fertilizer in the organic scenario). We assumed that GCB had a N fixation capacity of 51 kg per hectare (Frankow-Lindberg, 2003). The P and K requirements per hectare are also shown in Table S2.

2.1.5. Energy use

In terms of energy use, we assumed that each sow place in Conv_Ref, Conv_TMR, Org_Enrich, and Org_Enrich_GM required 738 kWh per year and that each sow place in Org_TMR_Pas required 524 kWh per year (7 kWh/month during four summer months and 62 kWh/month during the remaining eight months) (Länsstyrelsen Västra Götalands län, 2021a; Länsstyrelsen Västra Götalands län, 2021b). Each fattening pig place was assumed to require 62 kWh per year (Edström et al., 2005). For feed processing, we assumed that 30 kWh electricity was required for mixing a tonne of feed and that 0.014 kWh electricity (Cederberg and Flysjö, 2004b) and 0.095 kWh light fuel oil (Edström et al., 2005) per kg crop were used for drying. The amount of diesel used in crop cultivation (Table S3 in the supplementary material) was different for organic and conventional scenarios, following Länsstyrelsen Västra Götalands län (2021a), Länsstyrelsen

Table 2
Pig diets in the five pig production scenarios.

	Wheat, %	Barley, %	Oats, %	Potato protein, %	Faba beans, %	Rape-seed,%	Rapeseed cake, %	Rape meal, %	Hydrolyzed feathermeal, %	Peas, %	Silage /Grass as TMR, %	Amino acids, %	Premix, %	Feed intake, kg/animal
Sows and gilts														
Conv_Ref	42.6	21.3	8.1	1.0	13.1	0.0	0.0	7.7	0.0	4.2	0.0	0.1	2.0	1400/sow, 720/gilt
Conv_TMR	37.0	18.2	6.3	0.7	11.6	0.0	0.0	7.2	0.0	4.0	12.9	0.1	2.0	1500/sow. 810/gilt
Org_Enrich/ Org_Enrich GM	18.5	44.9	9.1	0.0	12.0	1.9	0.0	0.0	3.4	7.7	0.0	0.0	2.5	1500/sow. 710/gilt
Org_TMR_Pas	17.9	38.0	7.0	0.0	10.8	1.7	0.0	0.0	3.1	7.1	12.1	0.0	2.2	1500/sow, 790/gilt
Piglets from birth to approximately 35 kg														
Conv_Ref	48.6	18.2	0.0	5.5	18.0	2.0	0.0	5.0	0.0	0.0	0.0	0.2	2.5	35
Conv_TMR	44.0	16.5	0.0	5.0	16.3	1.8	0.0	4.5	0.0	0.0	9.4	0.2	2.3	43
Org_Enrich/ Org_Enrich GM	24.2	42.1	0.0	4.6	11.8	0.0	0.0	0.0	3.7	10.5	0.0	0.0	3.1	38
Org TMR Pas	22.0	38.2	0.0	4.2	10.7	0.0	0.0	0.0	3.4	9.5	9.3	0.0	2.8	47
Pigs from approximately 35 kg to slaughter weight														
Conv_Ref	43.4	19.8	0.0	0.0	20.0	2.2	0.0	12.0	0.0	0.0	0.0	0.2	2.5	260
Conv_TMR	33.1	15.1	0.0	0.0	15.3	1.7	0.0	9.2	0.0	0.0	23.7	0.2	1.9	290
Org_Enrich/ Org_Enrich GM	25	30.2	0.0	0.0	16.7	0.0	12.5	0.0	0.6	12.0	0.0	0.0	3.0	260
Org_TMR_Pas	19.2	23.2	0.0	0.0	12.8	0.0	9.6	0.0	0.5	9.2	23.1	0.0	2.3	290

Table 3
Total quantities (tonnes dry matter) of feed ingredients produced on a 100-ha farm.

Crop	Conv_Ref	Conv_TMR	Org_Enrich	Org_Enrich GM	Org_TMR_Pas
Wheat	260	230	84	71	77
Barley	120	92	120	100	110
Oats	8.6	6.0	6.5	5.5	5.2
Potato protein	4.9	4.2	2.1	1.8	2.4
Faba beans	110	86	54	46	49
Rapeseed	11	9.3	1.2	1.0	1.1
Rapeseed cake	0	0	30	25	26
Rapeseed meal	61	53	0	0	0
Premix	14	12	10	8.7	2.4
Peas	4.4	4.2	39	33	35
Amino acids	1.1	0.86	0	0	0
Feather meal	0	0	5.5	4.7	5.5
Grass-clover silage	0	130	31	27	44
Grass-clover silage from pasture	0	0	0	0	32

Table 4
Characterization factors used for assessing eutrophication and acidification potential.

Substance	Medium	Eutrophication		Acidification
		Characterization factor CML 2001	Characterization factor Henryson 2018	Characterization factor CML 2001
NH_3	Air	0.35	–	1.6
NO_x	Air	0.13	–	0.5
SO_2	Air	–	–	1.0
NO_3	Aquatic	0.10	–	–
PO_4	Aquatic	1.00	–	–
N	Aquatic	0.42	0.31	–
P	Aquatic	3.06	1.00	–

Västra Götalands län (2021b). The diesel emissions factor for machinery (tractor and combine harvester) was assumed to be 960 g carbon dioxide (CO_2) per kWh engine power output (Lovarelli et al., 2018).

2.2. System boundaries, functional unit, and allocations

We assessed the pig production scenarios from cradle to farm gate. On the farm, we included the following processes: cultivation of wheat, barley, oats, faba beans, rapeseed, peas, and silage and pig production. Inputs for crop production processes on the farm were fertilizers, pesticides (only for conventional), electricity, diesel, and light oil. We also included transport for fertilizers and other inputs to the farm, assuming 115 km transport distance by road and 400 km by sea for conventional fertilizers and pesticides. For organic fertilizers, we assumed a transport distance of 400 km by road, while for lime in both the conventional and organic scenarios we assumed a transport distance of 500 km. Off-farm feed-related activities included production of rapeseed cake, rapeseed meal, feather meal, synthetic amino acids, potato protein, and mineral and vitamin premix.

The functional unit was set to 1 kg meat (slaughter weight) and no impacts were allocated to pork by-products. However, for rapeseed we allocated impacts using an economic allocation factor of 0.36 for rapeseed cake (Fridrihsone et al., 2020) and 0.22 for rapeseed meal, based on 386 euros per tonne rapeseed meal (Commodity 3, 2022), 1890 euros per tonne rapeseed oil (Index Mundi, 2022), 41% rapeseed oil, and 56% rapeseed meal (Cederberg and Flysjö, 2004b). We did not include capital goods such as buildings, for simplicity.

2.3. Assessment methods

2.3.1. Environmental impacts

The climate impact per kg of meat was calculated using guidelines from IPCC (2019) and by using GWP_{100} factors from the IPCC's Sixth Assessment Report (IPCC, 2021), i.e., 1 for CO_2, 27.2 for biogenic methane (CH_4), 29.8 for fossil methane (CH_4), and 273 for dinitrogen oxide (N_2O). We used CML 2001 (Guinée et al., 2002) and Henryson et al. (2018) to assess eutrophication potential and CML 2001 (Guinée et al., 2002) to assess acidification potential. We chose CML 2001 because it is the most commonly used method in pig life cycle assessment studies (Monteiro et al., 2019) and Henryson et al. (2018) to capture site-dependent marine eutrophication in Västra Götaland. Henryson et al. (2018) derived characterization factors for all Swedish agricultural soils in the catchment of the Baltic Sea, based on nutrient transport data. The characterization factors used in this study are shown in Table 4.

Primary energy was assessed as the cumulative energy demand (CED) from fossil, geothermal, nuclear, primary forest, solar, hydro, and wind power, in MJ. Land use was characterized as the land occupied by pig and crop production, in m^2 per year.

Table 5
Nitrogen emissions factor applied to fertilizers, manure (organic amendment), and excreta in the pig production systems.

Input	Emission factor kg per kg		Source
N_2O direct			
Synthetic fertilizer (AN[a])	0.016	N in fertilizer	IPCC (2019)
Crop residues	0.006	N in crop residues	IPCC (2019)
Organic fertilizer ('Ekoväx')	0.006	N in fertilizer	IPCC (2019)
N_2O indirect			
Synthetic fertilizer (AN)	0.014	Volatilized N from fertilizer	IPCC (2019)
Manure semi-solid	0.014	Volatilized N from manure	IPCC (2019)
Runoff N	0.011	N leached	IPCC (2019)
NO_x			
Manure semi-solid	0.0001	TAN[b] in manure	EEA (2019)
Manure solid	0.01	TAN in manure	EEA (2019)
NH_3			
Synthetic fertilizer (AN)	0.05	N in fertilizer	IPCC (2019)
Organic fertilizer	0.21	N in fertilizer	IPCC (2019)
Manure semi-solid (pig house)	0.10	N in manure	IPCC (2019)
Manure liquid (pig house)	0.14	N in manure	IPCC (2019)
Manure deep straw bed (pig house)	0.25	N in manure	VERA (2019)
Manure semi-solid/liquid (storage)[c]	0.09	N in manure	VERA (2019)
Manure deep straw (storage)[c]	0.20	N in manure	VERA (2019)
Manure semi-solid/liquid (spreading)	0.40	TAN in manure	VERA (2019)
Manure solid (spreading)	0.35	TAN in manure	VERA (2019)

[a] Ammonium nitrate.

[b] Total ammonical nitrogen.

[c] Ammonia reduced by 90% due to covering.

Animal and manure management

The methane emissions from enteric fermentation in the pigs were calculated assuming annual emissions of 1.5 kg CH_4 per sow (IPCC, 2019) and 0.5 kg CH_4 per fattening pig (Dalgaard et al., 2007). We assumed that average N leaching from the sandy loam soil was 40 kg per hectare for cereals, 48 kg per hectare for rapeseed, and 6 kg per hectare for grass-clover (Johnsson et al., 2019). We assumed that the N leaching for legumes was the same as for cereals (Jensen et al., 2020) and that P losses were 0.72 kg per hectare for all crop production (Johnsson et al., 2019).

Nitrogen losses in the form of N_2O, nitrogen oxides (NO_x), and ammonia (NH_3) were estimated using the emission factors shown in Table 5. For the conventional scenarios, we assumed that 56% of manure from the sows was liquid manure and 44% was solid manure, and that 100% of manure from the fattening pigs was liquid manure (pers. comm. Research Institute of Sweden 16 August 2022). For the organic scenarios, we assumed that 60% of manure from the sows was semi-solid manure and 40% was solid manure, and that 100% of manure from the fattening pigs was solid manure (pers. comm., Gård och djurhälsan, 3 November 2022). Liquid manure was assumed to have 14% dry matter and a C/N ratio of 12, semi-solid manure to have 25% dry matter and a C/N ratio of 15, and solid manure to have a C/N ratio of 30 (Jordbruksverket, 2021). We calculated the amount of N retained in the pigs as (Rigolot et al., 2010):

$$N_{body} = e^{(-0.9892-0.0145\text{Lean\%})} \times \text{EBW}^{(0.7518+0.0044\text{Lean\%})}/6.25 \qquad (1)$$

where N_{body} is nitrogen in the body and Lean% is lean meat content of empty body weight (EBW), defined as 96% of the body weight of the animal.

Nitrogen in fresh manure was calculated as N in feed minus N_{body}.

Methane emissions from manure storage were calculated based on an assumed volatile solids (VS) content of 120,000 kg, 130,000 kg, 72,000 kg, 62,000 kg, and 82,000 kg for Conv_Ref, Conv_TMR, Org_Enrich, Org_Enrich_GM, and Org_TMR_Pas, respectively. Methane generation potential was assumed to be 0.45 m^3/kg VS and a methane conversion factor of 3.5% was used for liquid manure, 2% for semi-solid manure, and 17% for deep litter manure (Swedish Environmental Protection Agency, 2021).

2.3.2. Edible feed conversion ratio

Human-edible feed conversion efficiency (heFCE) was calculated as human-edible protein output per human-edible protein input (based on the current protein consumption) (Ertl et al., 2015). The human-edible fraction of protein is the amount that can be used for human food based on the food processing technology available (Ertl et al., 2015). We assumed that the human-edible protein fraction for oats was the same as for barley, and that for faba beans was the same as for peas (Table 6).

Table 6
Human-edible protein fraction of the different feedstuffs.
Source: Ertl et al. (2016).

Feedstuff	Human-edible protein (%)
Wheat	100
Barley	80
Oats	80
Faba beans	90
Rapeseed	87
Rapeseed cake	87
Rapeseed meal	87
Peas	90
Grass-clover silage	0

2.3.3. Estimated changes in soil carbon

Introducing GCL into cereal-dominated crop rotations can increase soil organic carbon content, as the input of biomass (through mainly roots) is increased (Poeplau et al., 2015). We estimated this increase in soil carbon content using the Introductory Carbon Balance Model (ICBM) (Andrén and Kätterer, 1997). In ICBM, carbon is divided into three pools, young belowground carbon, young aboveground carbon, and old carbon. Crop cultivation adds aboveground and belowground carbon through crop biomass and inputs such as manure. We estimated aboveground and belowground soil carbon inputs from crop residues and GCL using IPCC (2019). We assumed that manure was evenly spread across all fields on the farm. Young carbon is broken down into old carbon based on a humification factor h and we used a value of $h = 0.15$ for aboveground crop residues (Ericsson et al., 2017) and $h = 0.35$ for manure (Menichetti et al., 2020). Belowground carbon was assumed to be 2.3 times more stable than aboveground carbon, for all crops and for GCL (Kätterer et al., 2011). Breakdown of soil carbon is affected by soil conditions captured by the parameter re. We assumed $re = 1.07$ for cereals, $re = 1.06$ for oilseed for winter crops, $re = 1.16$ for spring crops, and $re = 0.86$ for grass-clover ley (personal communication, Department of Energy and Technology, SLU, 26 October 2021) and used a degradation rate constant of $ky = 0.8$ for young carbon and $ko = 0.0085$ for old carbon (Kätterer et al., 2004). We calculated the steady carbon state for all production scenarios reflecting the land use in Fig. 1 and subtracted the steady state in the four experimental scenarios (i.e., Conv_TMR, Org_Enrich, Org_Enrich_GM, and Org_TMR_Pas) from that in Conv_Ref (reference) to reflect potential soil carbon changes from changing the management from Conv_Ref to the other four scenarios. The climate impact factored for changes in soil carbon was calculated based on this difference and was done by subtracting the Conv_Ref steady state soil carbon content from that in the other scenarios, dividing by 100 (the approximate number of years it would take for soil to come close to steady state), and then adding this yearly change in soil carbon to other GHG emissions.

2.4. Sensitivity analysis

We performed a series of sensitivity analyses to test how certain assumptions affected the results. Concerning pre-crop effects, we tested how the climate impact was affected by not accounting for these effects. Dry sows can consume more GCB than fattening pigs, because they have a fully developed digestive system. We calculated the climate impact of providing GCB as silage to dry sows alone compared with providing it to all pigs. Keeping pigs outside, instead of indoors all the time, can create electricity energy savings. We assessed the change in CED from having sows in the conventional scenarios outdoors during summer. We also assessed the effect on eutrophication impact of changing from sandy loam to clay, as clay soils have 50% lower nutrient leaching losses than sandy loam soils (pers. comm., Research Institutes of Sweden, 2 December 2021).

3. Results

Compared with Conv_Ref, the climate impact was 13%–17% lower in scenarios that included GCB (Table 7), which was explained primarily by N fixation by clover in GCL providing N to the cropping system and by pre-crop effects reducing the need for mineral fertilizers. The reduced use of mineral fertilizer lowered N_2O emissions from soils and emissions from production of mineral fertilizers. Replacing annual crops in pig diets with GCB also reduced diesel use, which contributed to the reduction in climate impact but to a lesser extent. On average, about 45% of the climate impact came from feed production, 40% from manure management, 11% from enteric fermentation, 2% from transport of inputs, and 2% from energy use in pig housing.

The difference in steady carbon state between Conv_Ref and Conv_TMR was estimated to be 18 tonnes carbon per hectare, due to increased plant biomass input from introduction of GCL and higher yields due to the pre-crop effect, resulting in more plant biomass above and below ground and thus more carbon input to soils in Conv_TMR. In contrast, the organic scenarios had a lower steady carbon state than Conv_Ref despite the introduction of GCL, because of lower crop yields (1.56 tonnes carbon per hectare for Org_Enrich, 1.61 tonnes for Org_TMR_Pas, and 1.65 tonnes for Org_Enrich_GM), but the green manure in Org_Enrich_GM improved the soil carbon input compared with the other organic scenarios. When

Table 7
Results at farm gate for the different scenarios (per kg carcass weight of pork for environmental indicators).

Indicators	Units	Conv_Ref	Conv_TMR	Org_Enrich	Org_Enrich GM	Org_TMR_Pas
Environmental						
Climate impact	kg CO_2e	2.4	2.0	2.1	2.2	2.0
Climate impact accounting for soil carbon changes (Conv_Ref as reference)	kg CO_2e	2.4	1.6	3.7	3.5	3.5
Eutrophication potential (CML 2001) (Guinée et al., 2002)	g PO_4e	28	26	32	33	31
Marine eutrophication (Henryson et al., 2018)	g Ne	8.5	7.2	14	15	13
Acidification potential (CML 2001) (Guinée et al., 2002)	g SO_2e	73	75	56	57	61
Land Use	m^2*year	6.6	6.7	12	14	12
Cumulative energy demand	MJ	16	14	19	20	17

the climate impact was adjusted for soil carbon changes compared with Conv_Ref, Org_Enrich had the highest impact and Conv_TMR had the lowest, because of lower yields, especially of wheat, in the organic scenarios compared with the conventional scenarios (Table 7).

The different pig production scenarios contributed to eutrophication potential mainly by nitrate leaching from fields during crop production. Feed production contributed 78% of total eutrophication impact, housing and storage of manure 20%, and grazing 2%. Approximately 97% of the eutrophication potential came from N and the remaining 3% came from P. Among the different pig production scenarios, Org_Enrich and Org_Enrich_GM had the highest marine eutrophication impact and Conv_TMR had the lowest with N and P contributing 99% and 1% of the impact respectively. Eutrophication was highest in Org_Enrich and Org_Enrich_GM and lowest in Conv_TMR (Table 7). This was because Org_Enrich and Org_Enrich_GM had lower N efficiency since GCB was only used for enrichment purposes. Acidification was high in conventional scenarios and low in organic scenarios, because of lower ammonia emissions in manure spreading due to the greater proportion of solid manure in organic scenarios than in conventional scenarios. Feed production, including spreading manure on soils, contributed 62% of the total acidification impact, housing and storage of manure 34%, and grazing 4%. For acidification, 99% of the impact was from N and the remaining 1% was from sulfur (from combustion of fossil fuels).

Yield of pork meat per hectare was substantially lower in the organic scenarios compared with the conventional scenarios (0.84, 0.72, and 0.85 tonnes per hectare in Org_Enrich, Org_Enrich_GM, and Org_TMR_Pas, compared with 1.5 tonnes in both Conv_Ref and Conv_TMR). This was due to lower crop yields in the organic scenarios, leading to higher land use per kg of pork produced in those scenarios.

Crop production accounted for 74% of CED (mainly diesel use in field machinery and production of mineral fertilizers), while heating of animal houses, manure management, and other energy use in the houses (feed equipment, lighting, ventilation, etc.) accounted for the remaining 26% (Table 7). Cumulative energy demand was highest in Org_Enrich and Org_Enrich_GM and lowest in Conv_TMR, due to Org_Enrich and Org_Enrich_GM using most diesel per kg of pork produced and Conv_TMR using the least diesel of all scenarios. Organic production generally used more diesel per kg of pork produced, since it involved more mechanical operations than conventional production.

The heFCE value was 0.25, 0.30, 0.26, 0.26, and 0.29 for Conv_Ref, Conv_TMR, Org_Enrich, Org_Enrich_GM, and Org_TMR_Pas, respectively. Thus the feed used for pigs in Conv_TMR had the smallest fraction of human-edible protein and the feed in Conv_Ref had the largest fraction.

3.1. Sensitivity analysis

When the pre-crop effects on soil fertility were not accounted for, the climate impact of Org_Enrich increased by 14% (to 2.4 kg CO_2e per kg pork), making it equal to Conv_Ref. Providing GCB to dry sows, compared with providing GCB to all pigs, only increased the climate impact by 15% in Conv_TMR and by 5% in Org_TMR_Pas. Having sows outside during summer, compared with having them indoors all the time, decreased CED by 6%–7% for the conventional scenarios. A change of soil texture from sandy loam to clay resulted in a decrease in eutrophication (CML) by 19%–39% and marine eutrophication by 49% in all scenarios. With clay soil, the eutrophication impact (CML) of Org_Enrich decreased by 41% (to 19 g PO_4e per kg pork), making it lower than that of Conv_Ref.

4. Discussion

This study compared the environmental performance, including feed-food competition, of different ways of incorporating GCB into pig diets, as a feed replacement or enrichment. Use of GCB as TMR in the conventional scenario had positive effects in reducing climate impact, eutrophication potential, marine eutrophication, energy demand, and feed-food competition compared with a reference system with no GCB. In organic scenarios, incorporation of GCB as

TMR and pasture had positive effects in reducing all environmental impacts except acidification. This was because the organic scenarios had lower ammonia losses as a result of more solid manure than in conventional scenarios, and reduced feed-food competition compared with use of GCB for enrichment purposes only.

We performed a Monte Carlo simulation (500 runs) to examine if our results hold with variations in crop production i.e. crop and silage yields, tillage operations and dinitrogen emissions. When we compared systems that followed different crop rotations, we simulated yields using normal distributions (mean and standard deviations) for wheat, barley, oats, rapeseed, faba beans, peas and grass-clover silage yields and corrected for correlations between the yields using Cholesky decomposition correlation matrices. We also assumed that dinitrogen emissions (IPCC, 2019) followed log normal distributions and diesel for tillage operations followed a normal distribution. We found that Conv_Ref had higher climate change impact than Conv_TMR, Org_Enrich and Org_TMR_Pas in 91%, 80% and 93% of the runs respectively. Conv_TMR had higher climate change impact than Org_Enrich and Org_TMR_Pas in 69% and 57% of the runs respectively. Org_Enrich had higher climate change impact than Org_TMR_Pas in 74% of the runs.

The indicator used to evaluate environmental impacts, e.g., site-specific marine eutrophication versus generic eutrophication and factoring in changes in soil carbon or not for climate impact, had an influence on the results. Using generic eutrophication produced a difference of 11% between Conv_Ref and Org_Enrich, but this difference increased to 53% when using site-specific marine eutrophication. This was because site-specific marine eutrophication was estimated based on the effects of N and P leaching (waterborne emissions) only, whereas generic eutrophication was estimated based on the effects of NH_3, NO_x, N and P leaching (air and waterborne emissions). This means that the higher amount of ammonia emitted by the conventional scenarios compared with the organic scenarios is not captured in the marine eutrophication characterization factors developed by Henryson et al. (2018). Factoring in soil carbon changes when calculating climate impact altered the differences between Conv_Ref and the organic scenarios compared with omitting soil carbon changes. Conv_Ref had lower climate impact when soil carbon changes were factored in, while the organic scenarios had lower climate impact when soil carbon changes were not factored in. Even including 20% GCB could not compensate for the lower cereal yields in the organic system, leading to lower soil carbon inputs from cereal crop residues. Organic cereal yields would need to be 100% higher for Org_Enrich_GM to be on a par with Conv_Ref in terms of soil carbon given the different diet compositions. This means that transitioning from Conv_Ref to organic scenarios would probably result in soil carbon losses, but it does not necessarily mean that organic systems produce net soil carbon losses, as they could be at lower steady state or accumulate carbon if applied on depleted soils (Leifeld and Fuhrer, 2010). In general, organically managed soils have higher soil carbon than conventionally managed soils based on reviews of studies e.g. Gattinger et al. (2012). However, in our case, we have high soil carbon input in the reference system than in the organic systems, due to a high amount of crop residues retained in the conventional systems than in the organic systems and this is in agreement with another study by Poeplau et al. (2015). Furthermore, our conventionally managed soils, even in the reference system do not have monocultures but have well planned crop rotations thus reducing soil carbon loss. There could be difference in the humification factors between organically and conventionally managed soils but based on the characteristics of systems we did not expect a difference and such data is not available for Sweden but this could be an interesting subject for future model development. However, the organic scenarios used considerably more land, which could in theory be used to sequester carbon through forest plantation (Searchinger et al., 2018).

Capturing pre-crop effects in life cycle assessment is a challenge, due to the fact that it is difficult to distribute the effects across the different crops and animal products produced from the crops. The pre-crop effects considered here of including GCB, oats, legumes and rapeseed in the crop rotation were based on the well-planned crop rotations described in 2.1.4, and not those that would strictly match the different pig diet compositions (reflected in Fig. 1), as these would not be agronomically viable. In the rotation in Conv_Ref, 59% was grain, 31% grain legumes, and 10% rapeseed, which means that grain legumes would need to be grown at least every three years. However, grain legumes should not be grown in the same field more often than every six years, to avoid problems with certain plant diseases (Levenfors et al., 2001). Additionally, the pig diets in Conv_TMR contained too much grain legumes to be achievable in a well-designed crop rotation, even though the proportion of grain legumes decreased to 25%, while cereals made up 49%, rapeseed 8%, and GCL 18%. According to the scenarios in this study, pig farms cannot grow their own feed and part of the grain legume component would need to be grown in a longer rotation with other crops. This means that the positive pre-crop effects included in the calculations do not directly correspond to those in actual pig production, which might lead to pig production being credited with positive effects (increased yields, reduced mineral nitrogen fertilizer, increased carbon storage) to which it is not directly connected. However, not including any of these effects at all in the calculations would also be misleading, because including crops as components in pig feed drives production of crops in farm fields, e.g., feeding more GCB to pigs has the potential to increase GCL inclusion in areas dominated by cereal production. Therefore, we evaluated how climate impact was affected by the assumption of pre-crop effects, factoring in soil carbon changes. We found that the climate impact of pork per kg increased by 5% for Conv_TMR when pre-crop effects were not included, while carbon storage decreased by 6%. On the other hand, there is no guarantee that more GCL would be included in cereal-dominated crop rotations following incorporation of GCB into pig diets, since this biomass can be purchased from other farms where GCL is the dominant crop. Today, only 12% of the GCL area in Sweden is part of a crop rotation where the GCL is grown in 1–3 years of a seven-year rotation, while 46% of GCL is grown in monoculture ley cropping systems (Karlsson, 2022). In order to realize all the benefits of incorporating GCB in cropping systems, it is necessary for GCL to be grown in rotation with other crops.

Pigs eat to meet their energy requirements and the modern pig has an exceedingly high energy demand, which may lead to lower consumption of GCB if the feed particles are not the same. We assumed that the pigs consumed as much GCB as possible and that there was no feed sorting due to fine-chopping of GCB in the TMR (Friman et al., 2021). However, the quality of silage required by pigs may require the use of new forage seed mixtures and set new quality requirements. Stage of harvesting is also important, because pigs require silage with a low fiber fraction, especially younger and growing pigs.

Internationally, animal health and welfare is defined by the World Organization for Animal Health (OIE, 2019) as "the physical and mental state of an animal in relation to the conditions in which it lives and dies". According to organic farming standards, animals should be provided with conditions for living a natural life in accordance with their physiological and behavioral conditions and well-being, in an environment closely resembling that to which the species is evolutionarily adapted. The ability of animals to live a natural life is thereby considered a prerequisite for good animal welfare (IFOAM, 2005; EU, 2018). Including GCB as feed and enrichment material could be regarded as improving animal welfare, based on reports of better animal welfare from including silage in pig diets (Presto Åkerfeldt et al., 2018, 2019; Friman et al., 2022) and comfort from pasture (Miao et al., 2004). According to Presto Åkerfeldt et al. (2020) animals in organic systems have greater possibilities to perform species-specific behaviors due to the supply of enrichment material. Effects of GCB or GCL could therefore be regarded as positive for the pigs with TMR and with pasture, in terms of longer eating times and more possibilities to perform foraging, rooting, and exploration behavior, compared with the Conv_Ref scenario with no GCB.

Changing from the dominant pig production system in Europe, which is similar to the Conv_Ref scenario where the pig diet is dominated by cereals, to including GCB in a TMR, as in Conv_TMR, would reduce direct feed-food competition by 16%–20%. However, the heFCE value would still be less than 1 (indicating that the pigs consume more human-edible food than they produce in the meat), which is inevitably the case for all meat production based on grain. If a farm with a cereal-dominated cropping system introduces GCL into its crop rotation, there is potential to sequester approximately 18 tonnes carbon per hectare or more, depending on climate and soil type, to use less N fertilizer due to pre-crop effects, and to use less diesel compared with a situation dominated by cereal production. Considering that pork is one of the most consumed meats in Europe, changes in pig farming are much needed to manage shocks like the recent feed, N fertilizer, and energy price shocks caused by e.g., the war in Ukraine and other geopolitical unrests, and to mitigate and adapt to climate change. Changing from conventional to organic production would make pig farms less dependent on mineral fertilizers. However, on organic farms N has to be supplied as bought-in organic fertilizers, which are in limited supply, or as green manure, requiring more land. The optimum solution will be context-specific and will depend on how demand for pork and food waste can be managed. For example, Röös et al. (2022) showed that reductions in meat consumption and in food waste would provide scope for agroecological practices in European farming.

Changing conventional farms by allowing sows access to the outdoor environment can have energy-savings benefits, due to 37% lower electricity requirements compared with keeping the sows indoors all the time. This could be an important strategy for managing the energy crisis in Europe, but other inputs such as labor, maintenance of pastures, and provision of feed and water outside would need to be considered. In addition to the energy savings, allowing outdoor access could also improve pig welfare, through providing the freedom to express species-specific behavior. Changing from conventional to organic pig production would reduce the N input per hectare, but would give higher eutrophication impact per kg of pork produced. Increasing the yield of organic crops without additional use of fertilizer and growing organic crops on clay soils could increase N use efficiency, since soil texture has a considerable effect on N leaching. For example, normal leaching losses from spring barley and grass-clover ley grown on a loamy sand soil are around 50 kg N and 20 kg N per hectare, respectively, while growing these crops on a clay soil would reduce leaching to about 10 kg N and 1 kg N per hectare, respectively (Johnsson et al., 2019). While changing from conventional to organic farming on clay soil is not straightforward, because choice of the production system is also influenced by issues such as personal preferences of the farmer, it could be a good way to adapt to increases in mineral N fertilizer prices or fertilizer shortages.

The concept of including GCL in conventional systems can be worthwhile in Europe because grasses can grow well in its relatively cold and humid climate conditions (Manevski et al., 2018) but having GCL in the rotation reduces land availability for crop production and can generate excess GCB. There are alternative uses for excess GCB, such as energy generation and protein production in biorefineries (Yilmaz Balaman et al., 2022), or for silage juice (Adler et al., 2018), but the environmental impacts of such side-systems were beyond the scope of this study and should be investigated in future studies.

5. Conclusions

Inclusion of GCL in crop rotations and use of GCB as pig feed can reduce the environmental impacts of pig production, through reduced use of inputs such as fertilizer and diesel and through soil carbon sequestration and reduced feed-food competition. However, some of these benefits depend on having the GCL integrated into cropping systems currently dominated by cereals. We found that introducing GCB as a TMR in conventional pig diets reduced the climate impact (17%), eutrophication potential (7.1%), marine eutrophication (15%), energy use (13%), and feed-food competition (20%) per kg of pork meat, while acidification (2.7%) and land use (1.5%) were slightly increased. When feeding GCB as enrichment only or as TMR (hence replacing other feed), organic production scenarios had higher environmental impacts than the conventional reference scenario for all impact categories except climate change when changes in soil carbon were not considered (due to reduced use of fertilizer) and acidification (due to lower ammonia losses as a result of more solid manure in organic scenarios). The organic scenarios had a higher climate impact than the conventional reference scenario when soil carbon changes were considered (due to lower production efficiency in organic production). Factoring in the potential to sequester carbon in an organic scenario using 20% of the area for producing green manure (reflecting current practices in organic farming) gave a slightly lower climate impact than in an organic scenario without green manure.

CRediT authorship contribution statement

Stanley Zira: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Data curation. **Eva Salomon:** Conceptualization, Methodology, Writing – review & editing. **Magdalena Åkerfeldt:** Conceptualization, Methodology, Writing – review & editing. **Elin Röös:** Conceptualization, Methodology, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2023.103068.

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