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Nutrient footprint and ecosystem services of carp production in European fishponds in contrast to EU crop and livestock sectors

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A B S T R A C T

There have been some arguments concerning supplementary feed (cereals) based common carp production in fishponds and water pollution, mostly in Central Europe. Using Czech Republic (top producer in EU) as a benchmark and combining data on nutrient digestibility of feedstuffs used combined with analyses of literature data, we have assessed – nutrient footprint (~9.4–10.8 kg N ha^{-1}, ~2.7–3.2 kg P ha^{-1}; 1.5–4 × < EU crop-livestock sectors); nutrient utilization efficiencies (NUE_N ~36%, NUE_P ~50%; 1.5–1.7 × > EU livestock average); autochthonous nutrient removal (~8–9.2 kg N ha^{-1}, 1.4–1.6 kg P ha^{-1}); eco-cost burden (13–29 × ≪ positive services); eco-services (~74.5–100.6 million € $country^{-1}$; ~2375 € ha^{-1}) of carp production in Central Eastern European Region (CEER). Digestible nutrients offered by natural prey (7.9% N, 1% P on dry matter basis) to carp are ~5–8 times higher than those provided by cereals and remains the key determinant for production. Despite this, 70–90% of nutrient footprint from feeding is contributed by cereals. Neutral footprint (~374 kg ha^{-1}) and exclusively natural (up to 300 kg ha^{-1}) carp production intensities were identified, following which, commercial interest of carp farming may falter (costing intangible losses >56.5 million € in CEER), despite achieving 'greener-goals'. Per production cycle, carp aquaculture in CEER fishponds offer at least 579 million € worth of services. Our results show that carp production in ponds have lesser nutrient burden than crop and livestock productions in EU. Existing management of fishponds 'barely meet' optimum P requirements of common carp and present production intensity should not be vilified as a pollution causing activity. Risks and solutions for achieving both environmental (minimized footprint) and aquaculture goals (uncompromised production) are discussed.

1. Introduction

For decades, the 'land-locked' central European countries have been relying mostly on carp culture for fisheries production (Adámek et al., 2012; Gál et al., 2015; Woynarovich et al., 2011). Common carp (*Cyprinus carpio* L.) farming in fishponds has remained the mainstay, both traditionally and commercially (Gál et al., 2015). About 80–88% of the aquaculture production in these countries come from carp farming in fishponds (Eurostat fish_aq2a 2017). Czech Republic followed by Poland, Hungary and Germany (ranked in order of production) support ~80% of carp production in the European Union (EU) (Eurostat fish_aq2a 2017). The apparent per capita consumption of carp in the region varies between 0.6 and 1.2 kg (EUMOFA, 2016). Since the late 1960s, carp farming in Europe has undergone intensification with yield <190 kg ha^{-1} to >450 kg ha^{-1} (Pechar, 2000). The higher stocking density corresponded higher input of supplementary feed. Today, about 86% of Czech fishponds involved in production are fed with supplementary feed, mostly cereals (CZ-Ryby, 2019). Present practices include semi-intensive farming with a low to moderate stocking density (0.2–0.4 ton ha^{-1}) and having a production ceiling of ~0.5–1 ton ha^{-1}, partly supported by supplementary feeding (Sterniša et al., 2017). In most of these fishponds, ~50–60% of carp growth (protein growth) is believed to be supported by natural food while cereals (rich source of energy) are provided as

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Abbreviations

FCR	Food conversion ratio (= dietary intake / biomass gain) used in relative sense (in the presence of other food component in fishponds *i.e.* natural food or cereals)
$FCR_{cereals}$	Relative FCR of cereals in the presence of carp's natural food in fishponds
$FCR_{natural\ prey}$	Relative FCR of carp's natural food in the presence of cereals as supplementary feed
CEER	Central Eastern European region
EU	European Union
NUE	Nutrient Utilization Efficiency
NUE_N	NUE of Nitrogen
NUE_P	NUE of Phosphorus
LCA	Life Cycle Assessment
GHG EI	Greenhouse gas Emission Intensity (kg CO_2-equivalent per kg consumable weight)

supplementary feed (Adámek et al., 2009, 2012). This co-feeding by carps on natural prey and cereals require at least two growing seasons to reach marketable table-sizes (>1.5–2 kg) under temperate conditions in Western and Central Europe (Gál et al., 2016; Pechar, 2000). Unlike Asia (e.g. Indian major carp production, up to 10–11 tons ha^{-1} $year^{-1}$ (ICAR, 2011)), the carp farming in Europe is occurring at far lesser intensity, with state and/or EU ratified environmental legislations in place (reviewed in O'Hagan et al., 2017).

Unlike Asian fishponds, fertilizing fishponds in Europe have already different levels of restrictions among different countries (Gál et al., 2015), e.g. prohibited in the Czech Republic. Most carp farmers therefore regard their pond sediment as the only fertilizer they need and are anxious not to flush it out (Knösche et al., 2000; Potužák et al., 2016), while some perform green manuring on dried pond beds and later filling them (Hartman et al., 2015). This narrows it down to a more regular practice *i.e.* supplementary feeding; probably the only major, 'deliberate' allochthonous nutrient source. The leading role played by feed and feeding efficiency on the environmental impact of any aquaculture practice is well recognized (Aubin et al., 2009; Henriksson et al., 2015; Papatryphon et al., 2004). Likewise, a great deal for nutrient loading from carp dominated systems depend on the choice and proportion of supplementary feed used (Biermann and Geist, 2019; Jahan et al., 2002, 2003; Watanabe et al., 1999). Common carp (*Cyprinus carpio*) can lose about 50–79% of N intake through metabolizable and faecal losses (Kaushik, 1995; Roy et al., 2019). Apart from its natural prey, carps lose quite a lot of dietary P (53–73% of dietary P intake) from most of the artificial feedstuffs (Hua and Bureau, 2010; Roy et al., 2019), including cereals. Half of the excreted P from carps was reported to be directly available for algal production (Lamarra, 1975), probably corresponding to the fractions of ortho-phosphate which is readily assimilated.

The present water directive of EU insists carp waters (waters for/from cyprinid culture) to maintain ≤0.4 mg L^{-1} PO_4 and ≤1 mg L^{-1} NH_4 (EU Directive, 2006/44/E Article 3 & 5, Annex I). There have been concerns surrounding the impacts of carp culture in fishponds on eutrophication of associated water bodies (reviewed in Roy et al., 2019). It has resulted in arguments and lobbying between environmentalists and carp farmers regarding fishpond-environment legislations (e.g. Czech Republic: Duras and Potužák, 2016, 2019; Duras, 2019; Germany and Hungary: Knösche et al., 2000; Poland: Kufel, 2012, Mazurkiewicz, 2009). Amidst these arguments, even the supplementary feeding gets tagged as a 'harmful substance' applied to fishponds (Duras and Potužák, 2019). Such stringent measures or presumptions restricting the intensity of carp farming in European fishponds, in order to reduce environmental footprint, have impacts on commercial viability too. The market prices of common carp have in fact come down significantly in most European countries (FAO Globefish, 2018; Gál et al., 2015). Present farm-gate prices of carp in the Czech Republic and Germany are ~2–2.5 € kg^{-1} live weight (EUMOFA, 2016; O'Hagan et al., 2017) or even lower (1.9 € kg^{-1} live weight) in Hungary (FAO Globefish, 2018). Although the concerns of environmentalists are in good faith, however, being too harsh on carp farming without 'clarified' knowledge is unfair.

In order that sustainable management strategies in aquaculture be based on environmental impact analyses, life cycle assessment (LCA) often is the first choice (Aubin et al., 2009; Mungkung et al., 2013; Philis et al., 2019). Albeit the advantages (Biermann and Geist, 2019), ambiguities in inventory creation, methodological incompleteness and limited comparability across production systems or studies exists (reviewed in Philis et al., 2019, Biermann and Geist). The supply chain of agriculture-livestock sector, for example cereals supply chain, is also important in achieving cleaner production goals. Novel approaches in supply chain assessment and inventory management already exists (Duan et al., 2018; Hoseini Shekarabi et al., 2019; Gharaei et al., 2019a,b,c,d). To the best of our knowledge, the environmental impact of carp farming has been subject to only three LCA case studies – Indonesian net cage system (Mungkung et al., 2013), Indian carp polyculture system (Aubin et al., 2011) and German fishponds (Biermann and Geist, 2019). These LCAs were more focused on 'percentage contribution' of various management parameters towards multiple threat categories (e.g. climate change, eutrophication, toxicity, energy use, etc.). Employing an alternative approach, we rather focused on quantifying the key parameters itself (*i.e.* primary nutrients, N and P) in the dominant pathway (feeding activity) of the core production stage (fishponds) driving a threat category (freshwater eutrophication). The LCA and supply chain concepts were beyond the scope of our present, already extensive exercise.

In our present attempt, we have assessed the primary environmental macronutrient (N and P) footprint of carp farming in Czech Republic. By the term 'footprint', we imply nutrients excreted (faecal and metabolic losses) into the aquatic environment by the carps. The aim is to have an objective assessment of eutrophication incriminated by carp farming in the region. The objectives were to assess – (a) nutrient footprint of carps feeding on supplementary feed (cereals) and natural prey in fishponds, employing different methodologies; (b) nutrient footprint of carp production in comparison to EU crop and livestock production; (c) nutrient utilization efficiencies by carps in fishponds and comparison with other EU food production sectors; (d) autochthonous nutrient removal by carps; (e) environmental cost burden worth of nutrient footprint in contrast to total ecosystem services offered by carp production in fishponds; (f) required production intensity in fishponds to neutralize nutrient footprint and its practicality; (g) trade-offs between good growth (optimum digestible nutrient supply) and reduced footprint. We have further extrapolated our findings onto the production scenarios of Germany, Hungary, Poland and Russian Federation to generate a comprehensive picture of the central-eastern European region (CEER) – a complimentary fit to existing assessments on EU crop-livestock sectors (Buckwell and Nadeu, 2016, Csatho et al., 2007, Gerber al. 2014, Kronvang et al., 2007, Leip et al., 2011, 2014, 2015, Richards and Dawson, 2008, Rosendorf et al., 2016, van Dijk et al., 2016, Velthof et al., 2007). The managerial implication of the present study is discussed at the end.

2. Materials and methods

2.1. Collection of baseline statistics for carp production

Carp production statistics (18460 tons from 41080 ha of fishponds; yield 449.4 kg ha^{-1}) was obtained from CZ-Ryby (2019). Relative feeding coefficient (*i.e.* relative food conversion ratio in the presence of natural food) of cereals supporting carp production in fishponds of the region have been estimated at 2–2.5 (Woynarovich et al., 2010, Jan Mraz, IAPW FROV Ceske Budejovice – *unpublished data*, Martin Oberle, LfL-Bayern Bavaria – *unpublished data*). Collating higher nutrient richness and digestibility of carp's natural prey over cereals (Table 1), natural food was found to be 6–8 times superior in terms of digestible nutrient supply per unit dry matter. Therefore, FCR of natural prey was back calculated from standardized FCR of cereals and estimated at 0.3–0.4. Here, the term 'FCR' implies food conversion ratio (= dietary intake / biomass gain) in relative sense. $FCR_{cereals}$ imply FCR of cereals in the presence of carp's natural food in fishponds. $FCR_{natural\ prey}$ imply FCR of carp's natural food in the presence of cereals as supplementary feed.

In the absence of supplementary feeding with cereals (*i.e.* exclusively natural production), the annual yield in temperate Czech fishponds (thermal cycle 6.9–26.8 °C; Řezníčková et al., 2016; Kopp et al., 2016) is around 250–300 kg ha^{-1} (Pechar, 2000; Duras and Dziaman, 2010, Mraz – *unpublished data*). In this case, absolute FCR of natural food was estimated at least ~0.7 to fulfill the optimum digestible nutrient supply for growing carps.

2.2. Assessment of nutrient availabilities from supplementary feed (cereals) and natural food

Apparent digestibility of N and P of commonly used cereals in Czech fishponds (wheat, corn, triticale) and carp's natural prey (daphnia, chironomid larvae, cyclops) were determined, following standard procedures (NRC, 2011; Glencross et al., 2007). Digestibility trials were conducted in a 12 tank Guelph system (6 control + 6 treatment; 120 L capacity each; Cho and Slinger, 1979) for facilitating passive collection of faeces from carps (*Cyprinus carpio*) weighing 150–475 g (mixed assortment of sizes; 6–7 kg carp biomass per tank). Trials were conducted under species optimum conditions: temperature 19–21 °C, dissolved oxygen >4 mg L^{-1}, pH 6.8–7.3 and unionized ammonia <0.05 mg L^{-1}. The procedures entailing experimental feed preparation, feeding, faeces collection and sample processing have been detailed in supplementary text. Apparent digestibility coefficients of N (ADC_N) and P (ADC_P), both diet and ingredient level, were calculated following the formula given in NRC (2011). All calculations were done on 100% dry matter basis. In total, the entire experiment lasted for 7 months.

2.3. Collection and use of reference metadata

From the online databases, literature metadata were compiled for the following categories: (a) N:P balances, NUEs of EU agriculture-livestock sectors (*data* from Buckwell and Nadeu, 2016, Csatho et al., 2007, Gerber al. 2014, Kronvang et al., 2007, Leip et al., 2011, 2014, 2015, Richards and Dawson, 2008, Rosendorf et al., 2016, van Dijk et al., 2016, Velthof et al., 2007); (b) cost of removing 1 kg N or P from wastewaters (freshwater origin) (*data* from Bashar et al., 2018; Huang et al., 2015; Mangi, 2016; Mackay et al., 2014; Molinos-Senante et al., 2011; Vinten et al., 2012); (c) valuation of regulatory eco-services by fishponds of CEER origin (meta-analysed by Frélichová et al., 2014; Czech Republic), and; (d) farm-gate prices of common carp, live-weight basis (EUMOFA, 2016; O'Hagan et al., 2017). All these metadata were used for further comparison or calculation (indicated below).

3. Calculation

3.1. N and P losses from carp's feeding in fishponds

N and P losses from carp's feeding in fishponds involved the following calculations in sequence: (a) total input of feed, dietary N and P; (b) estimating digestible, metabolic and total losses; (c) calculation of nutrient balances from diffused losses – approach A; (d) calculation of net nutrient balances from feed (cereals) losses – approach B; (e) calculation of net nutrient balances from cumulative losses – approach C, and; (f) representative footprint merging all approaches and comparison with other sectors. Considering the space limitations, these sub-chapters are explained in the supplementary text.

3.2. Nutrient utilization efficiency and comparison with other sectors

N and P retentions in carp were back calculated by assuming 2.88% N and 0.76% P content on whole body basis (Ramseyer, 2002; Roy et al., 2019, Mraz et al. *unpublished results*). These values were multiplied with harvested biomass of carp to estimate N and P harvested. Harvested values were subtracted from total dietary N or P (cereals and natural prey combined) and expressed in percentage (NUE_N, NUE_P). For comparison, we used published estimates on NUE_N, NUE_P from crop and livestock production sector(s) within EU region.

3.3. Autochthonous nutrient extraction by carps

There is inherent complexity in determining nutrients of autochthonous origin extracted by carps from fishponds (Potužák et al., 2016), especially in the presence allochthonous input like

Table 1
Results from the digestibility trials with common carp (data on dry matter basis).

Food	Crude N (%)	ADC_N (%)	Digestible N (g 100 g^{-1})	Crude P (%)	ADC_P (%)	Digestible P (g 100 g^{-1})
Corn	2.14	70.9	1.52	0.38	24	0.09
Triticale ↘	2.5	37.8	0.95	0.36	1	–
Wheat ↗	3.24	75.7	2.45	1	36	0.36
Average $_{cereals}$	**2.62**	**61.5**	**1.61**	**0.58**	**20.3**	**0.12**
Chironomid larvae ↗	8.46	91.9	7.77	0.99	99	0.98
Cyclops ↗	11.3	74.9	8.46	1.24	72.1	0.89
Daphnia ↗	8.95	80.5	7.2	1.34	72.2	0.97
Average $_{natural\ prey}$	**9.57**	**82.4**	**7.89**	**1.19**	**81.1**	**0.97**
Skretting® Carpe-F 3.5 mm™ (commercial carp feed)[a]	5.93	85.2	5.05	1.05	40.6	0.43

Intra-group comparison (cereals or natural prey): ↗ *Comparatively good;* ↘ *Comparatively poor.*
[a] Control diet. Results given for reference purpose. ADC = Apparent digestibility coefficient.

supplementary feeding. We attempted to grossly indicate the nutrients of autochthonous origin withdrawn by carps. The portion of retained nutrients from natural prey in carp body was grossly budgeted (in the absence of stable isotope approach). It was calculated by subtracting total losses of natural prey origin from total dietary intake (nutrient) of natural prey. The terms autochthonous and allochthonous refer to nutrients either originating from within the fishponds or introduced to the fishponds from outside, respectively.

3.4. Environmental cost burden and ecosystem services of carp production in fishponds

With the existing water treatment technologies, cost of removing 1 kg N or P from wastewaters (freshwater origin), were meta-analysed. The inter-quartile ranges of costs were 3–5 € kg^{-1} N removed and 19–35 € kg^{-1} P removed. These costs were multiplied with calculated nutrient footprint and regarded as environmental cost burden. Under ecosystem services offered, following aspects were summed up: (a) non-production or regulatory services offered by fishponds in Czech Republic (1257 € ha^{-1}); (b) commercial production services offered by fishponds (~2–2.5 € kg^{-1} live weight), and; (c) valuation of autochthonous nutrient removed (cost mentioned above). All valuations were made on 'per ha fishpond' basis.

3.5. Neutral-footprint carp production scenario

The required cereals-based production intensity in fishponds to neutralize existing footprint to 'near-zero' levels was coined as 'neutral footprint' production. For its mathematical derivation, median values between 'exclusively natural' and 'existing' production scenarios were calculated for certain variables, *i.e.* $FCR_{natural\ prey}$, $FCR_{cereals}$, yield (kg ha^{-1}), NUE_N and NUE_P. Nutrient balances from feeding within this 'median scenario' was calculated and validated for sub- or near-zero values.

3.6. Trade-offs between nutrient supply, good growth and reduced footprint

An exercise was done with different relevant combinations of cereals and natural prey ($FCR_{cereals}$ 0–4.3; $FCR_{natural\ prey}$ 0.1–0.7) covering 'exclusively natural' to 'completely cereals dominated' production scenarios. Digestible N and P (g kg^{-1} fed basis) from cereals and natural prey were multiplied with their respective FCRs and summed up for total diet. NRC (2011) recommendations on optimum digestible nutrient requirement of common carp were used as baseline, *i.e.* 49.6 g digestible N kg^{-1} of diet and 7 g digestible P kg^{-1} of diet. The instances of FCR combinations which successfully 'hit the target' (*i.e.* fulfilled baseline) were demarcated from the ones that failed. Multiple linear regression models were generated to aid such budgeting.

Similar exercise was repeated with footprint (faecal losses in g kg^{-1} diet basis) from cereals and natural prey under different FCR combinations (same range as above). Complimentary contribution curves of faecal footprint under different FCR combinations were plotted in ggplot2 using linear fitting (Wickham, 2016; R Development Core Team, 2015). The FCRs at the intersection was designated as trade-off point to reduce faecal footprint without deviating from optimum digestible nutrient supply. By the term 'trade-off', we imply a balanced compromise where we accept some degree of disadvantage (reduced footprint) to retain a benefit (uninterrupted production), which otherwise are two incompatible features.

3.7. Data application in Central and Eastern European Region (CEER) production scenario

Values obtained on Czech carp production were upscaled and applied for Germany, Hungary, Poland and Russian Federation to derive figures representing Central and Eastern European Region (CEER). The strategy is detailed in supplementary text. In addition to the text above, infographics on the methodological framework are provided in Supplementary Figs. S4–S5 for better clarity.

4. Results

4.1. Nutrient availabilities from cereals and natural prey

On dry matter basis, the average N and P contents in cereals commonly used in Czech fishponds (corn, triticale, wheat) is 2.62% and 0.58%, respectively. Carp's natural prey (chironomid larvae, cyclops, daphnia) have much higher N (9.57%) and P (1.19%) contents. Apparent digestibility of N in cereals and natural prey were 61.5% and 82.4%, respectively. Natural prey-N is therefore ~1.3 times more digestible than cereal-N. Likewise, apparent digestibility of natural prey-P (81.1%) is ~4 times superior to cereal-P which is only 20.3% digestible. The digestible nutrients offered by natural prey (N: 7.89 g 100 g^{-1}; P: 0.97 g 100 g^{-1}) are ~5–8 times higher ($p < 0.05$) than cereals (N: 1.61 g 100 g^{-1}; P: 0.12 g 100 g^{-1}). Detailed results are summarized in Table 1.

4.2. N and P losses from carp's feeding in fishponds

4.2.1. Cereals

It was estimated about 36920–46150 tons of cereals (~967.3–1209.1 tons N, 214.1–267.7 tons P) supported carp production in Czech fishponds (Table 2). Combining the global metadata and our digestibility results, the N and P digestibility of cereals usually range between 61.5–71% and 20.3–25% respectively. It implies 29–38.5% of cereal-N and 75–79.7% of cereal-P are not digested by carps. Considering the metabolic N losses through gills and urine, another 17–30% of N intake is lost. Faecal and metabolic losses from feeding on cereals was estimated at 24.1–44.9 kg N and 8.7–11.6 kg P ton^{-1} of carp produced or, 10.8–20.2 kg N and 3.9–5.2 kg P ha^{-1} fishpond. The N:P ratio of cereals derived losses is ~3:1–4:1 (Table 2).

4.2.2. Natural prey

About 5538–7384 tons of natural prey dry matter (~530–706.6 tons N, 65.9–87.9 tons P) was supposedly consumed by the carp production in Czech fishponds (Table 2). Due to lack of pre-existing data on N and P digestibility of natural prey, only results obtained from our digestibility trials were used. About 17.6% of natural prey-N and 18.9% of natural prey-P are not digested by carps. Another 17–30% of N intake is lost as metabolic losses. Carp's digestive losses from grazing on natural prey was estimated at 9.9–18.2 kg N and 0.7–0.9 kg P ton carp $produced^{-1}$ or, 4.5–8.2 kg N and 0.3–0.4 kg P ha^{-1} fishpond. The N:P ratio of natural prey derived losses is ~14:1–20:1 (Table 2). Compared to cereals, the losses of natural prey origin are far less and with better N:P ratio. If the sum of losses from cereals and natural prey is considered, cereals has the major share of total footprint (>70% of N and >90% of P footprint).

4.3. Nutrient footprint through the production cycle and comparison with other sectors

Using multiple approaches, the nutrient balance from carp's feeding activity in fishponds were calculated (Table 2). The spatial footprint (footprint expressed per unit farmed area) of common

Table 2
Nutrient footprint from natural and supplementary feeding supporting 18460 tons of common carp production from 41080 ha of fishponds (yield 449.4 kg ha^{-1}) in Czech Republic.

Cereals (FCR 2–2.5)		Natural food (FCR 0.3–0.4)	
Dietary input			
Requirement: 36920–46150 tons (dry matter)		Requirement: 5538–7384 tons (dry matter)	
Avg. N: 2.62% and P: 0.58% (dry matter)		Avg. N: 9.57% and P: 1.19% (dry matter)	
52.4–65.5 kg N ton carp^{-1}		28.7–38.3 kg N ton carp^{-1}	
23.5–29.4 kg N ha^{-1} fishpond		12.9–17.2 kg N ha^{-1} fishpond	
11.6–14.5 kg P ton carp^{-1}		3.6–4.8 kg P ton carp^{-1}	
5.2–6.5 kg P ha^{-1} fishpond		1.6–2.1 kg P ha^{-1} fishpond	
Faecal and metabolic losses			
Faecal losses: 29–38.5% N; 75–79.7% P		Faecal losses: 17.6% N; 18.9% P	
Metabolic losses: 17–30% of N intake		Metabolic losses: 17–30% of N intake	
24.1–44.9 kg N ton carp^{-1}		9.9–18.2 kg N ton carp produced^{-1}	
10.8–20.2 kg N ha^{-1} fishpond		4.5–8.2 kg N ha^{-1} fishpond	
8.7–11.6 kg P ton carp^{-1}		0.7–0.9 kg P ton carp produced^{-1}	
3.9–5.2 kg P ha^{-1} fishpond		0.3–0.4 kg P ha^{-1} fishpond	
N:P ~3:1–4:1		N:P ~14:1–20:1	
Spatial footprint on environment (per ha fishpond)			
Approach A (diffused)	**Approach B (allochthonous)**	**Approach C (cumulative)**	**Representative footprint (merged)**
7.6–14.2 kg N ha^{-1}	2.4–11.2 kg N ha^{-1}	6.9–19.3 kg N ha^{-1}	7.08–13.45 kg N ha^{-1}
2.1–2.8 kg P ha^{-1}	2.6–3.5 kg P ha^{-1}	2.9–3.9 kg P ha^{-1}	2.65–3.35 kg P ha^{-1}

carp production in Czech fishponds was estimated at 7.08–13.45 kg N and 2.65–3.35 kg P ha^{-1} (equivalent to 15.8–29.9 kg N and 5.9–7.5 kg P ton^{-1} of carp produced). In terms of N footprint, carp production in European fishponds appear ~4–6 times less burdening than other food production sectors. Regarding P, carp production is ~1.5–2.4 times less burdening than other sectors (Fig. 1a and b).

4.4. Nutrient utilization efficiency and comparison with other sectors

Comparing the total nutrient input (cereals + natural prey) with output through harvested carp biomass (12.9 kg N and 3.4 kg P ha^{-1} fishpond), NUE_N in fishponds was estimated at 27.7–35.4% and NUE_P at 39.1–50% of dietary intakes. In case of completely natural carp production (input from natural prey: ~20.7 kg N and ~2.6 kg P ha^{-1} fishpond; output carp biomass: ~8.6 kg N and ~2.3 kg P ha^{-1} fishpond), the NUE_N and NUE_P are ~41.5% and ~88% respectively. A marked improvement in NUE_P is evident. Inter-sectoral comparison of NUEs, with cereal-fed (present regime), fully natural and neutral footprint production scenarios are depicted in Fig. 2a, b.

4.5. Autochthonous nutrient extraction by carps

Under the present production regime, about 18.8–20.1 kg N and 2.9–3.9 kg P of autochthonous origin (*i.e.* from live prey) is withdrawn per ton of carp produced. It is equivalent to 8.4–9 kg N and 1.3–1.7 kg P ha^{-1} of fishponds. It should be noted that despite this nutrient removal, the above-mentioned nutrient footprint is a spin-off product of the production cycle. Hence, it should not be double subtracted while comparing. If the production scenario is assumed 'exclusively natural', autochthonous nutrient removal is ~19.2 kg N and ~5.1 kg P ton^{-1} of carp produced, or, ~8.6 kg N and ~2.3 kg P ha^{-1} of fishponds. In this case no nutrient footprint occurs, and the autochthonous nutrients removed by carps contributes to positive ecosystem service. The present cereal-based production regime seems only ~2.2 times or ~1.5 times less efficient in terms of autochthonous N and P removal respectively, compared to natural production.

4.6. Environmental cost burden and ecosystem services of carp production in fishponds

The environmental cost burden, under the present production regime, was estimated at ~72–184 € ha^{-1}. Whereas, ecosystem services offered by carp production and fishponds amount to ~2206–2485 € ha^{-1}. It is obvious that environmental cost burden $\ll$ ecosystem services. Environmental cost burden of carp production amounts to <10% of its positive services to the environment and commerce combined. Present carp production regime is already inclined towards positive ecosystem services with 'net worth' of 2134–2300 € ha^{-1}. Under completely natural carp production, with zero environmental cost burden, the service amounts to ~1926–2130 € ha^{-1}. It is apparent that cereals-based carp production delivers ~8–10% higher services than completely natural production. This difference is driven by saleable amount of carp from fishponds, realized by the application of cereals. A comparative and self-explanatory account has been depicted in Fig. 3 and Fig. S7 respectively.

4.7. Assessment of neutral footprint carp production scenario

Neutralizing existing footprint to negligible levels might require $FCR_{cereals}$ 1–1.3 and $FCR_{natural\ prey}$: 0.5–0.6 with a yield limitation of 374.7 kg ha^{-1}. In this scenario, NUE_N and NUE_P is expected to be in the range of 34.6–38.5% and 63.6–69% respectively. The nutrient footprint under such circumstances is estimated to be −0.8 (removal) to 2.4 kg N ha^{-1} fishpond and 0.2 (negligible) to 0.5 kg P ha^{-1} fishpond. Although theoretically proposed, some application bottlenecks might render its practicality questionable (clarified later).

4.8. Trade-offs between nutrient supply, good growth and reduced footprint

4.8.1. Digestible nutrient supply

Digestible N requirement is easily met under semi-intensive rearing conditions. However, meeting the digestible P demand remains a concern under low natural prey availability – might be even inadequate (red zones; Table 3). Increasing supplementary feed inputs (cereals, from FCR 2 to 2.5) under low support from

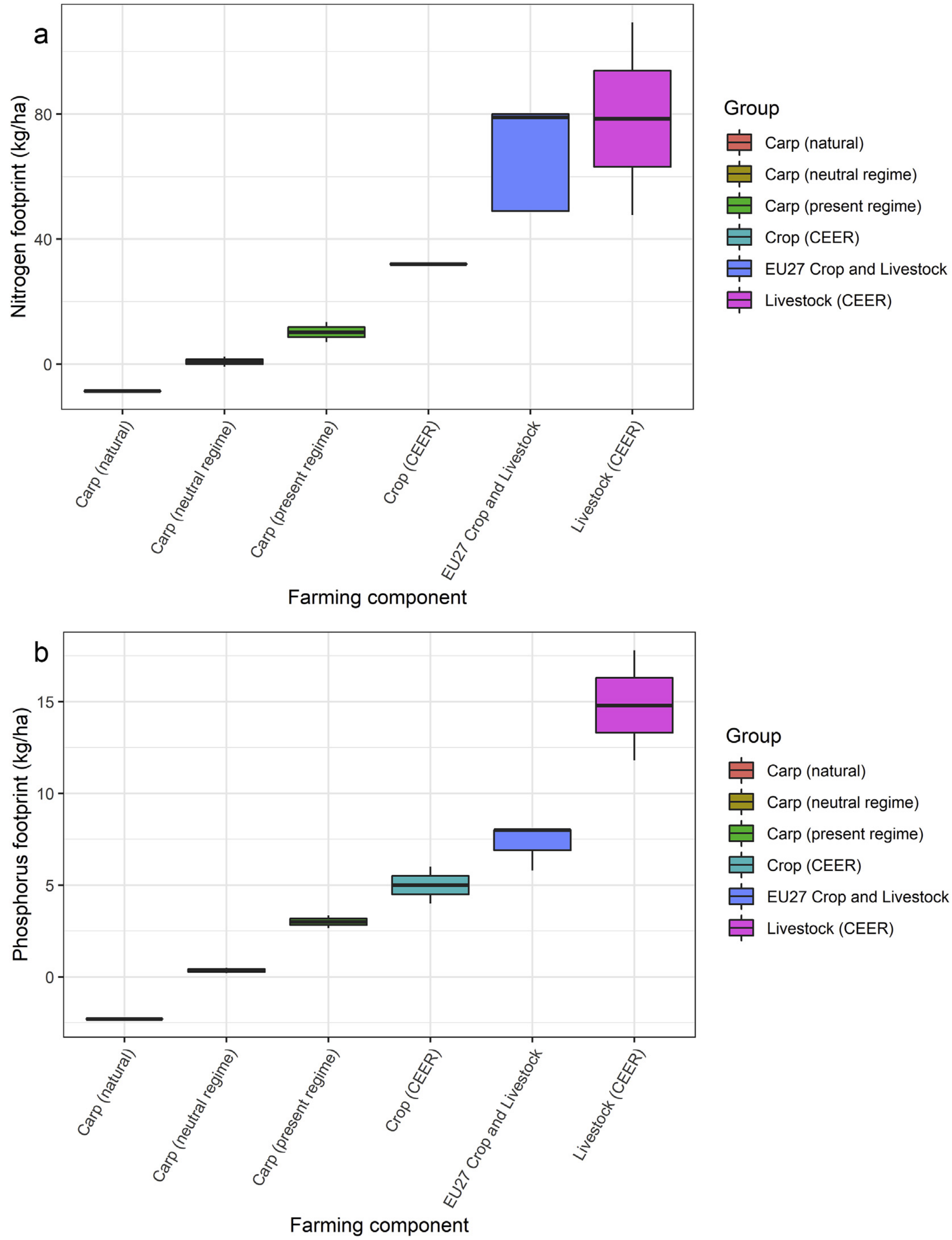

Fig 1. (a, b): Spatial nitrogen (a) and phosphorus (b) footprints of different farming sectors within EU or Central Eastern European Region (CEER). Data from Buckwell and Nadeu (2016), van Dijk et al. (2016), Rosendorf et al. (2016), Leip et al. (2015), Richards and Dawson (2008), Csathó et al. (2007), Kronvang et al. (2007), Velthof et al. (2007) and present study. Carp production in fishponds, in general, have the least nutrient burdens to environment than any other food production sector in Europe. Nutrient footprint below zero indicates nutrient removal from fishpond ecosystem.

natural prey ($FCR_{natural\ prey}$: $\leq$0.3) does not necessarily help. The nutritionally fulfilling combinations of relative FCRs have been identified as ‘green zones’ in Table 3. To reduce the use of cereals (by −15% to −25%) in fishponds, the minimum support from natural prey must be pushed by +0.1 units (or, +25%), *i.e.* $FCR_{natural\ prey}$ should be $\geq$ 0.4 for supporting carp production (modified scenario; Table 3). Although this 25% (+0.1 FCR) increase of dependency on natural prey appears theoretically promising, it is difficult practically (discussed below). Multiple linear models for calibrating digestible nutrient supply in fishponds have been generated (Table 3).

4.8.2. Footprint of fecal origin (excluding uneaten feed)

Faecal nutrient losses progressively increase with relative increase in $FCR_{cereals}$ while decrease with relative increase in $FCR_{natural\ prey}$ (Fig. 4). It means higher dependency on cereals has

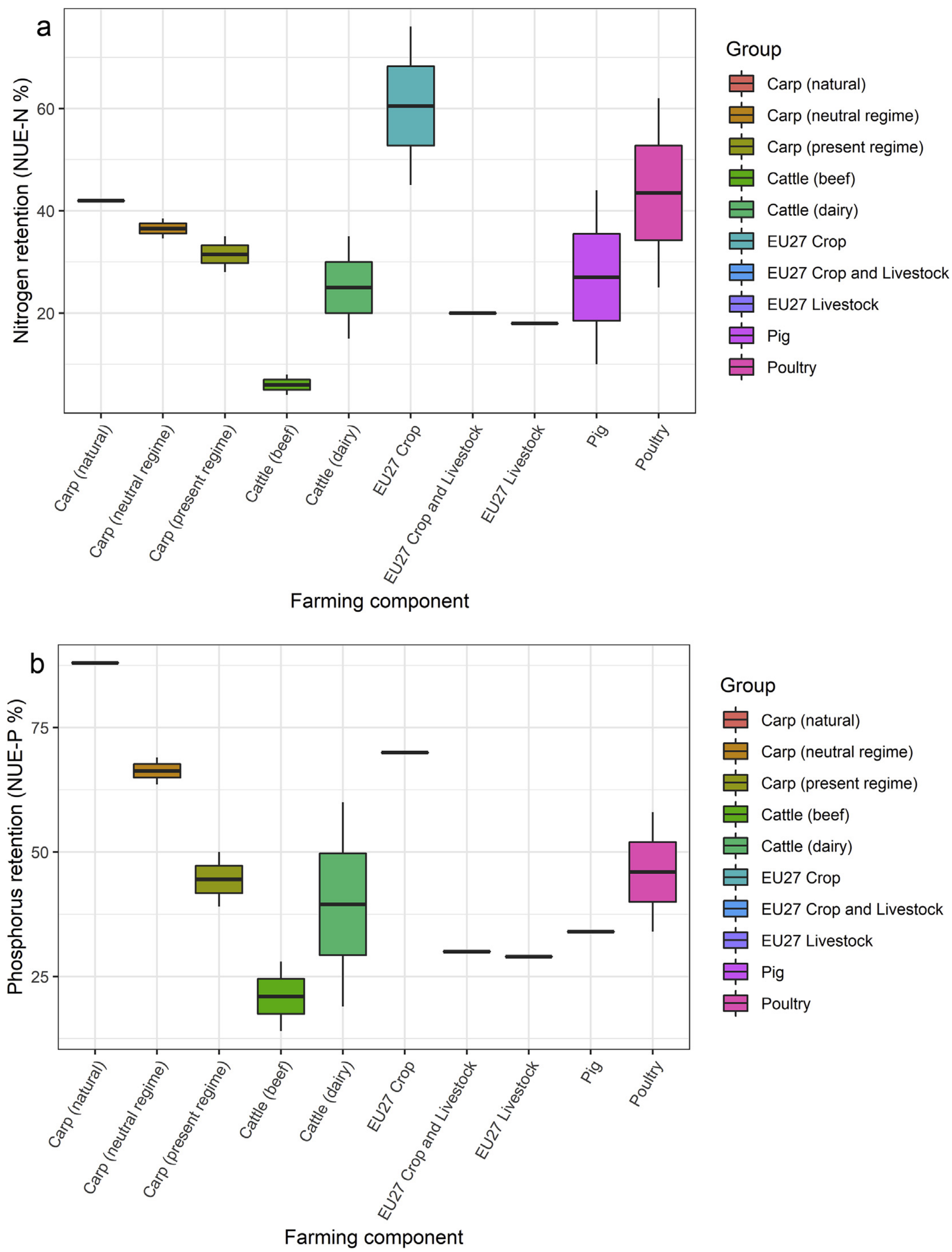

Fig 2. (a, b): Animal or plant level nutrient utilization efficiencies for nitrogen (a) and phosphorus (b) of different farming components within EU. Data from Buckwell and Nadeu (2016), Gerber et al. (2014), Leip et al. (2011) and present study. In terms of NUE_N and NUE_P, common carp is superior than EU27 livestock or EU27 crop and livestock average but inferior to EU27 crop sector average.

inevitable consequences on magnification of nutrient footprint; indicated by the red line in Fig. 4a, b. Increased reliance on natural food have positive environmental consequences; blue line in Fig. 4a, b. The trade-off FCRs for minimizing footprint and yet supplying optimum digestible nutrient were identified at $FCR_{cereals}$ $\leq$2.2 and $FCR_{natural\ prey}$ $\geq$0.35 (Fig. 4). Compliance to these relative FCR recommendations may result in ~10% reduction in existing footprint without compromising growth (digestible nutrient supply) or production (discussed below).

4.9. Central and Eastern European Region (CEER) carp production scenario

Data on nutrient footprint, nutrient removal, eco-cost burden and eco-services of carp production in Europe are provided in Table 4. The profile is based on five major European producers of common carp (Czech Republic, Poland, Hungary, Germany and Russian Federation) producing >72% of the total carp in Europe. The yield, nutrient footprint and removal, eco-burden and services are

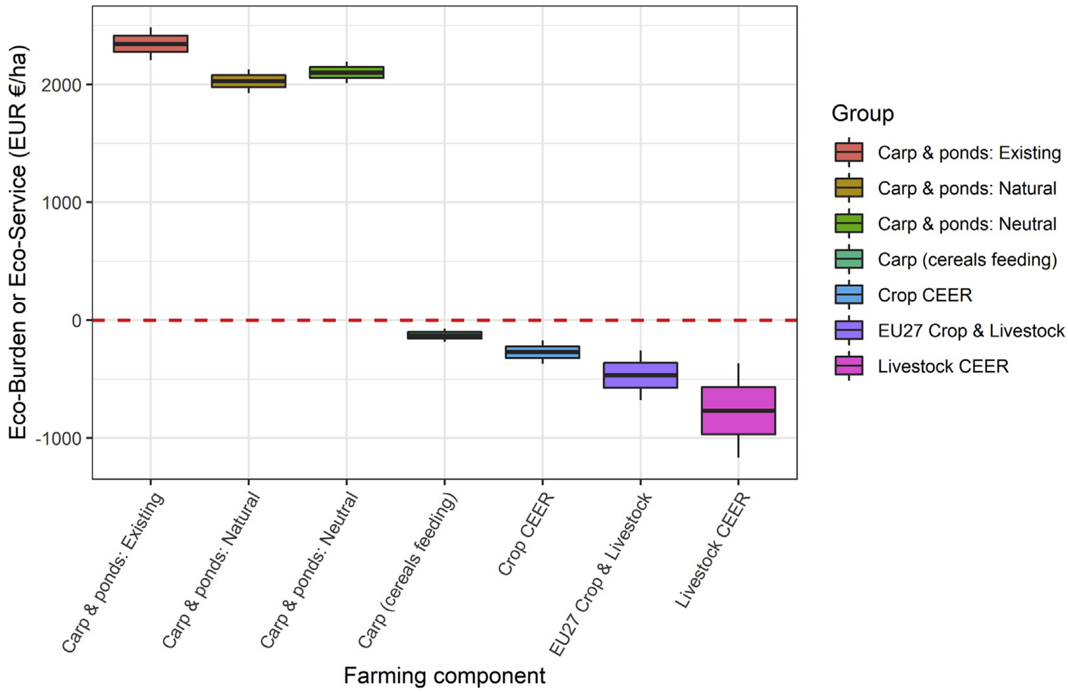

Fig. 3. Comparative account of ecosystem services (*above red line*) and environmental cost burden (*below red line*): Carp production in fishponds has far greater positive services compared to miniscule negative effect of supplementary feeding through cereals. Crop and livestock sectors in EU or CEER (Central Eastern European Region) have greater environmental cost burdens than carp farming. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

comparable among Czech Republic, Germany, Hungary and Poland ($p > 0.05$); Germany being slightly on a lower side than others. Russian Federation has significantly higher figures in all aspects ($p < 0.05$).

With a yield of 488.8 kg carp ha^{-1}, the N and P footprint from CEER is currently estimated at ~7.7–14.6 kg N and ~2.9–3.7 kg P ha^{-1} respectively. This amounts to ~19.7–50.9 million € of eco-cost burden in the region. The autochthonous N (8–9.2 kg ha^{-1}) and P (1.4–1.6 kg ha^{-1}) bioremediated by carps from fishponds in CEER, coupled with production value and regulatory services of fishponds is worth ~578.9–656.2 million € on regional scale (Table 4). The European country level averages of spatial footprint are ~9.4–10.8 kg N and ~2.7–3.2 kg P ha^{-1} with an average eco-cost burden of ~3.5–5.3 million €. The autochthonous nutrient

Table 3
Digestible nutrient supply (g kg^{-1} diet) from cereals (supplementary feed) and natural prey under different FCR (relative feeding coefficient) combinations for optimum carp growth in fishponds.

FCR (cereals)	FCR (natural prey) 0.7[d] N	0.7[d] P	0.6[c] N	0.6[c] P	0.5[b, c] N	0.5[b, c] P	0.4[a, b] N	0.4[a, b] P	0.3[a, b] N	0.3[a, b] P	0.2[e] N	0.2[e] P	0.1[e] N	0.1[e] P
0[d]	55.2	6.8												
1[c]			64.7	7.1	56.8	6.1								
1.3[c]			69.9	7.5	62	6.5								
1.5[b]					65.5	6.8	57.6	5.8	49.7	4.9				
1.7[b]					68.9	7.1	61.1	6.1	53.2	5.1				
2[a]							66.3	6.5	58.4	5.5				
2.5[a]							74.9	7.1	67.1	6.2				
3.5[e]											76.5	6.5		
4.3[e]													82.5	6.6

Good | Bad

Recommended supply (NRC 2011)
~49.6 g digestible N and ~7 g digestible P kg^{-1} diet.

Multiple linear regression models

Digestible N supply = 0.11 + 17.33*$FCR_{cereals}$ + 78.72*$FCR_{natural\ prey}$ (*Adj.* R^2 *0.99,* $p<0.01$)

Digestible P supply = −0.01 + 1.3*$FCR_{cereals}$ + 9.67*$FCR_{natural\ prey}$ (*Adj.* R^2 *0.99,* $p<0.01$)

[a] Present production regime.
[b] Modified production scenario. Reduced supplementary feed and increased reliance on natural food.
[c] Neutral footprint carp production scenario.
[d] Completely natural production scenario. Exclusive reliance on natural food.
[e] Almost complete reliance on supplementary feed (cereals) for production. Low natural food.

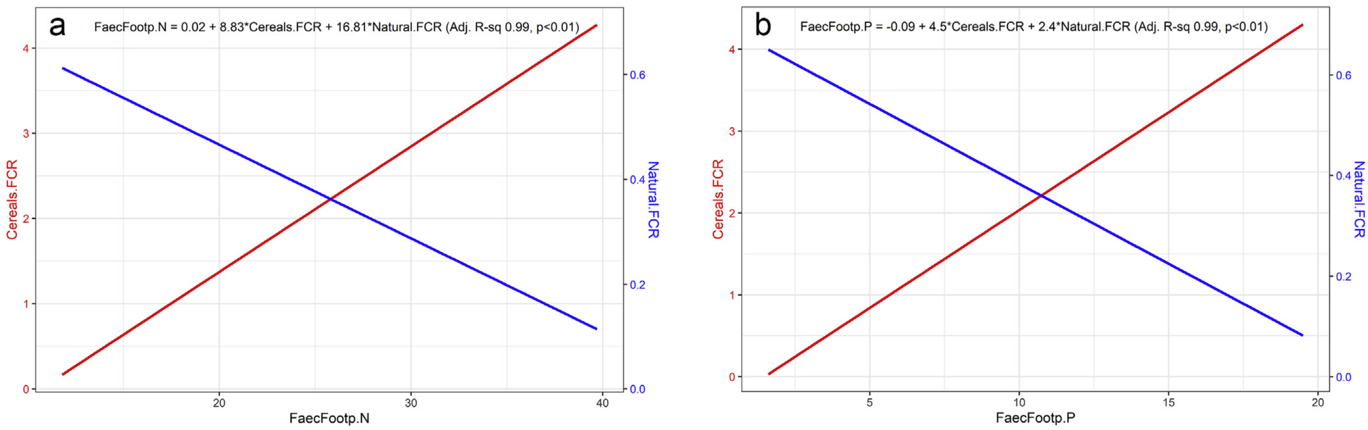

Fig 4. (a, b): Complimentary footprint (faecal) curve under relative proportions of cereals and natural food in fishponds. Point of inter-section denote trade-off FCRs (cereals ≤2.2 and natural prey ≥0.35) to reduce faecal nutrient losses in fishponds (FaecFootp.N, FaecFootp.P; in g kg^{-1} diet) without compromising optimum digestible nutrient supply for good growth. Red line and blue line correspond relative feed efficiency of cereals (supplementary feed) and natural prey, respectively. Nutrient footprint from feeding increases with relative increase in cereals input and relative decrease in natural food availability.

removal (average 9.2–9.8 kg N and 1.4–1.9 kg P ha^{-1}), coupled with production value (average ~1042.9 € ha^{-1}) and regulatory services by fishponds (~1257 € ha^{-1}) is worth ~74.5–100.6 million € on national scale (Table 4). The positive services of carp farming in European fishponds is many folds higher (~13–29 times) than any cost burden through nutrient footprint (Figs. 5 and 6).

5. Discussion

5.1. Nutrient availabilities from cereals and natural prey

The apparent protein (*i.e.* N) digestibility of various cereals by common carp have been well studied over last six decades (Roy et al., 2019), whereas data are sparse as regards to the availability of P. The existing studies have been listed in supplementary text. From the global metadata (Roy et al., 2019), the inter-quartile range (IR) of N digestibility for corn and wheat is 74–80% and 62–92% respectively. No data on P digestibility of corn and wheat for common carp was encountered in the reviewed literature (Roy et al., 2019). The present results are possibly the first ones. To the best of our knowledge, N and P digestibility of triticale (a hybrid between corn and wheat) by *Cyprinus carpio* is reported here for the first time. Generally, 71–93% of cereals-N and 25–57% (IRs) of cereals-P are digested by common carp (Roy et al., 2019). Our digestibility results agree with this general range but near the lower end of IRs (*see* supplementary text). The reason behind the poor P digestibility is predominantly phytate bound P fractions in cereals that are indigestible by carps (Hua and Bureau, 2010). N digestibility of cereals is moderate to good in nature, depending on their amino acid (AA) profile. Deficiencies in certain AAs render lower N digestibility (Kaushik, 1995; Nwanna et al., 2012; Schwarz et al., 1998).

To the best of our knowledge (Roy et al., 2019), digestibility of natural preys (chironomid larvae, cyclops and daphnia) by *C. carpio* are reported here for the first time. No prior data existed on digestible N and P supply, although their superior nutrient contents have been discussed before (Bogut et al., 2007; Steffens, 1986). Here, we have observed ~5–8 times higher digestible N, P supply from natural prey than cereals.

5.2. N and P losses from carp's feeding in fishponds

Within Europe, especially from the Central region, only a handful of 'published' estimates on carp fishpond nutrient balances exists: e.g. Austria (Kainz, 1985), Czech Republic (Duras et al., 2018; Potužák et al., 2016; Prikryl, 1983), Germany (Knösche et al., 2000) and Hungary (Gál et al., 2016; Knösche et al., 2000; Oláh et al., 1994). From these studies it could be summarized that: (a) average balance of N is ~23 kg ha^{-1} or ~24 kg ton^{-1} of carp produced; (b) maximum balance of P is ~6.7 kg ha^{-1} or ~2.7 kg ton^{-1} of

Table 4
Environmental footprint and bio-remediation services of carp production in Europe. Profile based on major European producers of common carp.

Country/Region [a]	Yield (kg ha^{-1})	Footprint N (kg ha^{-1})	Footprint P (kg ha^{-1})	N removed (kg ha^{-1})	P removed (kg ha^{-1})	Eco-burden (million €) [b]	Eco-service (million €) [b]
Czech Republic	449.4	7.1–13.4	2.7–3.4	8.4–9	1.3–1.8	2.9–7.6	90.6–102.2
Germany	250	4–7.5	1.5–1.9	4.7–5	0.7–1	1.6–4.1	71.4–77.7
Hungary	470.8	7.4–14.1	2.8–3.5	8.9–9.5	1.4–1.8	2–5	58.5–66.2
Poland	410	6.5–12.3	2.4–3.1	7.7–8.2	1.2–1.6	2.9–7.5	94.9–106.3
Russia	638.8	10.1–19.1	3.8–4.8	12–12.8	1.9–2.5	10.3–26.6	263.5–303.9
Central Eastern European Region [c]	488.8	7.7–14.6	2.9–3.7	9.2–9.8	1.4–1.9	19.7–50.9	578.9–656.2
Country average [d] (European)		9.4–10.8	2.7–3.2	8–9.2	1.4–1.6	3.5–5.3	74.5–100.6

[a] *Carp Production/carp fishpond area* (as of 2017; in parenthesis): Czech Republic (18460 tons/41080 ha), Germany (10000 tons/40000 ha), Hungary (12240 tons/26000 ha), Poland (18325 tons/44700 ha) and Russia (64587 tons/101100 ha).
[b] Eco-burden: cost burden due to nutrient footprint. Eco-service: regulatory services of fishponds, autochthonous nutrients bioremediated by carp, farm-gate sale value of harvested carps. All values in million € – on national scale.
[c] Derived from total carp production (123612 tons) and total carp pond area (252880 ha) in the region (sum of countries).
[d] Inter-quartile range of medians. Median value derived from the minima-maxima span of top five common carp producing countries in Europe.

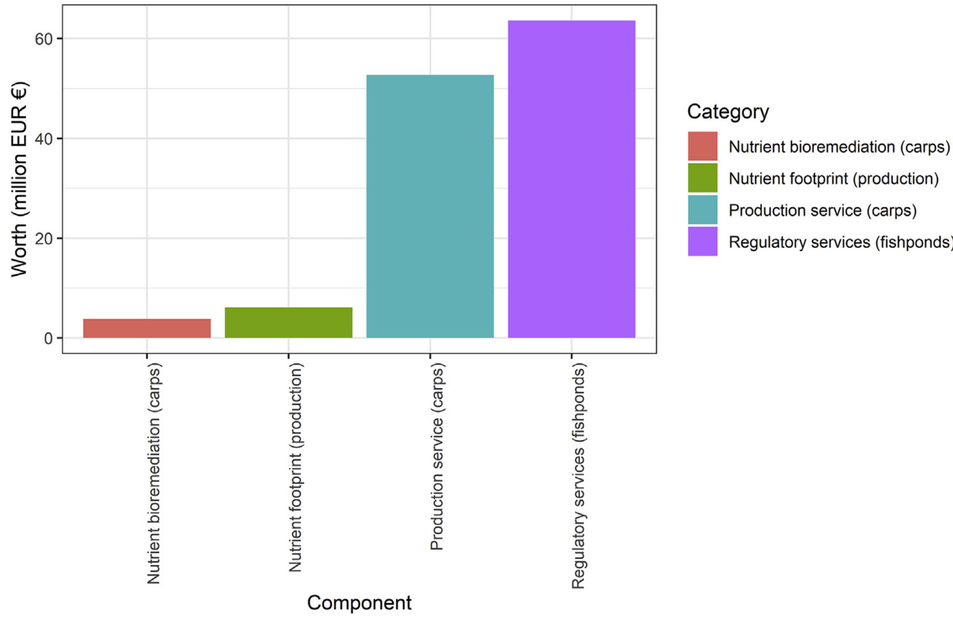

Fig. 5. Breakdown (million €) of different eco-services associated with carp production in fishponds on national scale. Figure depicts national scale average from top 5 producers in Europe (Russian Federation, Czech Republic, Poland, Hungary and Germany; contributing >70% production in Europe). Per hectare averages of top producers: Nutrient bio-remediated by carp worth ~75.3 € ha^{-1}, nutrient footprint of production (*negative service*) worth ~120.8 € ha^{-1}, production value of harvested biomass worth ~1042.9 € ha^{-1} and regulatory ecosystem services by fishponds worth ~1257 € ha^{-1}.

carp produced; and, (c) fishponds have special benefits of acting as a sink for P, trapping ~0.5–78 kg P ha^{-1} (average ~34 kg P ha^{-1}). Although most of them emphasized the non-polluting nature of carp production in fishponds through mass balance approach, no attempt pin-pointed the nutrients left behind by the growing carps through their feeding activity per production cycle. The most dynamic fluctuation of nutrients in fishponds is perhaps through the type and quantity of food consumed (Biermann and Geist, 2019; Knösche et al., 2000; Pechar, 2000; Watanabe et al., 1999). N or P balance of fishponds beyond carp's excretory losses from feeding

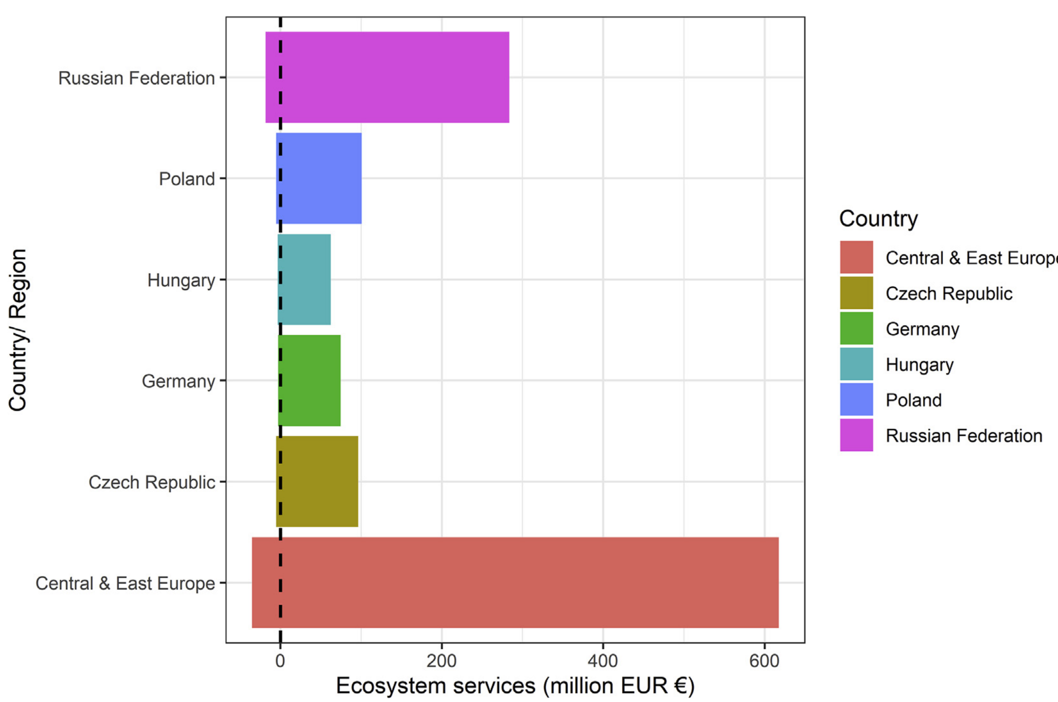

Fig. 6. Worth of positive (right of dotted line) and negative (left) ecosystem services from carp production in fishponds on national/regional scale. On country scales, Czech Republic and Poland almost have 100 million € of total services. *Scale for comparison*: total budget of EU spent on aquaculture during 2000–2014 amounts to 1170 million € (Guillen et al., 2019), 50% of which appears to be intangibly paid back by carp production alone in CEER fishponds per production cycle. Assuming 5 carp production cycles during 2000–2014, carp aquaculture 'alone' might have intangibly paid back ~2.9 billion € which is 2.5 times over the invested budget.

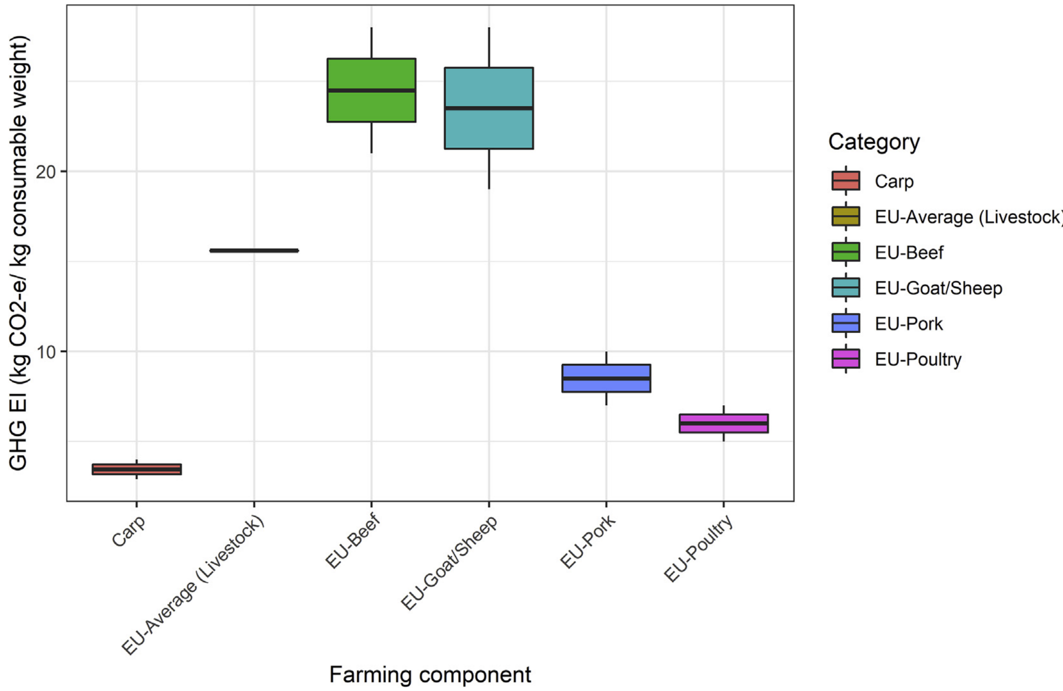

Fig. 7. GHG EI (kg CO_2-equivalent per kg consumable weight) of European livestock produce in comparison with farmed carp. Maximum GHG EI of carp production is ~4 times less than the average GHG EI of livestock sector (big/small ruminants, poultry). Carp farming in fishponds is cleaner than most terrestrial animal farming. Carbon emission of EU/CEER carp production was recalculated from dataset in MacLeod et al. (2019), then corrected with slaughter yield range for common carp (Prchal et al., 2018) to arrive at carp level GHG EI values. For inter-sectoral comparison, data were taken from Weiss and Leip (2012).

on natural prey and cereals (*i.e.* beyond our estimated footprint), might have been the nutrients received through inflow water or catchment fertilization. The present work highlights this overlooked interference in most fishpond nutrient budgeting results.

Potužák et al. (2016) earlier validated the results derived through the traditional methodology *i.e.* mass balance equations between input and output of fishponds. They demonstrated 'mass balanced' results when validated under practical conditions seldom make any sense. Alternative nutrient budgeting methods more appropriate for Central European fishponds were proposed (Hejzlar et al., 2006; Potužák et al., 2016). Our results, if compared with the 'mass-balanced' results, appears to be on a conservative side; probably more realistic. Interestingly, our results are in close agreement with an independent LCA by Biermann and Geist (2019) on conventional and organic carp farming in Germany. The footprint from carp and feed combined was estimated ~10.5–50.5 kg N and 5.7–6.3 kg P ton^{-1} of carp produced (recalculated from Biermann and Geist, 2019); reinforcing our findings.

5.3. *Nutrient footprint through the production cycle and comparison with other sectors*

The EU crop and livestock (terrestrial) production sectors, together, have spatial footprints in the range of 32–80 kg N and 4–8 kg P ha^{-1} farming area (Buckwell and Nadeu, 2016; Csatho et al., 2007; Kronvang et al., 2007; Leip et al., 2015; Richards and Dawson, 2008; Rosendorf et al., 2016; van Dijk et al., 2016, Velthof et al., 2007). Hence, the spatial footprint of European agriculture and livestock production is at least 1.5 times (for P) to 4 times (for N) higher than fishpond-based, cereals-fed carp production (European average: 9.9–11.4 kg N ha^{-1}; 2.2–2.6 kg P ha^{-1}). Linking the estimated footprint with existing observations on nutrient trapping by fishponds (e.g. outflow water-P < inflow water-P; Gál et al., 2016; Knösche et al., 2000; Potužák et al., 2016; Všetičková et al., 2012), we suspect the quantified footprint might not always end-up enriching downstream waters. Long term water-residence period is known to precipitate P into fishpond sediments (Hejzlar et al., 2006; Potužák et al., 2016), only a part of which is released during harvesting through sludge (Duras et al., 2018; Knösche et al., 2000; Potužák et al., 2016). It can be avoided, provided careful harvesting measures are adopted (Knösche et al., 2000; Potužák et al., 2016).

We have further hinted a neutral footprint production intensity in fishponds, following which, the commercial interests of 'profitable' carp production may falter – despite fulfilling 'greener-goals'. Downscaling the existing production to 'neutral' or 'natural' modes may reduce earning by at least −170 € ha^{-1} or −223 € ha^{-1} respectively. This view, from environmentalist's perspective, is a traditional argument 'sold' by the producers. Present production regime, with 'still intact' commercial interests, is close to the neutral footprint zone (Fig. 1a and b). However, compliance to the trade-off FCRs (discussed below) and better pond management practices (listed in supplementary text; Woynarovich et al., 2011) is recommended. Present supplementary feeding provisions in fishponds for supporting production should not be incriminated as an anthropogenic driver of eutrophication.

Beyond eutrophication, two additional analyses on greenhouse gas emission (e.g. CO_2-equivalent and CH_4) are presented for additional clarity: (a) carbon emission from European carp production in contrast to EU livestock sectors (illustrated in Fig. 7), and; (b) methane emission from Czech fishponds in contrast to Asian carp ponds, Czech agricultural farms and livestock units (Fig. S6). The greenhouse gas emission intensity (GHG EI) of EU livestock products (range 5–28 kg CO_2-e, average 15.6 kg CO_2-e kg^{-1} consumable weight) appear much higher than farmed carp (2.9–4 kg CO_2-e kg^{-1} consumable weight) (Fig. 7). Overall, the results reinforce European carp farming in fishponds as relatively 'cleaner' way of production than other food production sectors.

5.4. Nutrient utilization efficiency (NUE) and comparison with other sectors

Under controlled conditions and with good quality protein diet, common carp may retain up to ~50% of dietary N intake (Kaushik, 1980, 1995; Roy et al., 2019). Metabolic losses (as soluble NH_4—N), predominantly through branchial pathway and little through urine, are the major N losses in carps (Kaushik, 1980). In Czech fishponds, carps feeding on natural prey and cereals overall have mediocre NUE_N (up to 36% of dietary N intake). This might be attributed to endogenous obligatory losses (NRC, 2011) to meet energy expenditure, especially during survival through the ice-covered winter months (90–120 days), in the absence of adequate food. This is a situation unlike experimental or indoor aquaculture systems where optimum temperature is maintained with uninterrupted food supply. Carps even suspended feeding in our indoor systems when water temperature dropped below 13 °C. Concerning P, suspended losses through faeces remains the most dominant pathway (Kaushik, 1995; Roy et al., 2019). Present estimates indicate ~50% of dietary P intake are likely retained by the carps in Czech fishponds; little better than NUE_N. Carps excrete more P in already high P environment (Chumchal and Drenner, 2004); a phenomenon which might coincide with spring thawing (and blooming) of fishponds. During late spring to summer, Czech fishponds are known to release the highest amount of P from sediments due to internal loading (Pokorný and Hauser, 2002; Vystavna et al., 2017).

The EU livestock sector (dairy cattle, beef cattle, pigs, poultry) has animal level NUE_N and NUE_P in the range of 4–62% (average 18%) and 14–60% (average 29%) respectively (Buckwell and Nadeu, 2016; Gerber et al., 2014; Leip et al., 2011). Hence, the average NUEs of EU livestock sector appears 1.5–1.7 times inferior than cereals based common carp production in European fishponds. Plant level NUE_N and NUE_P in the EU crop sector is 45–76% and 70% respectively (Buckwell and Nadeu, 2016); superior to both livestock and carp production. With increasing reliance on natural prey and decreasing production intensity (existing → neutral footprint → natural regime), a progressive improvement in NUE_P has been predicted. In fact, the achievable NUE_P for common carp under neutral or natural production regime are comparable or superior than the maximum NUE_P of crop and livestock sectors (Fig. 2a and b). Hence, presumptions surrounding inferior NUEs of common carp, at animal level, should be reconsidered; a lot depends on man-made choices.

5.5. Autochthonous nutrient extraction by carps

Our present estimate highlights the amount of autochthonous nutrients carp extract from fishponds through retention in body (European average: 8–9.2 kg N and 1.4–1.6 kg P ha^{-1}). Like in the case of footprint, our estimate of extracted nutrients is also on conservative side compared to 'mass balanced' results (explained in supplementary text). In terms of autochthonous nutrient extraction, present production regime is only ~1.5–2.2 times less efficient than natural carp production. A more precise estimation would require stable-isotopes approach; conveniently for N but difficult for P. Nonetheless, greater retention of dietary N and P by farmed fish is the key to balance aquaculture and environmental sustainability goals (Rerat and Kaushik, 1995).

5.6. Environmental cost burden and ecosystem services of carp production in fishponds

Carp production in European fishponds has been 'qualitatively' attributed to various positive services (Szücs et al., 2007; Bekefi and Varadi, 2007, Popp et al., 2019). Ecosystem services include flood control, biomass production, nutrient remediation, biodiversity support, groundwater recharge, oxygen production, micro-climate regulation, carbon sequestration, aesthetics, etc. (Pokorný and Hauser, 2002, Popp et al., 2019). Even the maximum production service (up to ~1123 € ha^{-1}) comes after average eco-service (1257 € ha^{-1}; Frélichová et al., 2014) offered by regional fishponds. In addition, the production benefit (+298.8–373.5 € ha^{-1}) over natural yields due to use of cereals (as supplementary feed) outweighs the little environmental cost burden caused (72–184 € ha^{-1}). This advantage (Fig. S7) only applies given that weed fish biomass does not select-out mature stages of zooplankton (natural prey) and result in their population collapse (Musil et al., 2014; Zemanová et al., 2019).

In the Czech Republic, present carp production regime offers positive services of net worth ~2134–2300 € ha^{-1} (European average: ~2375 € ha^{-1}); almost 100 million € on country scale. On regional scale (CEER), total net worth of services is at least ~579 million €. If we consider the total budget of EU spent on aquaculture (1.17 billion €) during 2000–2014 (Guillen et al., 2019), carp production in CEER fishponds appears to have intangibly paid back half of it 'per production cycle'. Assuming 5 production cycles (average 3 years per cycle; Gál et al., 2016; Pechar, 2000) during the EU investment period (2000–2014), carp aquaculture 'alone' might have intangibly paid back ~2.9 billion € *i.e.* ~2.5 times over the invested budget. The positive services of carp farming in European fishponds is many folds higher (~13–29 times) than any cost burden caused through nutrient footprint; little-bad compared to the greater-good. This situation may be reversed to 'greater-bad, lesser-good', losing >1118 € ha^{-1} or >56.5 million € worth of services in CEER, if production regime is adjusted to purely environmentalists' interests (explained in supplementary text).

5.7. Trade-offs between nutrient supply, good growth and reduced footprint

Over the last four decades in Europe, there have been reports alleging carp production in fishponds as polluting and studies not corroborating such allegations (listed in supplementary text; reviewed in Roy et al., 2019). From a nutritional point of view, the 5–8 times superior digestible nutrient supply of natural prey over cereals is not as straightforward as it seems. For example – digestible N or P in one corn grain kernel (weighing ~0.38 g) is available from ~0.05 to 0.08 g natural prey dry matter, but in fishponds, it is equivalent to ~0.38–0.6 g natural prey biomass (wet weight) roughly amounting to ~1230–1969 Daphnids or ~258–414 Chironomids (*data* from Bezmaternykh and Shcherbina, 2015; Řezníčková et al., 2016, Simčič and Brancelj, 1997). One must imagine the differences in energy allocation by carps in fetching one static corn grain versus filtering equivalent numbers of active natural prey(s) in fishponds. Cereals itself are rich and easy source of digestible energy for carps (~2759.4 kcal kg^{-1}; our data) having an energy profile slightly below their optimum requirement (~3200 kcal kg^{-1} diet; NRC (2011)). On the other hand, production solely on natural food has its own limitations. High value proteins or lipids in natural prey, in the absence of cereals, are utilized for energy rather than acting as building blocks for biomass gain (Füllner, 2015). Here, the importance and role of cereals must be recognized before including it in legislative discussions concerning fishpond environment (e.g. Czech Republic, Duras and Potužák, 2019). Importance of a good balance between natural food availability, supplementary feed application and nutrient footprint is discussed below.

5.8. Managerial implications

Conclusions from previous life cycle assessments (LCAs) highlight the feed and feeding efficiency as fundamental to the environmental impact of most aquaculture production systems (e.g. Aubin et al., 2009; Biermann and Geist, 2019; Henriksson et al., 2015; Mungkung et al., 2013; Papatryphon et al., 2004). In a recent LCA assessment on German carp production in fishponds (Biermann and Geist, 2019), feed contributed almost unanimously to the impact category: eutrophication. The feed types and amounts were proposed as point-of-action to improve environmental sustainability of carp production atop other parameters. Any reduction in supplementary feeding alone greatly lowers the freshwater eutrophication threat scenario posed by fishpond effluents (Biermann and Geist, 2019). Here, using an alternative approach, we highlighted the same and quantified it. To the best of our knowledge, this is the first data-driven effort to demarcate possible trade-offs in relative FCR combinations ($FCR_{cereals}$ and $FCR_{natural\ prey}$) for balancing environmental and commercial goals of carp production.

The existing feeding regimen ($FCR_{cereals}$ 2–2.5; $FCR_{natural\ prey}$ 0.3–0.4) in European fishponds already has its own bottlenecks; detailed in the supplementary text. On both sides of the proposed trade-off FCRs, it is either forcing farmers to reduce carp production (e.g. maintaining $FCR_{natural\ prey}$ of 0.5 in fishponds), or inadequate supply of digestible nutrients for carp's optimum growth (e.g. if $FCR_{natural\ prey}$ is below 0.3, increasing cereals will only cause footprint, not production). In the former case, at least eco-subsidies should be offered to the farmers for their environmental contribution. In the latter case, better supplementary feed *i.e.* options beyond cereals should be availed (discussed below). In the present study, we have mostly dealt with N while discussing about protein. Fish need all 20 amino acids in adequate quantities for protein growth (Kaushik, 1995; Rerat and Kaushik, 1995). Cereals alone under low natural food availability cannot provide that. Poor protein quality or amino acid profile of carp's diet in fishponds, caused by lower natural food availability (*i.e.* abundant, high-quality protein) and excess cereals application (*i.e.* scarce, low-quality protein), can aggravate metabolic N losses up to 46.7–58.6% of dietary N intake (Roy et al., 2019). This will most likely manifest into lower NUE_N and higher N footprint than presently estimated. In this situation, both N and P might be of equal concern.

5.9. Future suggestions

Feeding management decisions in European carp farming should involve – (a) further LCAs of arable cereals (Biermann and Geist, 2019), including supply chain concepts (mentioned above); (b) efforts toward lowering the overall FCR (Mungkung et al., 2013; Biermann and Geist, 2019, present study) for improving environmental performance; (c) validate our proposed trade-off FCRs under practical conditions; (d) calibrate the stocking densities (lower carp heads feeding on natural food) for reducing existing footprint without compromising production; (e) changing frequency, timing and dosages of feed application depending on environmental conditions (Roy et al., 2019); (f) 'supplementing the supplementary feed' under low natural food availability – e.g. use of commercial carp feed (not cereals at critically low natural food availability), partial replacement of cereals with pulses-legumes having ~2.7 times higher digestible P, or, brewery wastes offering ~4–5 times higher digestible P than parent cereals (Roy et al., 2019, Vlastimil Stejskal, JCU-FROV Ceske Budejovice, *personal communication.*). If reduced production intensity is still imposed, at least the farmers should be compensated with 'eco-subsidies' for their environmental contribution. To some extent, this would offset their decreased farm-gate income.

6. Conclusion

The present study revealed that carp production in fishponds has the least nutrient burdens to environment compared to other food production sectors in Europe. Existing feed provisioning in carp ponds and production intensity cannot thus be considered as a pollution causing activity. Focus should be on actual management of the fishponds. The ecosystem and production services offered by carp farming in fishponds have immense societal and economic advantages. Majority of nutrient footprint from carp's feeding activity is contributed by supplementary feeding with cereals. Monetary benefit of improved production over natural yields, by using cereals, out-weighs the slightly increased environmental burden caused. Reducing the production intensity to neutralize footprint might cause rural societal disturbances and intangible economic losses in the region. In such a case, at least eco-subsidies should be offered to the farmers for their environmental contribution. Carp production exclusively based on natural productivity has its own limitations; high value protein from natural prey is utilized for energy supply, rather than building biomass. Here the role of cereals, as rich source of energy, must be recognized. For producers, over-relying on cereals for growth under low natural food availability is most likely futile – only aggravates environmental footprint. Yet, opportunities exist to calibrate the present feeding practices for achieving both environmental (minimized footprint) and aquaculture goals (uncompromised production).

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.

CRediT authorship contribution statement

Koushik Roy: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing - original draft, Visualization. **Jaroslav Vrba:** Validation, Writing - review & editing, Funding acquisition, Project administration. **Sadasivam J. Kaushik:** Validation, Writing - review & editing. **Jan Mraz:** Methodology, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.122268.

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