The devil is in the details – the carbon footprint of a shrimp

Kauffman and colleagues (2017) reported new estimates of greenhouse-gas (GHG) emissions resulting from the conversion of mangrove forests into aquaculture ponds and concluded that 1603 kg of carbon dioxide equivalent (CO_2e) are emitted for every kilogram of shrimp produced on lands formerly occupied by mangroves. The authors consequently argued for inclusion of land use and land-use change (LULUC) emissions in life-cycle assessments of shrimp. We share Kauffman *et al.*'s concern about mangrove forest loss, but we believe that their land-use carbon footprint for farmed shrimp has been overestimated. Two previous studies – conducted by various authors of this letter – found LULUC-associated GHG emissions from shrimp farming to be one to two orders of magnitude lower (Jonell and Henriksson 2015; Järviö *et al.* 2017) than that of the Kauffman *et al.* study.

As explained by Kauffman *et al.* (2017), the carbon footprint of converting 1 ha of mangrove forest to 1 ha of aquaculture plot is dependent on data and assumptions with respect to several parameters. Although the three studies generated relatively similar estimates of carbon stocks (see next paragraph for details), model assumptions can substantially influence model output (Table 1). For instance, extensive shrimp farms generally co-produce several other valuable products, and the respective GHG emissions of those products should also be considered (ISO 2006).

Jonell and Henriksson (2015) estimated a carbon stock of 406 metric tons of carbon per hectare (t C ha^{-1}) down to 1-m sediment depth based on a global estimate by Pendleton *et al.* (2012), and assumed 63% of that carbon to be oxidized into CO_2 (with alternative values in the sensitivity analysis). Likewise, Järviö *et al.* (2017) concluded a total carbon stock of 724 t C ha^{-1} down to 1.5 m depth based upon a review of geographically diverse sources from the literature, and assumed 55% of the belowground carbon to be oxidized (50% of sediments and 100% of roots). By way of comparison, Kauffman *et al.* (2017) measured carbon contents in mangrove forests in Mexico, Central America, and Indonesia, and reported values between 269 and 1663 t C ha^{-1} down to 3-m depth. They concluded a mean global carbon stock of 858 t C ha^{-1} of mangrove forest, of which 91% and 54% of the aboveground and belowground carbon stocks, respectively, were assumed to react with oxygen during the conversion of mangroves to shrimp ponds.

Extensive mangrove-integrated shrimp farms in Ca Mau, Mekong Delta (investigated by Jonell and Henriksson 2015 and Järviö *et al.* 2017) have been in operation since the early 1980s (Ha *et al.* 2012). These systems produce only 250–300 kg shrimp ha^{-1} yr^{-1} (Phan *et al.* 2011), resulting in large areas of land devoted to each kilogram of shrimp. However, besides the stocked Asian tiger shrimp (*Penaeus monodon*), large volumes of wild shrimp and crabs are also harvested (Jonell and Henriksson 2015). The lowest shrimp yield estimate cited by Kauffman *et al.* (45 kg shrimp ha^{-1}; Bosma *et al.* 2012) was also from a system that co-produces other species, including milkfish (*Chanos chanos*; 375 kg), wild shrimp (*Metapenaeus brevirostris*; 160 kg), and crabs (mostly *Scylla serrata*; 11–80 kg), but Kauffman *et al.* did not account for such co-production. In contrast, Jonell and Henriksson, as well as Järviö *et al.*, resolved the co-product issue using established allocation methods (ISO 2006).

The assumed lifetime of shrimp ponds is important because emissions will be annualized or amortized over this time period (IPCC 2006). According to Kauffman *et al.*, shrimp ponds are actively used only for between 5 and 10 years, with the final carbon footprint being amortized over 9 years. However, Jonell and Henriksson, as well as Järviö *et al.*, both reported that farms could be used for at least 50 years. Interestingly, all three studies focused on "extensive" shrimp farming, systems that are less susceptible to disease outbreaks and therefore more resilient than "intensive" shrimp farming (Bush *et al.* 2010). The increased use of compound feeds, paddle wheels, alkalines, sediment drying/removal, probiotics, and improved water management has also helped enhance yields and prolong the longevity of shrimp farms (Lebel *et al.* 2010; Bosma and Verdegem 2011). Compound feeds

Table 1. Summary of the central parameters used for calculating the LULUC emissions of converting mangrove to shrimp farms across three studies

	Jonell and Henriksson (2015)	Järviö *et al.* (2017)	Kauffman *et al.* (2017)
Sediment depth considered (m)	1	1.5	3
Sediments oxidized (%)	63%	50%	54%
LUC (average t C oxidized ha^{-1})	254*	577	554
Occupancy time (years)	50	50	9
Missed sequestration potential (t ha^{-1} yr^{-1})	2.26	1.25	n/a
Shrimp (kg ha^{-1} yr^{-1})	229–360	130	275
Shrimp of total yield (%)	39%	39%	100%
Resulting carbon footprint (kg CO_2e kg^{-1} live shrimp)	20	184	1603

Notes: *The article states 245, but this is a typographical error.

achieve this by reducing sediment build-up, alkalines by reducing sediment acidification, sediment drying and removal by reducing pathogens, and water management and probiotics by improving water quality (Bosma and Verdegem 2011; Yanong 2013). Abandoned ponds are also occasionally reused if the price of shrimp increases (Lebel *et al.* 2002).

Scaling up the assumptions behind Kauffman *et al.*'s carbon footprint estimate to global shrimp production (4.3 million metric tons *P monodon* and *Litopenaeus vannamei* in 2014) (FAO 2016) implies that 156,480 km^2 of mangroves would need to be converted into shrimp farms in the coming 9 years, an area larger than the current extent of existing mangrove forests worldwide (134,300 km^2) (Thomas *et al.* 2017). A more conservative estimate, using the average global shrimp production over the past 10 years (3.4 million metric tons) and assuming that only half of the shrimp produced worldwide originates from extensive farms similar to those described by Kauffman *et al.*, suggests that 61,000 km^2 of mangrove forests were converted to shrimp farms in the past 9 years. Approximately 46% of all mangrove forests would then have been lost to shrimp farms between 2006 and 2014, an estimate much larger than the 11.2% of mangrove forests affected by aquaculture/agriculture activities between 1996 and 2010 as detected by satellite imagery (Thomas *et al.* 2017). Therefore, shrimp yields are generally higher and the lifetime of shrimp farms longer than those assumed by Kauffman *et al.* (2017).

In conclusion, any assumptions made with regard to farm occupancy time, sediment depth, carbon fate, and co-product allocation clearly influence the consequent GHG emissions per unit of shrimp. Although we recognize the importance of the primary data presented by Kauffman *et al.* (2017), we believe that their modeling assumptions represent an unlikely worst-case scenario. Furthermore, competition between shrimp farms and mangrove forests has been greatly reduced over the past decade (Richards and Friess 2016), and more than half of all shrimp today are produced in semi-intensive or intensive shrimp production systems (Tacon 2002; Hall *et al.* 2011), with stocking densities of up to 35 tons of shrimp per hectare (FAO 2017). Thus, as demonstrated by the discussion above, none of the three studies were able to effectively calculate the carbon footprint of an "average" shrimp.

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