Forest Ecology and Management 432 (2019) 17–29

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Carbon dynamics and land use carbon footprints in mangrove-converted aquaculture: The case of the Mahakam Delta, Indonesia

Virni Budi Arifanti[a,b,*], J. Boone Kauffman[a], Deddy Hadriyanto[c], Daniel Murdiyarso[d,e], Rita Diana[c]

[a] Department of Fisheries and Wildlife, Oregon State University, 104 Nash Hall, Corvallis, OR 97331, USA
[b] Center for Research and Development of Social, Economy, Policy and Climate Change (P3SEKPI), Ministry of Environment and Forestry of the Republic of Indonesia, Jl. Gunung Batu No. 5, Bogor 16118, Indonesia[1]
[c] Faculty of Forestry, Mulawarman University, Kampus Gunung Kelua, Jl. Panajam, Samarinda 75123, Kalimantan Timur, Indonesia
[d] Center for International Forestry Research (CIFOR), Jl. CIFOR Situgede, Bogor 16115, Indonesia
[e] Department of Geophysics and Meteorology, Bogor Agricultural University, Kampus Darmaga, Bogor 16680, Indonesia

ARTICLE INFO

Keywords:
Carbon dynamics
Ecosystem carbon stocks
CO_2 emissions
Emission factor
Mangroves
Aquaculture
Carbon footprint
Climate change

ABSTRACT

Mangroves provide a number of important ecosystem services to humanity but their persistence is threatened from deforestation, conversion, and climate change. The Mahakam Delta was once among the largest mangrove forests in Southeast Asia comprising 2% of Indonesia's total mangroves. Currently, about 62% of this extensive mangrove in the Mahakam Delta has been lost mainly due to conversion into aquaculture. To understand the impacts of mangrove conversion on carbon losses and therefore their values in climate change mitigation, we sampled 10 intact mangroves and 10 abandoned shrimp ponds to quantify: (1) the total ecosystem carbon stocks; (2) potential CO_2 emissions arising from mangrove conversion to shrimp ponds; and (3) the land use carbon footprints of shrimp production. The mean ecosystem carbon stocks in shrimp ponds (499 ± 56 Mg C ha^{-1}) was less than half of the relatively intact mangroves (1023 ± 87 Mg C ha^{-1}). This equates to a potential annual emission factor over 16 years following mangrove conversion of 120 Mg CO_2e ha^{-1} yr^{-1}, which is similar with the total carbon loss from land conversion in freshwater tropical peat swamp forests. Inclusion of C losses from land use/cover change in a life cycle analysis (i.e., the land use carbon footprint) resulted in an estimated 2250 kg $CO_{2\text{-}e}$ emitted for every kg of shrimp produced in mangrove-converted ponds. Conversion of mangroves to shrimp ponds in the Mahakam Delta resulted in a carbon loss equivalent to 226 years of soil carbon accumulation in natural mangroves. Conservation of mangroves are of great value for inclusion in climate change mitigation strategies because of their large carbon stocks, the large carbon emissions generated from land use, and the potentially long period of time required to recover carbon stocks following abandonment.

1. Introduction

Mangrove ecosystems are wetlands consisting of woody vegetation that occur in intertidal marine and brackish environments (Giesen et al., 2007). They are distributed along coasts in tropical and subtropical regions between approximately 30°N and 30°S latitude (Giri et al., 2010). Indonesia has 29,000–31,894 km^2 of mangroves which is more than any other country on earth (i.e. 21–23% of the global total; FAO, 2007; Giri et al., 2010; Spalding et al., 2010).

Mangrove ecosystems provide many valuable ecological functions and services such as fish habitat (Alongi, 2009; Nagelkerken et al., 2008), timber, thatch and fuels (Blasco et al., 1996), habitat for endemic animals and organisms (Nagelkerken et al, 2008) and they provide coastal protection from extreme events such as tsunamis and hurricanes (Alongi, 2008; Giri et al., 2008, 2010). They also store and sequester relatively large quantities of carbon (Donato et al., 2011; Mitsch et al., 2012; Murdiyarso et al., 2015; Kauffman et al., 2017).

Farmed shrimp is now the largest seafood commodity accounting for 15% of the total value of all fishery products traded internationally in 2012 (FAO, 2014). A global export market for shrimp has led to large areas of mangrove loss (Bosma et al., 2012; Ilman et al., 2011; Pendleton et al., 2012). Aquaculture pond establishment has been the

* Corresponding author at: Center for Research and Development of Social, Economy, Policy and Climate Change (P3SEKPI), Ministry of Environment and Forestry of the Republic of Indonesia, Jl. Gunung Batu No. 5, Bogor 16118, Indonesia

E-mail addresses: vbudia@yahoo.com, Virni.Arifanti@oregonstate.edu (V.B. Arifanti).

[1] Permanent address.

https://doi.org/10.1016/j.foreco.2018.08.047
Received 29 January 2018; Received in revised form 16 August 2018; Accepted 27 August 2018

main cause of mangrove deforestation in Asia (FAO, 2007; Giri et al., 2008) followed by conversion to agriculture (oil palm plantations, pasture, etc.), urban development, infrastructure and tourism (Duke et al., 2007; FAO, 2007; Giri et al., 2008).

Land use change in mangrove ecosystems generates significant CO_2 emissions (Kauffman et al., 2017; Pendleton et al., 2012; Werf et al., 2010). Between 1980 and 2005 Indonesia lost about 30% of its mangrove forests which is equivalent to an annual deforestation rate of 1.24% or an estimate of 0.19 Pg CO_{2e} yr^{-1} (FAO, 2007; Murdiyarso et al., 2015).

While rates of land conversion of mangroves are high, very few studies have analyzed the carbon footprint from shrimp production that includes the emissions arising from land use/cover change (Järviö et al., 2017; Kauffman et al., 2017). This loss, when included in life cycle analyses, is termed the land use carbon footprint and is defined as the quantity of greenhouse gases produced from the land conversion that is required to produce any given commodity (Kauffman et al., 2017). The objectives of this study were to quantify the total carbon stocks in mangroves and abandoned shrimp ponds, the potential carbon emissions arising from mangrove conversion, and the estimated land use carbon footprint of shrimp produced in the Mahakam Delta, Indonesia.

We hypothesized that: (1) the ecosystem C stocks in intact mangroves are significantly higher than in shrimp ponds; (2) mangrove conversion to shrimp ponds will generate substantial carbon emissions to the atmosphere because of significant losses (oxidation) of the aboveground pools and soil carbon; and (3) potential CO_2 emissions arising from mangrove conversion to shrimp ponds result in a very high ecosystem carbon footprint from aquaculture ponds.

2. Materials and methods

2.1. Study area

The Mahakam Delta is a deltaic plain on the Eastern coast of Kalimantan (Borneo) Island, Indonesia. The Mahakam Basin is approximately 75,000 km^2 in area. The Mahakam River 900 km in length (Sassi et al., 2011; Storms et al., 2005) and is located between 0°18′ and 0°54′ South latitude, and 117°18′ and 117°36′ East longitude (Rahman et al., 2013). The delta was developed in the late-Holocene during the past 5000 years and has a distinct network of fluvial and tidal channels forming a lobate, fan shaped delta (Fig. 1; Storms et al., 2005).

Before 1950, the natural mangrove vegetation of the Mahakam Delta was relatively undisturbed. It was dominated by Nypa palm (*Nypa fruticans;* 50% of the delta area), freshwater tidal forests (17%) and broadleaved mangroves at the lowest reaches (33%) (van Zwieten et al., 2006). The development of aquaculture ponds was largely concentrated in the broadleaved mangroves until recently (Bourgeois et al., 2002). Rahman et al. (2013) estimated that 21,000 ha mangroves in the Mahakam Delta had been converted to shrimp ponds between 2000 and 2011. Mangrove deforestation in the Mahakam Delta from 1994 to 2015 totaled 59,480 ha, with about 36,820 ha of mangroves remaining in 2015 (Aslan, 2017). They reported that with a deforestation rate of 4.48% $year^{-1}$, about 62% of mangroves had been lost during this 21 year period.

The shrimp ponds in the Mahakam Delta are largely low input/low production operations that depend upon tides to fill and drain ponds. During the first year of pond establishment these ponds produce around 100–300 kg of shrimp ha^{-1} yr^{-1} (Bosma et al., 2012). After 5 years, the average shrimp production in the ponds in the Mahakam Delta significantly decreases to 45 kg ha^{-1} yr^{-1} (Noryadi et al., 2006). Decreased aquaculture productivity, sea level rise, diseases, and harvest failures ultimately results in abandonment of ponds (Bosma et al., 2012).

We quantified ecosystem carbon stocks in ten mangrove communities and ten abandoned shrimp ponds formed in mangroves across the Mahakam Delta (Fig. 1). The mangrove communities and abandoned shrimp ponds were polyhaline and mesohaline estuarine ecosystems (Mitsch and Gosselink, 2007) with soil pore salinity ranging from 13 to 25 ppt.

2.2. Field sampling and data analysis

Field measurements closely follow methods outlined in Kauffman and Donato (2012). Carbon stock measurements were conducted by establishing a linear transect that contained six plots of 7 m radius (0.0154 ha) at each site. Each transect was 125 m in length with plots established every 25 m. The transects were positioned randomly and perpendicular to the marine or river ecotone. We estimated tree biomass by measuring tree diameter at 1.3 m height (diameter at breast height) or 30 cm above the highest prop roots for *Rhizophora* spp. Above and belowground biomass of the trees were estimated using species specific allometric equations (Table A). Standing dead wood and downed wood were measured according to the methods outlined in Kauffman and Donato (2012).

Soil carbon pools were collected at the six plots at each site. We measured the soil depth utilizing an open-face peat auger of 6.4 cm radius around the plot center (Kauffman et al., 2014). The soil C stocks were measured by collecting soil samples at the following depths: 0–15 cm, 15–30 cm, 30–50 cm, 50–100 cm and 100–300 cm (Kauffman and Donato, 2012). At each depth interval, a 5 cm sub-sample was collected for laboratory analysis of bulk density and carbon concentration. Soil porewater salinity and pH were measured at each plot.

Mangrove conversion to shrimp ponds has resulted in soil compaction/collapse, thus resulting in increased bulk density and decreased soil porosity (Batey and McKenzie, 2006; Germer et al., 2010). As such, there would be more soil mass in the top 3 m of soils in the abandoned ponds compared to mangroves. Hence, a more realistic comparison would include differences based upon the equivalent soil mass in mangroves and shrimp ponds rather than volume. Comparisons were based on the same mineral soil mass occurring in the top 3 m of soils in mangroves (Kauffman et al., 1998; Kauffman et al., 2015). Mineral soil mass was calculated through subtraction of the carbon density from the total soil bulk density. Soil C density (C_d) was calculated as soil bulk density multiplied by soil C concentration (Warren et al., 2012). The soil C stocks of shrimp ponds were then calculated based on equivalent soil mass of the adjacent mangrove forests. Similar methods had been applied to estimate C losses from conversion to cattle pastures in the Amazon and Mexico (Kauffman et al., 1998, 2015) and is a conservative estimation on carbon loss as it assumes there was no erosional losses from the site (Kauffman et al., 2015).

2.3. Ecosystem carbon stocks and potential emissions

The ecosystem carbon stocks were estimated by summing all carbon pools (IPCC, 2006; Eq. B.1). The potential emissions arising from mangrove conversion into abandoned shrimp ponds were calculated by stock-difference method to estimate emissions due to land use change (IPCC, 2006; Kauffman et al., 2015; Eq. B.2).

2.4. Land use carbon footprints of shrimp production

We determined the land use carbon footprint of shrimp produced from mangrove conversion in the Mahakam Delta using the approach described by Kauffman et al. (2017) (Eq. B.3). The total ecosystem C loss (C_{conv}) is the potential CO_2 emissions arising from mangrove conversion to shrimp ponds calculated using stock difference method (IPCC, 2006). N_2O emissions (eN_2O) from shrimp production during active use was assumed to be 1.69 g N_2O kg^{-1} of shrimp produced (Hu et al., 2012). The global warming potential (GWP) of N_2O was assumed to be 298 (Myhre et al., 2013). Therefore, the N_2O emissions from shrimp production during active use is equal to 503.6 g CO_2e kg^{-1} of