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Carbon footprint of heliciculture: A case study from an Italian experimental farm

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ABSTRACT

Heliciculture for food production has huge potential and new opportunities for rural development and young entrepreneurs in Italy. No studies have yet been performed on the environmental performance of snail rearing which also might be a beneficial tool for producers. The aim of the present paper is to evaluate the impact of snail meat by a *cradle-to-farm gate* life cycle assessment centred on the carbon footprint (CF).
The study considered greenhouse gas (GHG) emissions linked to cultivation stages (indoor breeding, outdoor fattening, cleaning out and packaging) of *Helix aspersa maxima* meat production in a semi-intensive rearing system in Southern Italy. The shell potential for CO_2 sequestration was also taken into account.
Snail CF amounted to 0.7 kg CO_2 eq per kg fresh edible meat, with the highest share (about 60%) from the supplementary feeding production. Due to the combined effect of relevant amount input and restrained lifetime of HDPE mesh applied in the open field, the impact of breeding enclosures appeared considerable (about 29%). Greenhouse gas emissions linked to fodder cultivation and to the cleaning-out phase appeared restrained (nearly 4% and 5%, respectively), whilst the share of reproduction system, irrigation and packaging was negligible (<1%). The environmental load of supplementary feeding resulted to mainly ascribable (about 74%) to maize and field bean grain cultivation (for feed mixture). It was followed by grain transport (about 17%) and processing (about 4%) to feed mill and further transport of manufactured feed components (maize–field bean–limestone) to the snail farm (about 5%). The CF score might be reduced by 18%, including potential long term CO_2 sequestration in shells. As compared to other conventional macro-livestock meat sources, snail meat showed reduced GHG emissions.

1. Introduction

In some Southern European countries heliciculture represents a thriving market activity as far as food production and (recently) cosmetics are concerned. According to the Italian branch (Cherasco) of International Institute for breeding of edible snails (http://www.lumache-elici.com), Italy is a world leader in the sector with an annual sales volume of 265 million euro (data referred to 2013). From 1995 to 2010, Italian snail production and consumption have increased nearly four times, with consumption still largely relying (about 70%) on imports. The entire Italian heliciculture has more than seven thousands rearing plants extended over a surface of about 5.2 thousand ha, whilst in the South of Italy alone there are 1150 farms spread out over 998 ha The prevailing rearing system is represented by extensive (outdoor breeding and fattening) farming which characterizes about 83% of the total national snail farmed surface. On the other hand, the intensive (indoor breeding and fattening) or mixed (indoor breeding and outdoor fattening) systems are less common.

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On the whole heliciculture represents a low-tech and low-capital investment activity, with constrained fertilizers and energetic inputs and a low level of mechanization. In the South of Italy it is an emerging zootechnical activity carried out by young entrepreneurs. This applies also to the re-valuations of non-productive farmlands undergoing progressive abandonment, such as the Campania hinterland (Caserta and the Matese uplands) where snails belong to the local culinary tradition.

From a nutritional point of view, the high nutritive value of the snails' meat makes them a suitable and healthy alternative to other conventional meat sources. The average contents of macro-nutrients of 100 g of edible snail meat are: 12.9 g of proteins, from 0.6 g to 1.5 g of fats (polyunsaturated mainly), 2.4 g of minerals (Ca, P, Fe e Cu) and 60 mg of vitamin A (Picchi, 2003; INRAN, 2007). Compared to beef, pork and chicken, snail meat contains less proteins, whilst being smaller in fats and higher in vitamins.

Nowadays, the growing animal protein demand for human nutrition is expected to increase to 70–80% by 2050 (Pelletier and Tyedmers, 2010; Steinfeld, 2012). This generates an increased interest in the impact of global food production and in the achievement of environmental friendly macro-livestock supply chains.(Beauchemin et al., 2010, 2011; Nemecek et al., 2011; Schneider et al., 2011; Wirsenius et al., 2010).

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Among other sustainable possible alternative sources of proteins, special attention has recently been given to edible invertebrates (van Huis et al., 2013).

On a global scale the macro-livestock sector has a major impact on the environmental compartments. This applies to resource depletion (land, water and energy) and emissions of pollutants (greenhouse gases—GHGs, reactive N and P, etc). (Gerber et al., 2013; Steinfeld et al., 2006). As far as climate change is concerned the macro-livestock sector is responsible for 14.5% of the world's human-induced GHG emissions, due to feed production and ruminants' enteric fermentation mainly (Gerber et al., 2013; Steinfeld et al., 2006). Impacts are also from CO_2 emissions from land degradation and deforestation for fodder production (Röös et al., 2013; Nijdam et al., 2012; Steinfeld et al., 2006). These estimations apply to the Italian national scale, where emissions from enteric fermentation and manure management in animal productions were ranked among the top-10 level key sources of total national greenhouse gas emissions (Romano et al., 2014). Nonetheless, GHG emissions associated with conventional meats, can be effectively reduced through: (i) improvements in animal productivity and fertility; (ii) intensification of production as output/ha (provided that higher input requirements of feed and/or fertilizer are offset by higher levels of productivity); and (iii) CO_2 sequestering in grassland soil organic matter (Beauchemin et al., 2011; Crosson et al., 2011).

On the other hand, due to the small cold-blooded body size and moderate cultivation inputs, restrained impacts for invertebrate livestock were proved by the 2013 Food and Agriculture Organization (FAO) survey on edible insects (van Huis et al., 2013) and by a recent LCA analysis on protein production from mealworms (Oonincx and de Boer, 2012).

Snail meat might represent an environmentally friendly alternative to conventional livestock. However, to this day, no studies have been performed on the environmental performance of rearing snails for food production.

This paper aims at quantifying the *cradle-to-farm gate* amount of GHGs emitted and/or removed (carbon sequestration) along the production of *Helix aspersa maxima* fresh meat in an experimental snail rearing plant in the South of Italy, with the purpose of identifying the most impacting cultivation stages and possible mitigation strategies to constrain snail meat carbon footprint (CF).

On the one hand, the CF represents an accepted and standardized method to investigate environmental performance of products and processes (ISO/TS 14067:2013; BSI, 2008). It has widely been used to address the sustainability of meat production chains (Röös et al., 2013; Roy et al., 2012; Nijdam et al., 2012) and has the advantage of being easily understood by stakeholders, policymakers and consumers. On the other one, it only addresses the contribution of global warming and therefore cannot be used to assess the whole environmental performance of product life cycle.

An insight in snail potential for CO_2 sequestration by C incorporation in shells at the farm gate was also provided as useful information for snail farmers and other stakeholders dealing with further meat processing and environmental assessments encompassing the full life cycle. This was done in light of the growing interest in mollusc shell valorisation (Yao et al., 2014) and their prospective as a long-term sink for atmospheric carbon dioxide.

2. Methods

2.1. Goal definition

In the present study, a carbon footprint (CF) assessment was applied to a Mediterranean snail farming system under semi-intensive management. This aimed at: (i). quantifying GHG emissions and removals along the snail meat production chain and (ii) identifying the most impacting practices and inputs (for a further implementation of environmental performance of the rearing system from a CF perspective).

According to the recent ISO/TS 14067:2013 guidelines based on standard LCA procedures (ISO 14040-44, 2006a,b), CF measures the total amount of greenhouse gases emitted and/or removed along a supply chain of products and/or services within the selected spatial and temporal boundary. CF was expressed as carbon dioxide equivalent (CO_2 eq) by retrieving GWP of gases from the most recent pertinent IPCC guidelines (IPCC, 2013), using the relevant 100-year timeframe (GWP100). The conversion factors to CO_2 eq were 1 for CO_2, 28 for CH_4 and 265 for N_2O (IPCC, 2013).

The study represented a *cradle-to-farm gate* CF of snail meat. This dealt with *on-farm* activities for snail meat production: (i) indoor snail reproduction, (ii) outdoor fattening, (iii) snail cleaning-out, and (iv) final packaging for further dispatch. Upstream production of related farm inputs (i.e. feed mix, and plastic auxiliaries) was also included. The study did not encompass the impacts of distribution, store retail, and consumption of snail meat and final disposal of snail wastes. System boundary (*cradle-to-farm gate* snail farming), with process stages and related inputs, is summarized in Fig. 1.

Data were collected from a small snail producer in the Campania region and scaled up to a larger cultivation system (1 ha) which represents the increasing averaged size of Italian heliciculture. This was achieved assuming the use of regional (not polluted) marginal agricultural land.

According to the CF Technical Specification (UNI ISO/TS 14067:2013), carbon storage in a product for a specified timeframe is also accounted "*when performing cradle-to-gate studies, when this information is relevant for the remaining value chain*". GHG removals must be assigned to the life cycle stage in which they occur and be documented separately from the CF results when arising from fossil and/or biogenic carbon sources. The topic of carbon storage in harvested snail shells was also addressed given that at the farm gate a quote of C from atmospheric and fodder/feed sources has been incorporated in snail shells and, potentially, stored in the long term. To this end, possible routes of shell disposal and reutilization after snail meat retail were discussed, since they can highly affect CO_2 leakage from shells after collection.

The study did not compute CO_2 emissions from direct Land Use Change (dLUC), which also are known to be influential on the final outcome of the CF analysis applied to meat supply chains (MacLeod et al., 2013; Röös et al., 2013; Nijdam et al., 2012; Cederberg et al., 2011; Nguyen et al., 2010, 2012; Pelletier et al., 2010), but still represent a huge source of uncertainty in the CF calculation due to the lack of a standardized and harmonized methodology (Dudley et al., 2014; MacLeod et al., 2013; Röös et al., 2013; Nijdam et al., 2012). In the present case study GHG emissions from dLUC could be assumed to be of constrained relevance following: (i) the use of regional marginal cropped land for cultivation of snails, which should avoid significant *on-farm* dLUC emissions, and (ii) the reliance on regionally produced supplementary feed ingredients (see Section 2.3), avoiding the documented *off-farm* dLUC linked to conventional imported feed (eg. soy) from Latin America, where its cultivation is entailed through forest or grassland conversion (MacLeod et al., 2013; Röös et al., 2013; Nijdam et al., 2012; Cederberg et al., 2011).

Data were analysed by means of SimaPro 8.03 software coupled with IPCC (2013) v1.00 (GWP 100a). The functional unit was set as 1 kg of edible snail meat.

2.2. Description of the snail farm

2.2.1. Experimental pilot area

Primary data were collected in 2014 from a pilot area of 150 m^2 in the province of Caserta (Maddaloni, Campania region), which hosts a semi-intensive snail farming system.

At the site, egg laying and hatching occurred in a closed environment (indoor breeding phase), inside PVC boxes placed in concrete farm buildings, properly moistened by daily water supply (about 0.1 L d^{-1}

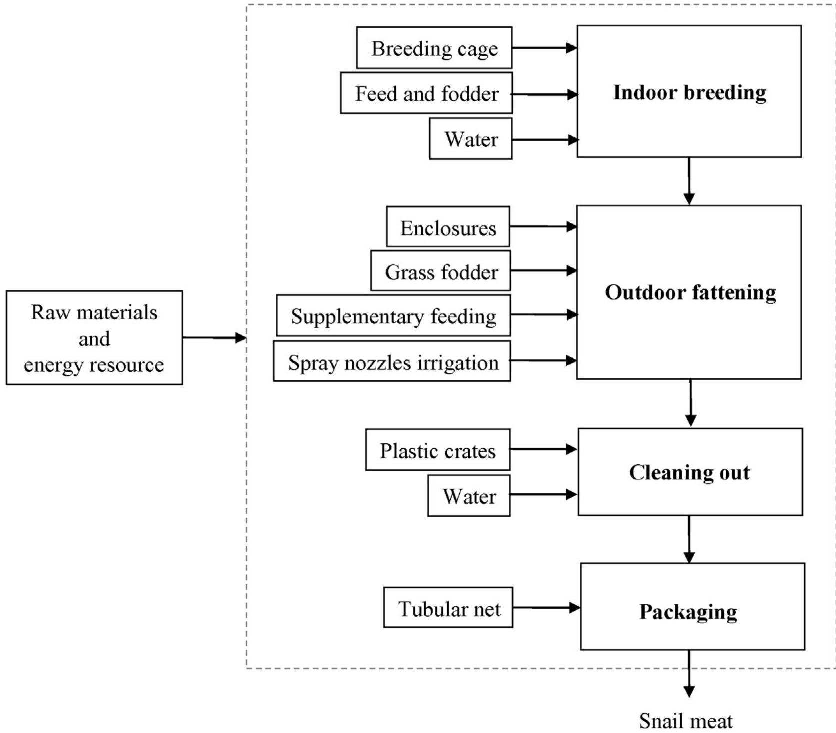

Fig. 1. The (simplified) flowchart shows the system boundary of snail meat production from *cradle-to-farm gate*. Transport of components and auxiliaries are included.

along the reproduction phase). There were two broods of young per year: out of 120 reproductive snails laying around 100 eggs in each brood, with an experimentally detected viability of 70%. Once the babies hatch (about two weeks after egg laying), the young snails (3–4 weeks old) were removed and placed inside free-range pens (outdoor fattening phase). The latter ones were fenced-in by a HDPE mesh (weight 90 g m^{-2}) which also covered the top to exclude predators and prevent hail damage. Free-range pens amounted to about 70% of the total pilot area (enclosures plus linked auxiliary area) and were earlier cropped with a mix of cabbage (*Brassica oleracea*, var. *viridis*) and beet fodder (*Beta vulgaris*, var. *cicla*), planted at a seed rate of about 9 g m^{-2}, after soil bed-preparation through rotatory harrowing (20 cm depth). During the cultivation, a mechanical weeding was necessary and irrigation water was supplied on a daily basis by a nozzle-spray system throughout the drought period, i.e. from the end of April to September (1.5 L m^{-2} d^{-1}, except on rainy days). Snails were fed on the fresh beet and cabbage fodder provided in the pens: about 0.3 ton y^{-1} and 0.2 ton y^{-1} of beet and cabbage respectively, as inferable from crop-specific averaged yield estimates (around 30 ton ha^{-1} and 22 ton ha^{-1}, respectively) retrieved from pertinent scientific literature and regional technical specifications (Regione Marche, 2007; Desai, 2004; Moschini, 1996; http://www.francescofiume.altervista.org/). The diet was also integrated for both breeders (along the reproduction period) and juveniles–adults (for about five months along the fattening phase), by a supplementary feed (about 149 kg y^{-1}, supplied ad libitum) made up of a well balanced mix of grains (maize and field bean) and limestone carbonates (confidential information for exact composition of the feed mixture). Fresh fodder and supplementary feed consumption along the outdoor fattening were accounted for nearly all the total yearly food supply (above 99%), whilst the share from the reproduction phase was negligible (below 1%).

After 9–12 months from hatching, the snails were ready to be harvested (average size of about 2.5–3 cm and 15–20 g) and purged in 6 PVC crates (average load of about 22 kg) through washing and deprivation of food for one week (cleaning-out phase). Finally, snails (flesh and shell) were packed in 5 kg bags of single-use PE tubular net, to be sold and supplied outside farm boundary. The total yield, as shell and flesh fresh weight, was 390 kg y^{-1} (2.6 kg m^{-2} y^{-1}), that is about 94 kg y^{-1} edible snail meat (0.6 kg m^{-2} y^{-1}), according to the estimate of snail edible fraction (24%) from the Italian National Institute of Research on Foods and Nutrition (INRAN, 2007).

2.2.2. Scaled-up cultivation

For the CF assessment, the snail farming was scaled up to 1 ha, by assuming the use and re-evaluation of regional non-polluted marginal agricultural land undergoing progressive abandonment. To this end, the authors assumed that the ratio between free-range pens and the total farm area was the same as mentioned in the experimental pilot area (about 70%) and simulated the consequent farm system design. Agricultural practices for fodder cultivation and snail meat yield (kg per m^2 of snail farm) were also considered similar to the pilot area. The study assumed the following:

- 26 fattening pens (3 m wide, 90 m long and 1 m high) enclosed on all sides and the top by a HDPE mesh (weight 90 g m^{-2}) fastened to hardwood poles (4 cm diameter and 1.5 m high) inserted into the soil (0.5 m depth) every 5 m. These enclosures, interspersed with passageways of about 1 m, were also equipped with a central row of similar supplementary hardwood poles to anchor the HDPE pipes of the irrigation system.
- irrigation water supply by gravity through a nozzles spray system of HDPE pipes, consisting of a main line (about 150 m long, external and internal diameter 32 mm and 30 mm respectively) and 26 lateral lines (each one 90 m long, external and internal diameter 25 mm and 23.3 mm respectively) fastened at the top of the central line of hardwood poles inside each fattening enclosure.
- the use of a newly designed multi-chamber breeding cage, consisting of a perimeter structure (1 m wide, 3 m long and 1 m high) made by steel posts (external and internal diameter 40 mm and 37 mm, respectively) and 100 internal HDPE plastic panels (1 m large and 1 m high, weigh 90 g m^{-2}) fastened every 3 cm to the external frame by steel wires (2 mm thick). About 9500 reproductive snails would be necessary (laying around 100 eggs in each brood) at a density of

about 90 breeders per m^2 of available surface, with an assumed egg viability of about 60%.

2.3. Inventory

2.3.1. Inventory of cultivation practices and inputs

As per Section 2.2, foreground inventory data collected at the experimental pilot plant were scaled up to 1 ha cultivation snail farming under mixed system. This was achieved: (i) linearly (according to the increased snail farmed area) for snail yield output, food supply (fodder and feed), fodder seeds, operation of agricultural machineries and linked diesel consumption, irrigation water, plastic crates and water for cleaning out; (ii) on the basis of the specific simulated up-scaled farm system design for plastic, wood and steel auxiliaries needed for the setting up of breeding cage, fattening enclosures and related irrigation system; and (iii) setting for auxiliary inputs (i.e. seeds, feed and HDPE net) a regional supply scenario within an average transport distance of 100 km by a 3.5 ton van (except for supplementary feed, for which a 16 ton lorry was assumed). Table 1 summarizes the material, energy, transport and other auxiliary inputs used in each production phase as referred to a one year time frame (2014). Material inputs characterized by a prolonged durability were properly divided by the respective expected service life time, to compute the specific input amounts on the one year timeframe window (Table 1).

Background processes, such as auxiliary production (agricultural machineries, feed ingredients, seeds, etc.), from the extraction and treatment of raw materials up to the final disposal, were selected from the EcoInvent v.2.0 database. For fodder seed and feed grain production, EcoInvent records were properly modified to achieve a better representativeness of the real national and regional agricultural context.

Impacts related to the production of fodder seeds and feed grains were computed according to: (i) agronomic inputs (site preparation, seeding, application rate of mineral fertilizers, etc.) scheduled in regional technical specifications for cabbage, beet seed crops (Regione Campania, 2011), maize and field bean crops (Regione Campania, 2014); and (ii) averaged yields retrieved from scientific literature and technical agronomic files for beet and cabbage seeds (Regione Marche, 2007; Desai, 2004; Moschini, 1996; http://www.francescofiume.altervista.org/), maize and field bean grains (Frascarelli, 2010; Bartolini, 2011).

2.3.2. Inventory of GHG emissions from cultivation practices and inputs

GHG emissions from both foreground activities (i.e. as exhaust gas emissions during agricultural machinery operation and tail pipe emissions along with the transport stages) and background processes (i.e. from supply of feed, diesel, electricity and construction materials) were retrieved from the EcoInvent database, according to the amounts of inputs specified in Table 1.

In absence of N fertilizer input to *on-farm* fodder (beet and cabbage) cultivation (Table 1) and to *off-farm* field bean cultivation for feed mix production (Regione Campania, 2011), Direct Field Emissions (DFE) from fertilizer application were exclusively linked to the *off-farm* cultivation of maize for supplementary feeding manufacture. These were calculated according to the most recent EcoInvent guidelines (Nemecek and Shnetzer, 2011) harking back to the IPCC methodology (IPCC, 2006). CO_2 (fossil, released from urea molecule processing in

Table 1
Primary inventory data related to each production stage needed for the 1 ha up-scaled snail farm along the selected 1 year timeframe (2014).

Production phases	Data	Amount	Unit
Indoor breeding[a]	Breeding cage		
	HDPE mesh — polyethylene, HDPE[b]	1.0	$kg\ ha^{-1}\ y^{-1}$
	Steel posts[c]	1.5	$kg\ ha^{-1}\ y^{-1}$
	Steel wire[c]	33	$g\ ha^{-1}\ y^{-1}$
	Water supply	0.6	$m^3\ ha^{-1}\ y^{-1}$
	Maize grain, field bean, limestone mix[d]	17	$kg\ ha^{-1}\ y^{-1}$
Outdoor fattening	Enclosure set-up		
	HDPE mesh[e]	0.4	$ton\ ha^{-1}\ y^{-1}$
	Wooden poles — sawn timber[f]	0.1	$m^3\ ha^{-1}\ y^{-1}$
	Beet and cabbage fodder cultivation[g]		
	Tillage harrowing	1	$ha^{-1}\ y^{-1}$
	Sowing	1	$ha^{-1}\ y^{-1}$
	Beta vulgaris, var. *cicla* — seeds[h]	30	$kg\ ha^{-1}\ y^{-1}$
	Brassica oleracea, var. *viridis* — seeds[h]	30	$kg\ ha^{-1}\ y^{-1}$
	Mechanical weeding by hoeing	1	$ha^{-1}\ y^{-1}$
	Supplementary feeding		
	Maize grain, field bean, limestone mix[i]	9.9	$ton\ ha^{-1}\ y^{-1}$
	Spray nozzle irrigation		
	Water supply	2085	$m^3\ ha^{-1}\ y^{-1}$
	HDPE water pipes — polyethylene, HDPE[j]	13	$kg\ ha^{-1}\ y^{-1}$
Cleaning out	Water supply	45	$m^3\ ha^{-1}\ y^{-1}$
	Plastic crates — polyethylene, HDPE[k]	67	$kg\ ha^{-1}\ y^{-1}$
Packaging	Tubular net — polyethylene, LDPE	13	$kg\ ha^{-1}$
Output	Snails[l]	26	$ton\ ha^{-1}\ y^{-1}$
	Edible snails[m]	6.2	$ton\ ha^{-1}\ y^{-1}$

[a] About 9500 breeding snails were taken into account in this study.
[b] Computed from total necessary input amount (9.7 kg ha^{-1}) divided by the assumed lifetime of HDPE mesh under indoor conditions (10 y).
[c] Computed from total necessary input amount of steel posts and wire (114.2 kg ha^{-1} and 2.5 kg ha^{-1}, respectively) divided by the assumed steel life time (75 y).
[d] Along the reproduction phase the diet also relied on fresh fodder planted inside the outdoor pens (less than 1% of total consumption along the fattening phase).
[e] Computed from total necessary input amount (1.1 ton ha^{-1}) divided by the assumed life time of mesh netting for fattening enclosures once applied in the field (3 y).
[f] Computed from total necessary input amount (2.5 $m^3\ ha^{-1}$) divided by the assumed life time of wooden poles (20 years).
[g] Expected fodder consumption in this study: 21 ton y^{-1} and 16 ton y^{-1} per beet and cabbage respectively.
[h] A specific record for seed preparation was implemented in SimaPro.
[i] Specific records were implemented in SimaPro.
[j] Computed from total necessary input amount (189 kg ha^{-1}) divided by the assumed life time of HDPE pipes (15 years).
[k] Computed from total necessary input amount (2 ton ha^{-1}) divided by the assumed life time of plastic crates (30 y).
[l] Taking into account the weight loss of 10% during the cleaning out phase.
[m] Edible fraction is 24% according to INRAN, 2007.

soil) and indirect N_2O emissions (from NH_3 deposition and nitrate leaching/run-off) were computed according to emission factors (EFs) retrieved from the IPCC methodology (IPCC, 2006). Direct biogenic N_2O emissions (following fertilizer application) were calculated over an average estimate of N_2O emission factor (kg N − N_2O evolved per kg N input applied − EF) for spring Mediterranean crops (0.5%) (Forte et al., 2015). This was done taking into account that EFs under Mediterranean conditions were highlighted to be markedly lower than the default 1% IPCC value (Castaldi et al., 2015; Aguilera et al., 2013).

2.3.3. Carbon incorporation and potential long-term sequestration in the shell of harvested snail

Potential long term carbon storage in the shells was computed according to the box diagram depicted in Fig. 2. Pertinent scientific literature was used in order to presume the amount and sources of carbon incorporated in aragonitic and calcitic matrix. This represents about 95%–99% of shells (Marin and Luquet, 2004) and might potentially persist in the long term. The remaining 1%–5% (Marin and Luquet, 2004) have been excluded given it has an organic matrix (proteins and other organic components such as neutral polysaccharides and lipids) and is therefore subjected to biological decomposition. Even if there is evidence that a quote of shell matrix proteins can persist in fossils (Sarashina et al., 2008), the external periostracum organic layer quickly disappears after the death of the mollusc as recently highlighted for land snails under field condition in forest soils (Říhová et al., 2014; Pearce, 2008).

According to the current LCA methodology, temporary storage is not accountable in terms of GHG benefits. The potential long term sequestration of shells was therefore discussed as a function of: (i) the carbon capture from atmospheric CO_2 and biological sources (fodder and feed) and (ii) the following carbon release along the possible disposal routes (Fig. 2).

On a national and regional context, mollusc shell wastes are collected both as organic waste (for compost production) and municipal solid waste (for landfill disposal) (Fig. 2). Specific collection platforms, currently absent, have been recently proposed in pertinent national research projects. This follows the increasing awareness of the effective shell valorisation as value-added source of $CaCO_3$ for: constructions (as partial cement replacement or as filler material in eco-friendly buildings), industrial applications as adsorbent and filtration media, and agricultural and zootechnical application such as supplements for feed mixtures (Yao et al., 2014).

A specific supply chain for further shell processors was hypothetically discussed (Fig. 2). This was based on the evidence that in foreign countries, companies for shell waste collection, cleaning and powdering, already operate.

2.4. Sensitivity analysis

Foreground input data and methodological assumptions (updated GWP, local N_2O EF and exclusion of CO_2 emission from LUC) were subject to a sensitivity analysis (ISO 14040-44, 2006a,b), by using a one-at-a-time approach (OAT), to check their influence on the final outcome of the CF analysis.

2.4.1. Foreground input data

Due to the lack of exhaustive primary data about variability of foreground flows, input requirements were tuned within arbitrary ranges (from ±10% to ±30%) with respect to the reference values applied in this study (Table 2). To highlight key parameters for the snail farming management, sensitivity results were further discussed in relation to the inferable degree of uncertainty for the different input parameters and to their actual variation when available.

2.4.2. Conversion factors

In this study, CO_2, CH_4, and N_2O emissions were converted into global warming potentials (GWP) with units of kg CO_2 equivalent (kg CO_2 eq) on the basis of the latest IPCC characterization values (IPCC, 2013). The conversion of nitrogen from fertilizer application into N_2O emissions was based on an average estimate of EF for spring Mediterranean crops (Forte et al., 2015). A sensitivity analysis was performed to determine how snail CF results would change by the use of the previous GWP

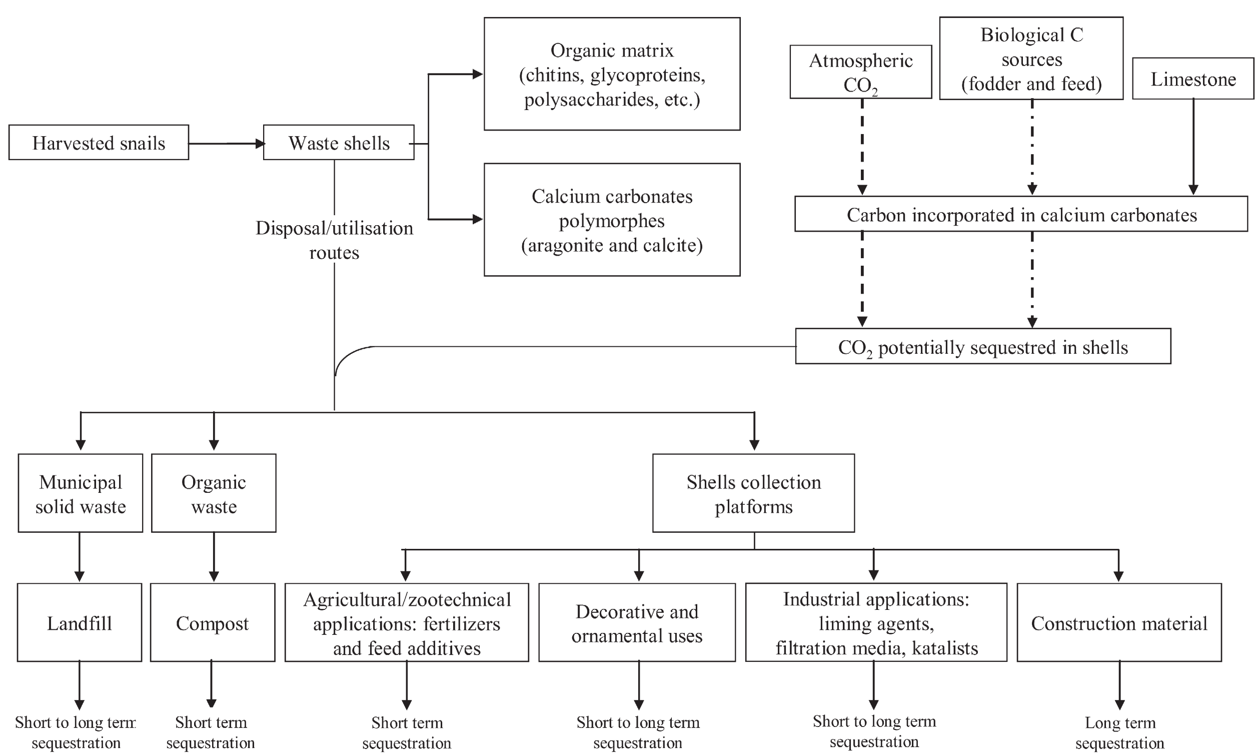

Fig. 2. Pathway of carbon incorporation inside snail shell calcium carbonates and entailed potential CO_2 sequestration according to the possible disposal/reutilization routes.

Table 2
Carbon incorporated inside shells of harvested snails and potential CO_2 sequestration entailed.

Unit	Waste shells	Calcium carbonates in shells	C incorporated in shell calcium carbonates	Potential CO_2 sequestration in shells
kg/kg harvested snail	3.3×10^{-1}[a]	3.2×10^{-1}[b]	3.8×10^{-2}	0.1[c]

[a] Primary data for this study.
[b] Assuming 97% of shells are calcium carbonate polymorphs, as averaged value from Marin and Luquet (2004) and not taking into account the impurities such as trapped sediment and water.
[c] Considering only the computation of direct atmospheric CO_2 and biological C sources (fodder and feed, as indirect CO_2 sources), and assuming 16%, 72% and 12% as percentage C sources from atmospheric CO_2, plant-feed and limestone, respectively (averaged values from Zhang et al., 2014 and Xu et al., 2010).

retrieved from the IPCC Fourth Assessment Report (IPCC, 2006) and by the IPCC default nitrogen to N_2O conversion factors (IPCC, 2007) (Table 4).

2.4.3. CO_2 emissions from direct LUC

Although GHG emissions from dLUC were assumed as a topic of restrained concern, the authors carried out a preliminary check of potential dLUC impacts along snail farming. This was done in light of a further discussion of snail CF results in the context of other meat source supply chains (for which LUC is known to be influential).

GHG emissions linked to potential direct Land Use Change (dLUC) associated with land use for snail farming were estimated using the "Direct Land Use Change Assessment Tool" (Blonk Consultants, Gouda, Version 2014.1). The tool was reviewed by the World Resource Institute and the World Business Council for Sustainable Development and developed alongside the PAS 2050-1 (BSI, 2012), based on FAOStat data (FAO, 2012) and IPCC calculation rules (IPCC, 2006, Tier 1), for quantification of rates of LUC and C loss/gain, respectively.

For the computation of GHG emissions from dLUC linked to *off-farm* crop cultivations for concentrated feed (maize and field bean) and seeds (for beet and cabbage fodder), previous land use was set as unknown. For LUC GHG emissions from *on-farm* cultivated land, computation was performed based on the hypothetical reference scenario of land still cultivated to produce annual crops (without satisfactory earnings). A second reference scenario was also included to test the extreme case of conversion of land already abandoned and shifted towards grassland/grazing land. For both hypothetical baseline scenarios the weighted average approach was chosen to compute GHG emissions from LUC (ton CO_2 eq ha^{-1} y^{-1}) in the GHG inventory. Further details can be found in footnotes of Table 4.

3. Results

3.1. Cradle-to-farm gate carbon footprint

As shown in Fig. 3, the total impact (mainly ascribable to CO_2 emissions) was mainly entailed (about 60%) by the supplementary feeding and followed by breeding enclosure set-up (about 29%). GHG emissions linked to the beet and cabbage fodder cultivation and the cleaning-out phase appeared restrained (nearly 4% and 5%, respectively), whilst the share of reproduction system, irrigation and final packaging was negligible (0.2%, 0.8 and 1%, respectively).

In the absence of supplementary electricity supply (no artificial lighting and heating in rooms for snail reproduction and cleaning out, spray nozzle irrigation by gravity and hand-packed dispatch bags), the environmental load of indoor breeding, enclosure set-up, irrigation, cleaning out and final packaging were ascribable to the production and successive processing of polyethylene granulate for the different auxiliary plastics together with the low alloyed steel for the breeding cage frame (Fig. 4). The impact appeared negligible for the breeding cage, the irrigation system and the packaging. This was due to the restrained amount of plastics and to the assumed extended life time of both plastic and steel involved materials (Table 1).

On the other hand, the rising amount of HDPE characterizing the set-up of enclosures and the final cleaning out (Table 1) led to relevant CO_2 emissions which were equally shared by HDPE granulate production and further moulding for plastic mesh and crate manufacture (Fig. 5a,

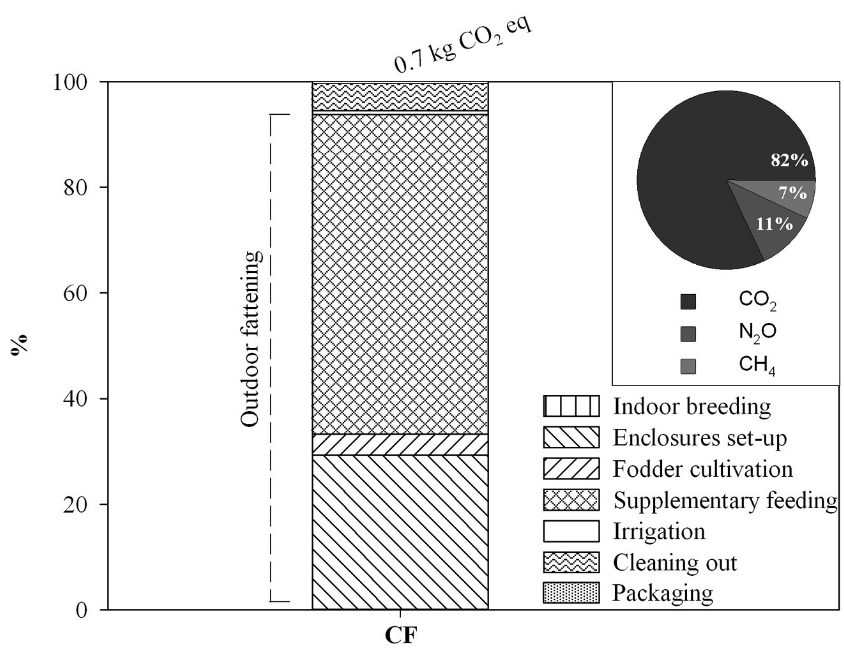

Fig. 3. Carbon footprint (CF) of 1 kg of edible snail meat. The absolute value (kg CO_2 eq) is at the top of the column, which highlights the contributions of the different cultivation stages to the total burden. Not clearly visible, since close to 1%, the contribution from indoor breeding, irrigation and final packaging. In the box on the right upper corner, there is a pie chart detailing the shares of the different GHGs.

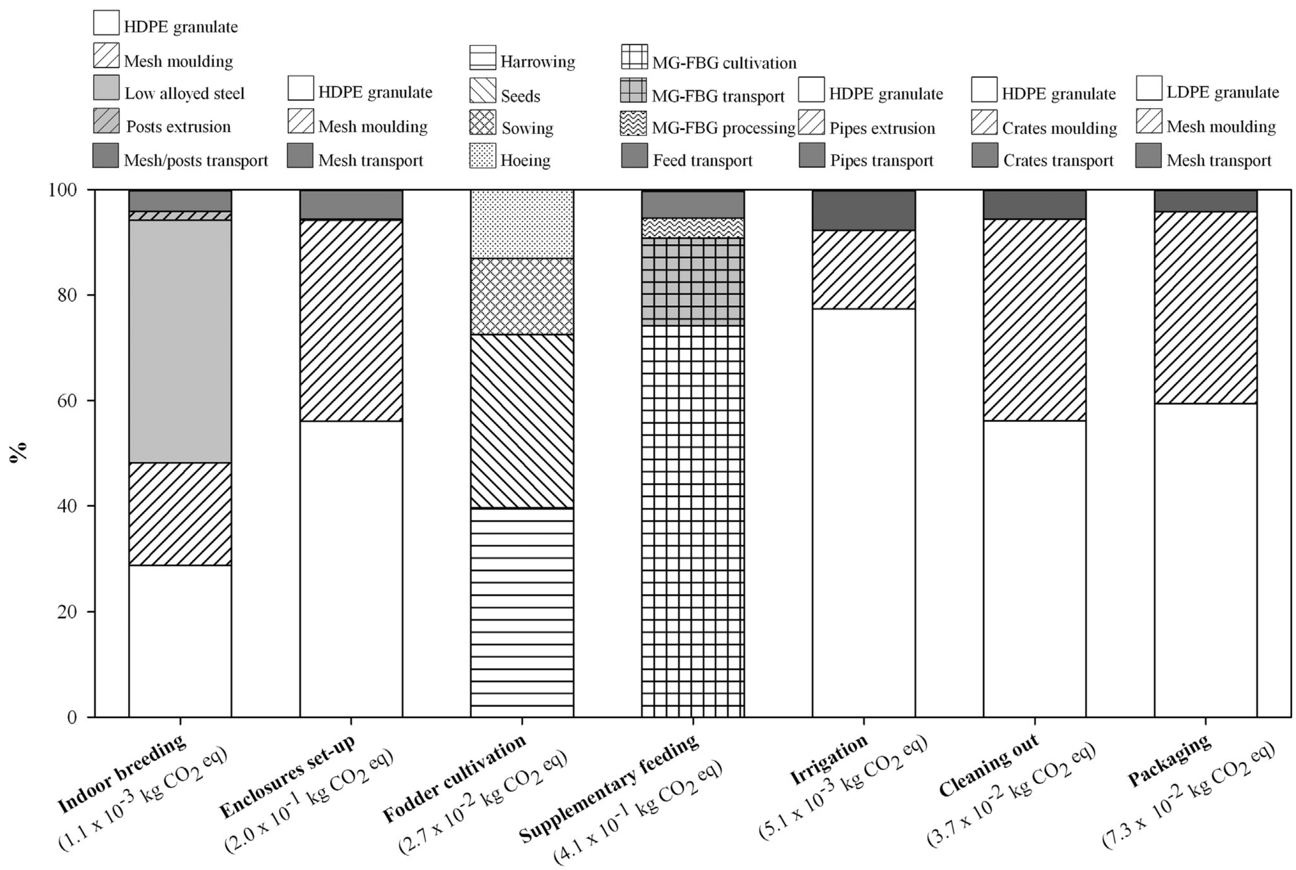

Fig. 4. The characterization graph shows the different contributions from specific material and process inputs for each cultivation stage. Not clearly visible sub-processes (below 1%) were: (i) sown timber production for wooden poles, (ii) crushed and washed limestone production for supplementary feed, and (iii) waste management of plastics and steel auxiliaries. Absolute values for each stage are also reported inside the labels. MG: Maize grains; and FBG: Field bean grains.

c). The impact appeared markedly higher for plastic mesh for fattening enclosures (Figs. 3, 5a, c) due to their restrained lifetime once they were applied in the open field (Table 1).

Cultivation of fodder without fertilization showed circumscribed burdens (Fig. 3), mainly linked to seed input and harrowing (Fig. 4). Beet and cabbage seed production and further transport to the farm accounted for about 31% and 7% of impacts respectively. Out of these, about 37% came from tillage, whilst the remaining was equally shared by sowing and mechanical weeding (Fig. 5b). The prevailing GHG was CO_2 (about 80% of the total burden) (Fig. 5b), linked to up-stream emissions from agricultural machinery, fuel and seed production and, markedly (in the range of 50–60%), to down-stream exhaust gas emissions from *on-farm* operation of agricultural machineries. The most marked impact (about 44%) was entailed by soil harrowing which needed higher fuel consumptions (Table 1). A relevant part of the total burden was also shared by N_2O emissions coming from beet and cabbage seed production. At this stage, nitrous oxide fluxes appeared as the main GHG pollutant (about 54% of total impact) and mainly represented (99%) by biogenic direct field emission from cropped soil following N fertilizer application.

As relating to the highly affecting supplementary feeding (Fig. 4), most of the impacts (about 95%) were shared by the maize and field bean grain feed production. Out of these, more marked contribution came from the feedstock cultivation stage (about 74%) which was followed by grain transport to the feed mill (about 17%) and further processing (4%). The share from limestone crushing and washing (<1%) was negligible. The remaining 5% was the result of the transport of manufactured feed components (maize–field bean–limestone) to the snail farm. Similar to the maize and field bean cultivation, CO_2 emissions were prevailing (about 74% of total burden) and mainly linked to up-stream emissions from fertilized production (Fig. 6). The remaining impact was shared by the different agronomic practices (soil treatments, fertilizer broadcasting, etc.), according to (i) the level of mechanization and fuel consumption involved in each stage (Table 1) and (ii) the following down-stream exhaust gas emissions from operating agricultural machineries. The most affecting practice which appeared is the urea supply along maize cultivation (Fig. 6). This was due to the up-stream CO_2 emissions (coming from fertilizer manufacture) and to the DFE from soil of CO_2 (fossil, from urea molecule) and N_2O (biogenic, from bacterial activities), the latter one amounting at about 22% of total impact for maize and field bean cultivation.

3.2. Carbon incorporated in shells and potential long-term sequestration

This study showed that about 4×10^{-2} kg of carbon could be incorporated in the shells as calcium carbonate polymorphs per kg of harvested snails (Table 2). According to recent estimates, the most relevant carbon source for shell carbonate is represented by : (i) plants and feed for diet (56–80%), (ii) atmospheric CO_2 (10–24%) and (iii) ingested limestone (0–27%) (Zhang et al., 2014; Xu et al., 2010). Therefore, about 88% of carbon incorporated in snail shell (Table 2) might represent a permanent stock both: (i) subtracted from the short term recycling of biogenic carbon between the interacting plant–soil–atmosphere compartments (indirect atmospheric CO_2 sequestration, i.e. previously fixed in plants for fodder and feed) and (ii) sequestered from atmospheric CO_2 pool (direct atmospheric CO_2 sequestration). Based on this assumption, the resulting potential long term C sequestration in the shells would

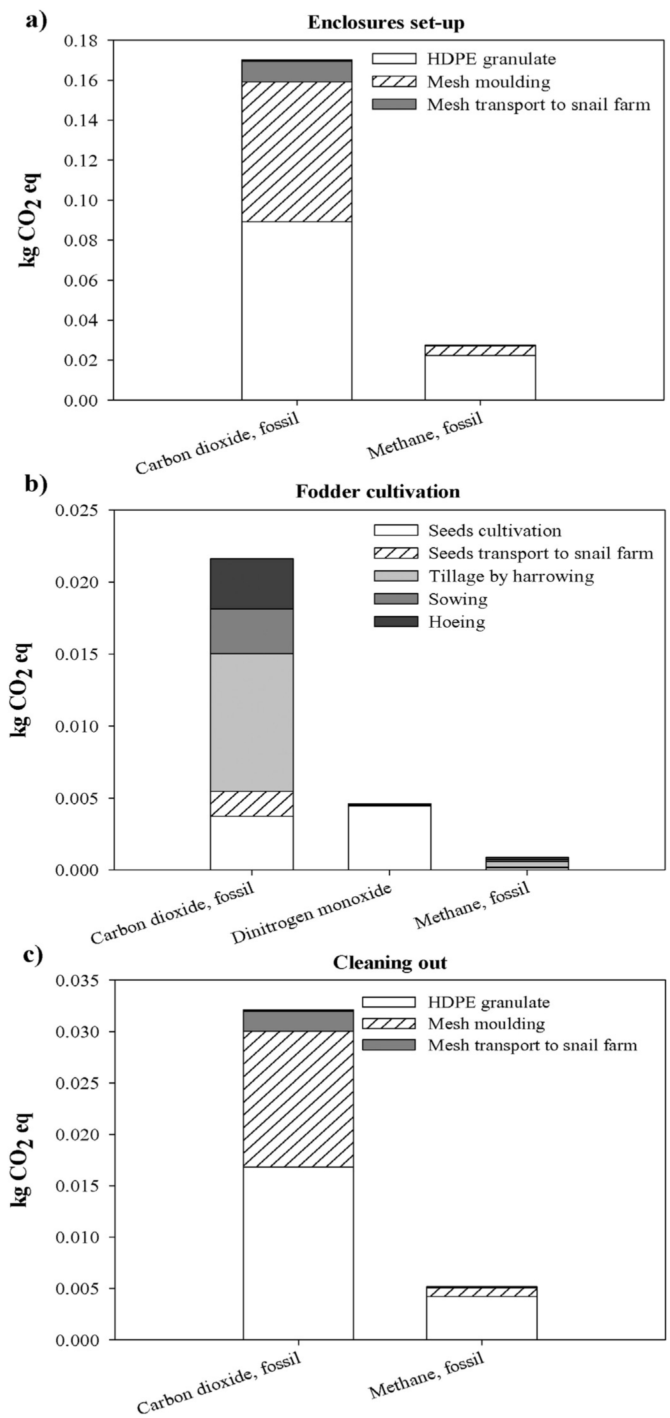

Fig. 5. The characterization graphs showing the specific GHG contributions from material and process inputs related to the stages of a) enclosure set-up, b) fodder cultivation and c) cleaning-out. Not visible sub-processes (below 1%), were: (i) sown timber production for wooden poles, and (ii) waste management of plastics and steel auxiliaries.

amount at about 0.1 kg CO_2 eq per kg of harvested snail (Table 2), that means about 3 ton CO_2 ha^{-1} y^{-1}, entailing a reduction of snail meat CF of about 18%.

Once computed the amount of carbon incorporated in the shells of living snail, the effective storage can be assessed in the long term only by taking into account the dynamics of CO_2 leakage from shells after snail meat consumption which is strictly linked to the different shell disposal routes.

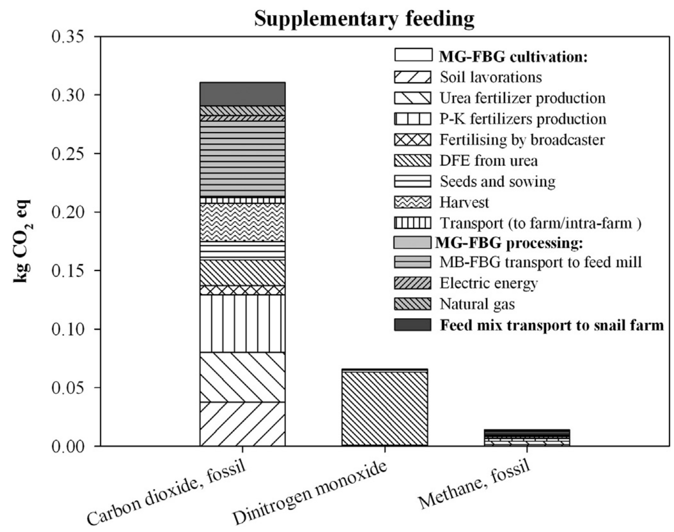

Fig. 6. Characterization graphs showing the specific GHG contributions from material and process inputs related to the stages of supplementary feeding. Not visible sub-processes (below 1%), were: (i) crushing and washing of limestone for supplementary feed mix, (ii) auxiliary inputs (water, infrastructure, etc) and sewage management related to MG (maize grains) and FBG (Field bean grains) processing at the feed mill.

3.3. Sensitivity analysis

3.3.1. Foreground input data

According to the sensitivity check on foreground inventory data, vegetal ingredients of the feed mixture and the plastic mesh for the fattening enclosures were the only parameters able to significantly affect the results within the selected range of input variations (Table 3). Coupling this finding with the assumed degree of uncertainty and actual variation (when available) of the different input flows, inventory data could be ranked into three different classes:

- Parameters: (i) whose changes of values significantly affected the snail CF score and (ii) characterized by a significant degree of variability. This group included supplementary feed and HDPE mesh. The activity level of snails, which also affects their rate of feeding, is highly dependent on ambient temperature and humidity. During the snail growing season (in the spring–summer drought period), the analysed farm management assured a moist suitable environment through regular watering of shelter forage and ground soil. Nonetheless, experimental observations on the site showed that changes in the average atmospheric humidity and temperatures throughout the years (wet years/dry ones) could affect feed consumption. This was particularly true in the range of $\pm 10\%$, with peaks of increased supply (up by 40%) in the case of markedly moist summers encouraging snails to be active. As relates to HDPE mesh, on the one hand the total amount necessary for the setting up of fattening enclosures on the farmed area can be considered as a fixed value, strictly linked to the designed geometry of pens. On the other hand, the rate of mesh deterioration in the field may vary depending on weathering conditions, thus affecting the resulting plastic input on a yearly basis. Moreover, at the pilot area, intensified maintenance regimes (with recurring repair works) showed increased average plastic mesh durability (3 y, applied in this study) also by 50%, which would reduce the yearly plastic input by about 33%. However, this might represent a time consuming and labour expensive management for the scaled-up farming system.
- Parameters: (i) whose changes of values did not significantly affect snail CF score and (ii) characterized by a significant degree of variability. This is the case of irrigation water, whose input amount is strictly affected by humidity levels along the drought period. According to the changing average spring and summer rainfall, irrigation water supply might range from about -12% to about $+3\%$. This resulted from the

Table 3
Sensitivity analysis applied to foreground input flows supplied yearly to the 1 ha up-scaled snail farm. The table shows the percentage variations from snail CF score (0.7 kg CO_2 eq per kg edible snail meat), in response to different percentage increases or decreases of each input data as referred to the reference amount value applied in the study.

Input	Reference value applied in the study		Percent CF variation Percent input variation		
	Amount	Unit measure	±10%	±20%	±30%
Feed mix:	9.9	ton ha^{-1} y^{-1}	±6%	±11%	±17%
MG and FBG in feed mix[a]	c.i.[b]	ton ha^{-1} y^{-1}	±6%	±11%	±17%
Limestone in feed mix	c.i.[b]	ton ha^{-1} y^{-1}	<±0.1%	<±0.1%	<±0.1%
HDPE plastics for:					
Fattening enclosures	0.4	ton ha^{-1} y^{-1}	±3%	±6%	±9%
Cleaning boxes	67	kg ha^{-1} y^{-1}	<±1%	<±1%	<±1%
Irrigation	13	kg ha^{-1} y^{-1}	<±1%	<±1%	<±1%
Breeding cage	1	kg ha^{-1} y^{-1}	<±1%	<±1%	<±1%
Beet and cabbage seeds	60	kg ha^{-1} y^{-1}	<±1%	<±1%	<±1%
Water (irrigation and cleaning out)	2086	m^3 ha^{-1} y^{-1}	<±0.1%	<±0.1%	<±0.1%
Steel auxiliaries	1.6	kg ha^{-1} y^{-1}	<±0.1%	<±0.1%	<±0.1%
Wooden poles	0.1	m^3 ha^{-1} y^{-1}	<±0.1%	<±0.1%	<±0.1%

[a] MG and FBG for maize and field bean grains, respectively.
[b] Confidential information (c.i.) for exact composition of the feed mixture.

analysis of precipitation data within a 10-year timeframe (2004–2014) from a nearby weather station in Vitulazio (province of Caserta, http://agricoltura.regione.campania.it/meteo/agrometeo.htm) and assuming there would be no irrigation inputs on rainy days (and in the first day after, in the case of daily precipitation above 20 mm).

- Parameters (i) whose changes of values did not significantly affect snail CF score and (ii) characterized by a low degree of variability. This class comprised fodder seeds, steel, wood and plastic auxiliary input data (HDPE mesh for fattening pens excluded), which could be assumed as fixed amounts with low uncertainty levels.

Variables inside the first group could be therefore identified as “key parameters” affecting the final CF score under real farming circumstances.

3.3.2. Conversion factors

The CF was not significantly affected by the substitution of both GWP and N_2O EF (Table 4). As per the 2013 up-dated GWP (reference values in this study), the reduced index for N_2O coupled to the increased index for CH_4 resulted in unchanged CF results as opposed to the outcome based on a previous 100-year GWP (IPCC, 2007). This was also due to the circumscribed share of N_2O and CH_4 emissions to the total snail CF score (Fig. 3).

As per the EF for N_2O emissions, the application of the 1% IPCC default value (as opposed to the local factor considered in this study) would entail additional 0.03 kg CO_2 eq per kg edible snail meat. These were biogenic nitrous oxide emissions following urea supply along the maize cultivation (for supplementary feed manufacture). Due to the restricted influence of total and biogenic N_2O emissions (Figs. 3, 6), the snail meat CF score would remain nearly unchanged again (about +4%).

Table 4
Sensitivity analysis applied to conversion factors for: (i) GWP of GHG and (ii) N_2O emission from N fertilizer input (EF). The table shows the different GHG emissions (as CO_2, N_2O and CH_4) and the total CF resulting from the application of: (i) reference values of GWP and EF in this study and (ii) current values generally applied in recent pertinent literature.

GHG emissions (kg CO_2 eq. per kg edible snail meat)	Conversion factors		
	GWP and N_2O EF values applied in this study[a]	2007 up-dated GWP[b]	IPCC N_2O EF[c]
CO_2	0.55	0.55	0.55
N_2O	0.07	0.08	0.11
CH_4	0.05	0.04	0.05
CF tot	0.7	0.7	0.7

[a] Reference values applied in this study: (i) 2013 up-dated IPCC characterization values for GWP (IPCC, 2013) and (ii) a 0.5% local EF for nitrogen to N_2O conversion factors (Forte et al., 2015).
[b] 2007 up-dated IPCC conversion factor to CO_2 eq: 1 for CO_2, 25 for CH_4 and 298 for N_2O (IPCC, 2007).
[c] 1% default IPCC EF for nitrogen to N_2O conversion factors (IPCC, 2007).

3.3.3. CO_2 emissions from direct LUC

The inclusion of CO_2 emissions associated with changes in land use and soil carbon stock did not significantly affect the results (Table 4). This was true except for the extreme case use of agricultural land abandoned long time ago.

In detail, as highlighted in Table 5, GHG emissions from *off-farm* LUC resulted exclusively from maize cultivation and appeared negligible (below 2% of the final partial CF). CO_2 emissions from *on-farm* LUC (linked to the conversion of marginal lands towards snail farming) appeared restrained in the case of revaluation of unproductive annual croplands. However LUC emissions turned to substantial, in the case of use of abandoned cropland put back to grass.

In the last case scenario, total GHG emissions from LUC might increase the CF of snail meat at the farm gate of about 57% (Table 5). This calculation, however, overestimated the impact related to the use of marginal croplands gradually shifting towards grassland. As a matter of fact the calculation was based on a well established grassland reference scenario which could be not appropriate in the case of a recently abandoned cropland. Nonetheless, this result highlighted the relevance of the baseline scenario and the consequent need of further detailed assessment of the *on-farm* dLUC topic in relation to the real regional context of snail farming realization.

4. Discussion

4.1. Hotspots of snail meat production

The supply of the vegetal components of feed mixture appeared as the prevailing carbon hotspot within snail farming. Feed production has been extensively highlighted in literature as a key contributor to the environmental impacts of ruminant and monogastric animal food products (Dudley et al., 2014; MacLeod et al., 2013; Nijdam et al., 2012; Pelletier et al., 2010; Roy et al., 2012, 2009). GHG emissions of feed production, within the whole retail meat production chain, summed up to 60%–73% for pigs (MacLeod et al., 2013; Nijdam et al., 2012), 78% for chickens (MacLeod et al., 2013) and to 11%–37% for beef meat (Dudley et al., 2014; Nijdam et al., 2012; Beauchemin et al., 2010; Pelletier et al., 2010). The latter one has an additional predominant contribution coming from enteric fermentation during pasture

Table 5
Potential GHG emissions from direct Land Use Change computed by means of the PAS 2050-1: Direct Land Use Change Assessment Tool (V2014.1, Blonk Consultants, Gouda).

	Reference scenario of marginal land for *on-farm* LUC	Land use				
		Off-farm[a]			*On-farm*[b]	Tot
		Maize crops	*Leguminous crops*	*Cabbages Brassica seed crops*	*Cabbages Brassica crops*	
GHG emissions from LUC (kg CO_2 eq per kg edible snail meat)	Unproductive annual cropland	0.01	0	0	0.03	0.04
	Abandoned unproductive cropland put back to grass	0.01	0	0	0.4	0.4

[a] *Off-farm* LUC CO_2 emissions from Italian cultivations of feed ingredients (maize and field bean) and seeds (for beet and cabbage fodder) were computed setting “previous land use” as unknown.
[b] *On-farm* LUC CO_2 emissions were computed on two different hypothetical reference scenarios for marginal land: (i) still cultivated, even if without satisfactory earnings, set as “annual crop”; and (ii) already abandoned and shifted towards grassland/grazing land, set as “Warm temperate dry grassland”. Other requested parameters for the current cultivation (i.e. snail farming) were set as follows: HAC soil, reduced tillage management and low input cultivation.

and feedlots (Dudley et al., 2014; Nijdam et al., 2012; Beauchemin et al., 2010; Pelletier et al., 2010). CF of snail meat was not affected by biogenic methane emissions. It mainly derived from feed crop cultivation and processing stages which amounted to about 68% of the total GHG emissions at the farm gate (Fig. 2). Fossil CO_2 was predominant and was released as up-stream emissions from input manufacture and as *on-farm* exhaust gas emissions (during the operations of agricultural machinery) and soil emissions (following urea spreading) (Fig. 6). Direct field N_2O emissions from maize grain production (Fig. 4) also appeared as a significant contributor (about 9% of the total partial CF of snail meat). However, due to reliance on feed ingredients from leguminous crops, N_2O feed emissions for snail meat appeared more restrained in comparison to the share reported for monogastric conventional macro-livestock. This scored to about 17% and 32% of total pig and chicken meat emissions respectively (MacLeod et al., 2013).

The environmental load of the supplementary feeding stage was also ascribable to the involved transport phases: (i) delivery of agronomic inputs for cultivation of feed crops, (ii) vegetal feedstock transport to the processing mill and (iii) final feed supply to the snail farm (Figs. 3, 6). They accounted for about 85% of the total share from transport which amounted to about 15% of the total snail CF. This finding was in line with the share highlighted in literature for transport phases in the life cycle of conventional meat sources which scored up to about one fifth of the total impact (Nijdam et al., 2012). Yet, the contribution from transportation of animal feed on the total snail CF (nearly 3%) was consistently below the share highlighted for other meat sources. For instance, the contribution of feed transport was about 10% for both pork and poultry meat CF (Nijdam et al., 2012), commonly relying on feed (i.e. soy) sourced from Latin America countries (Nijdam et al., 2012).

The feeding mixture input flows appeared also affected by a significant variability, which might lead to relevant change in the final CF (Section 3.3). These findings suggest the need of further assessing the viability of pasture production systems exclusively relying on roughage of *on-farm* produced fodder, in order to constrain the C of snail meat supply chain.

A second key parameter for snail CF was also represented by plastic materials used for breeding enclosures (Figs. 2, 3, 4; Section 3.3). A mitigation of this impact could be achieved through further investigation and implementation of farming practices. Examples of profitable large cultivations without apical mesh are also present on the national territory (http://www.lumache-elici.com). It might be useful to do experimental tests in the field to determine the actual benefits of top covering in terms of meat yield. Relevant benefits might also be achieved by using innovative plastic products such as HDPE mesh stabilized by UV which are able to resist longer under field conditions. As a matter of fact, the total CF of snail farming will be reduced by 21% in the case of an increase in the lifespan of plastic enclosures to 10 years (as inferable for such hi-tech plastic auxiliaries).

4.2. Comparison with other meat sources

In Fig. 7, the CF of snail meat was compared to the current findings on land and aquatic invertebrate meat (Oonincx and de Boer, 2012; Nijdam et al., 2012; SARF, 2012; Iribarren et al., 2010) and to the reviewed ranges of GWP for the most widespread consumed meats (i.e. beef, pig and chicken) in an average diet in OECD countries (FAOSTAT, 2009) as retrieved from Röös et al. (2013). The comparison was carried out on the basis of similar system boundary (*cradle-to-gate*) and functional unit (1 kg fresh edible bone/shell-free meat).

Among meat sources from invertebrates (Fig. 7), the snail CF appeared to be in line with the GWP of mealworm mini-livestock, about 2.7 kg CO_2 eq kg^{-1} edible meat (Oonincx and de Boer, 2012) and also with mussels from conventional aquaculture: about 1 kg CO_2 eq kg^{-1} edible meat and 0.7 kg CO_2 eq kg^{-1} edible meat from aquaculture in Spain (Nijdam et al., 2012; Iribarren et al., 2010) and Scotland (SARF, 2012) respectively. On the other hand, this appeared consistently lower than the *cradle-to-gate* CF of oysters (about 10 kg CO_2 eq kg^{-1} edible meat) which was characterized by lower edible portions and by more energy intensive *on-farm* operations as compared to mussels (Nijdam et al., 2012; SARF, 2012; INRAN, 2007) and which were

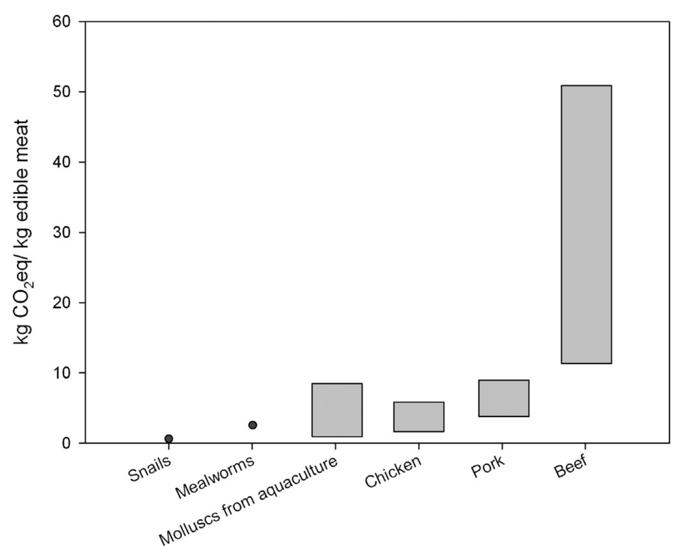

Fig. 7. Comparison of carbon footprints (CO_2 eq kg^{-1} edible meat for retail) of meat sources from snail (in this study), land and aquatic invertebrates and other conventional meat livestock in OECD countries. Dark grey circles for results of a single study and light grey bars for ranges of CF retrieved from literature.
Sources for CF scores: Oonincx and de Boer (2012) for Mealworms; Iribarren et al. (2010) and SARF (2012) for molluscs from aquaculture, converting results for mussels and oysters from SARF (2012) to kg edible shell free meat on the basis of specific edible portions retrieved from the Italian INRAN database (INRAN, 2007) and Röös et al. (2013) for CF ranges of chicken, pork and beef.

therefore much more distant from the concept of sustainable invertebrate mini-livestock.

Snail CF appeared significantly restrained when compared to conventional macro-livestock (Fig. 7). Livestock production chains have been recognized to have a significant impact on a wide range of environmental aspects, including climate change (Dudley et al., 2014; Roy et al., 2012, 2009; Nijdam et al., 2012; Pelletier et al., 2010; Steinfeld et al., 2006). A higher global warming potential was commonly reported for beef as compared to other conventional meat sources such as pork and chicken (Fig. 7). This is due to the higher energetic inputs, enteric methane emissions and feed-to-meat ratio (Dudley et al., 2014; Roy et al., 2012; De Vries and de Boer, 2010), coupled with a lower progeny and a later sexual maturity (De Vries and de Boer, 2010). Beef meat studies also showed a wider range of GWP (Fig. 7) as a consequence of: (i) the heterogeneous production systems (intensive/extensive, dairy cows/beef cattle) as compared to the worldwide standardized production methods for pork and chicken livestock (Nijdam et al., 2012; Pelletier et al., 2010); and (ii) the uncertainty in the assessment of net emissions during pasture from soil and enteric fermentation (Dudley et al., 2014; Nijdam et al., 2012).

The abovementioned key factors also affected the discrepancies between CF of snail meat and the other conventional livestock sources. Besides the restrained energetic and chemical inputs in foreground farming practices (Table 1) and the lack of biogenic methane emissions, snail studies show an efficient feed conversion ratio. Snails are in fact cold-blooded and can efficiently transform nutrients input into edible biomass. Our study shows that the feed conversion ratio (kg/kg of gained fresh weight) relative to the specific diet provided (roughage coupled to supplementary feed grains) was about 1.8. This value appeared similar to the estimates reported for mealworms (Oonincx and de Boer, 2012) and chicken meat (Blonk Agri-footprint BV, 2014a,b; Wilkinson, 2011). On the other hand it was consistently lower than the average estimates for other conventional livestock which consume a huge fraction of ingested energetic and nutrient input for body heat up and grazing (Steinfeld et al., 2006): 4 and up to 8.8 for pigs and beef cattle respectively (Blonk Agri-footprint BV, 2014a,b; Wilkinson, 2011). Moreover snails have a high fecundity (laying 40–170 eggs 1–3 times each growing season) and grow very fast. In this study they laid about 100 eggs each brood and reached their full size in 10–12 months under the mixed diet. Thanks to these drivers the investigated snail farming provided about 2.6 kg of living snails per m^2 of total *on-farm* land. As per the total land used, i.e. including *off-farm* land for feed ingredients and auxiliary input production (EcoInvent database v.2.0), meat yield appeared markedly higher than the one used for conventional livestock production (De Vries and de Boer, 2010). For instance, if compared to the needs for 1 kg of protein from beef, i.e. from about 150 m^2 to about 250 m^2 (De Vries and de Boer, 2010), the production of 1 kg protein from snail meat, according to their edible portion and protein content (INRAN, 2007), required on average only about 9% of land. This estimate was in line with the value (about 10%) recently highlighted for edible worms (Oonincx and de Boer, 2012).

Another factor which contributed to the lower CF of the snail meat, was the use of feed ingredients from regional production. In Italy, like Europe, besides feed ingredients from nationally produced maize, the manufacture of feed mixtures largely relies on soy imported from Brazil and Argentina (2013 updated statistics from ISMEA and ASSALZOO). This leads to relevant additional impact for animal feed transportation in the total CF of conventional livestock (Nijdam et al., 2012).

The use of regionally produced feed ingredients, with negligible GHG emissions from *off-farm* dLUC (Table 5), might also amplify the differences between snails and conventional livestock in the case that CO_2 LUC emissions were included in the CF computation. Assessments of LUC effect showed impacts increased by a 12% raise up to 25 fold for beef meat (Blonk Agri-footprint BV, 2014a,b; Cederberg et al., 2011; Nguyen et al., 2010) and by 42% and 129% raise for pig and chicken respectively (Blonk Agri-footprint BV, 2014a,b). This was mainly due to the supply of feed compounds through importation from sensitive areas in Latin America where expansion of land for feed ingredient cultivation is generally achieved by deforestation. On the other hand, as per beef/cattle livestock, permanent grassland can store significant amount of C in soil as stable organic matter: (i) under ongoing moderate grazing pressure management (i.e. in absence of LUC) and (ii) especially in the case of native pasture under improved grazing strategies and newly seeded grassland on previously cropped land (i.e. in presence of LUC) (Beauchemin et al., 2011; Crosson et al., 2011). This C sequestration in grassland soil might entail a "C-offset" ranging from about 40% to 70% of total GHG emissions from grassland based systems (Pelletier et al., 2010; Veysset et al., 2010). The C gain in soil organic matter might also be so high that it might change the beef production system from a net emitter to a net sink of C, in the case of recently planted pasture on previously cropped land (Beauchemin et al., 2011).

However, despite the general increased attention on C sequestration potential of grassland soils, difficulties still remain concerning its inclusion within GHG accounting procedures due to its spatial and temporal variability (Beauchemin et al., 2011; Crosson et al., 2011).

The controversial topic of changes in soil C stocks might also be relevant for snail farming, as suggested by the potential negative *on-farm* LUC in the case of setting-up on croplands abandoned long time ago (Table 5). On the one hand it is well established that conversion of cropland to grassland entails an increase of soil organic carbon stocks mainly concentrated in the surface profile (Deng et al., 2013; Su et al., 2009). On the other one, the dynamics of soil C re-accumulation after the abandonment of farmland appear not linear and still not well understood, with a decrease of soil organic carbon storage throughout the first years, followed by a net gain starting from 10 years onwards (Shaoxuan et al., 2015; Deng et al., 2013). Results should therefore be revaluated on the basis of more reliable estimates of C stock flows in relation to the hypothetical use of degraded land already reverted to grass.

4.3. Carbon incorporated in shells and potential long-term sequestration

Potential carbon sequestration in snail shells was in line with the findings inherent to mussels and oysters which sequestered up to 0.2 kg CO_2 eq and 0.4 kg CO_2 eq per kg of fresh meat respectively (SARF, 2012), according to the different shell weight per kg of total mollusc mass (about 2 times and 3 times higher than land snail, for mussels and oysters respectively). Moreover, the C gain appeared comparable, in the lower range, to sequestration reported for afforestation/reforestation in temperate regions, with absorption rate between 5.5 and 16.5 ton CO_2 ha^{-1} y^{-1} (IPCC, 2000).

However, there is a lack of a clear comprehension of decomposition dynamic of gastropod shells under natural and managed conditions (i.e. landfill). Consequently, only preliminary considerations could be done about the effective long term carbon sequestration in shells, as reported in the following sub-sections and summarized in Fig. 2.

4.3.1. Paths towards short term storage

This category included agricultural and zootechnical use of crushed/milled snail shell as compost, fertilizer additives and poultry feeding supplement. Indeed, crushed land snail shells showed a fast decomposition rate (from 6.4% to 10.2% per year) under forest field conditions (Pearce, 2008) whilst biogenic carbon ingested (both human food and animal feed) cannot be considered as a stock, following current LCA procedures. Otherwise, calcium carbonate as feeding supplement to the snails would generate a closed cycle entailing a net CO_2 gain throughout the snail cultivation timeframe. Among industrial applications, calcination is also featured in this class, since 1 mol of CO_2 is released from each mole of CaO produced.

4.3.2. Paths towards both short and long term storage

Calcium carbonate is commonly used as stable drainage material in municipal solid waste (MSW) landfills (Daniel and Koerner, 2007). However its complex dissolution dynamic derives from the interaction with rain, surface and waste water sources and has not yet been characterized in detail (Bennett et al., 2000). Calcite solubility can be controlled by pH, with increasing rate at lowering pH (Lackner, 2002). In an acidic environment, as that one characterizing the early life of the landfill (Abbas et al., 2009; Qasim and Chiang, 1994), shell carbonate solubilisation might be promoted. This would lead to the short-term release of gaseous CO_2 previously stored in the mineralized carbon. On the other hand, carbonated minerals appeared to dissolve significantly only at strong acid pH < 2 (Teir et al., 2006) and showed (both aragonite and calcite) constrained dissolution rate in organic acid solutions (Ryu et al., 2010). Based on these findings, shell carbonated minerals disposed in landfill might be assumed to be stable and entail a net CO_2 storage in the long-term.

As relating to granular activated carbon for industrial absorption applications, the resulting storage would be a function of: (i) the effective potential for repeated recycling through reactivation/regeneration stages (Samonin et al., 2013) and (ii) the degradation dynamics after the disposal of the spent carbon in landfill.

Similarly, the time horizon of sequestration in shells for decorative mulches and ornamental uses would depend by the lifespan of objects (basically short in the current consumerist society) and decomposition/dissolution pattern following landfill confinement.

4.3.3. Paths towards long term storage

Ordinary concrete buildings have a minimum life expectancy ≥50 years (D.M, 2008). The durability of highly specialized concrete structures appears markedly higher: (i) more than a century for bridges and tunnel (D.M, 2008; Dunaszegi, 1998; Holley et al., 1999; Langley et al., 1998) and (ii) up to 1000 years for high performance formulations used in foundations (Mehta and Langley, 2000). Therefore, shell recycling in construction materials could be reasonably assumed to entail long term storage. However, a multidisciplinary approach would be fundamental in order to check the expected timeframe of specific construction materials. This could be achieved through the use of lifetime performance assessment methods for concrete structures (Aït-Mokhtar et al., 2013; Tian et al., 2012; Petryna et al., 2002).

5. Conclusion

The supplementary feeding stage and the set-up of plastic fattening enclosures appeared to be the key farming practices to be considered and properly designed to constrain the carbon footprint of snail rearing under semi-intensive management.

Compared to the most widespread consumed meats (beef, pig and chicken), the snail supply chain entailed pronounced GHG benefits. This is the first direct evidence that snail meat could be a promising environmental friendly alternative source for human nutrition.

Snail farmers might also add C sequestration in shells among sustainability benefits of snail rearing. However, further assessments are needed to provide quantitative estimates of the effective long term C gain along the possible shell waste management/reutilisation routes.

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