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Integrating livestock production with crops and saline fish ponds to reduce greenhouse gas emissions

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Extensive grazing systems in the tropics have large greenhouse gas (GHG) emissions. Here an integrated cropping, livestock farming and saline pond aquaculture system is described which also reduces GHG emissions in tropical farming. The system was developed in the 1980s in the central Philippines and is re-evaluated in terms of its potential to reduce emissions from livestock production, particularly in wet and wet-dry tropical regions. The estimated cumulative annual GHG emission savings amount to 12.9 tonne CO_2-e per head of cattle exiting the integrated feedlot system after 300 days. Use of silage from crop by-products and implementation of a feed-lot programme enabled immediate and significant reductions of GHG emissions over extensive cattle grazing. Integration with a saline animal waste processing pond allowed production of natural feed products, cyanobacteria algal mat for use in aquaculture, as crop fertiliser and soil amendment or in the silage manufacture process. Fish production from ponds receiving the harvested algal mat resulted in an annual average of 3300 kg/ha compared to an average 700 kg/ha in inorganic fertilised ponds. The unitised ratios for the integrated system were respectively: 1 ha sugarcane: 4 head of cattle: 0.13 ha saline waste processing pond. Stoichiometrically, bio-processing of waste material in saline ponds provides a novel solution to GHG emissions from feedlots. It uses a multi-step process dominated by cyanobacteria mats in which all the captured liquid and solid waste is passed through fermentation and a mixed aerobic and anaerobic photosynthesis/photosynthesis and mixed aerobic/anaerobic sulphate reduction pathway to use organic wastes and also reduce GHG emissions. Sulphate is reduced and sequestered as iron sulphide eliminating the potential for harmful sulphide emissions. Calcium carbonate precipitation in the cyanobacteria mats results in significant sequestration of carbon. The process produces organic feed matter with a three-fold increase in nitrogen levels arising from nitrogen fixation in the treatment pond.

Keywords: fish farm; integrated farming; climate change mitigation; cyanobacteria mats; acid sulphate soil

1. Introduction

Meat production worldwide is projected to double from 229 million metric tons in 2001 to 465 million metric tons in 2050 and much of this is expected to occur in the tropics and subtropical regions (Steinfeld et al. 2006). The production of cattle, goats, sheep, poultry and pigs accounts for 70% of all agricultural land and 30% of

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the land surface of the planet. The livestock sector is responsible for 18% of greenhouse gas (GHG) emissions measured in carbon dioide equivalent (CO_2-e), a higher share than transport. It emits 65% of human-related nitrous oxide, a potent GHG, the majority from manure (Steinfeld et al. 2006). Approximately 98% of global GHG emissions from livestock manure occur as methane (IPCC 2006).

While there is a pressing need to improve agricultural productivity in rural areas of developing countries while minimising GHG emissions, it needs to be considered in the context of practicality, profitability and sustainability. This article describes an integrated bio-processing waste treatment system using crop, livestock and saline water fish production developed in the mid 1980s at Sycip Plantation in the central Philippines that can be used for abatement and mitigation of GHG emissions from grazing animals and whole-of farm processes. The estimated cumulative annual GHG emission savings on an entire farm budget amount to 12.9 tonne CO_2-e per head of cattle exiting the integrated feedlot system after 300 days.

The approach used at Sycip Plantation was innovatory in terms of both the use of salt water ponds and the integrated system's potential for large productivity increases using local crops and by-products as well as agricultural wastes from one component of the Plantation as inputs to a subsequent component of the system. The system generated significant employment opportunities for over 400 poor rural families and resulted in the Sycip Plantation becoming the highest earning agri-business enterprise in the central Philippines. The system developed had over 40,000 poultry layers, 200 head of feedlot cattle, 500 ha of sugarcane, 400 ha of cropping and grazing and 200 ha of milkfish production ponds which yielded close to 3 tonne of fish per hectare per year, about eight times greater than the national average. Here we also demonstrate that the system offers significant opportunities to reduce GHG emissions by using a closed loop integrated approach utilising agricultural wastes from one component of the system as inputs to another component.

The broad aims of the article are to describe the integrated livestock farming, croppping and saline pond aquaculture system, as well as the quantitative improvements it can provide in farm productivity while reducing GHG emissions in tropical farming regions. Its more specific objectives are to:

(1) Quantitatively describe the functional components and thee respective inputs and outputs of the integrated system for sugarcane, cattle feedlot and fish production respectively, in the integrated system;
(2) Compare the milkfish yields from aquaculture ponds in the integrated system with those produced under "normal" fertilisation regimes at the farm; and
(3) Use first principles stoichiometery and mass balance to estimate potential reduction in some components of the GHG emissions from beef and sugarcane production using this integrated system.

2. Context

2.1. *Milkfish production in the Philippines*

In the Philippines approximately 195,000 ha of predominantly mangrove wetlands were converted to fishponds during the 20th century for the farming of milkfish, *Chanos chanos* Forskal. This involved clearing of native vegetation, until it became illegal in 1980, and enclosing the cleared area by construction of bunds and installation of tidal control gates. Typically, prior to construction of fishponds, these landscapes had large areas of algal mats dominated by cyanobacteria in the upper intertidal zone and lower in the intertidal zone by mangrove assemblages.

Prior to conversion to fishponds, the benthic habitat in this intertidal zone was reliant on large natural organic carbon inputs and nutrient re-cycling, dominated by sulphate reduction, to carry out their critical ecosystem function in terms of food chain outwelling (Odum 1980) and trophic relay for coastal marine food webs (Kneib 2000). Given this prior landscape-scale food web system, it is not surprising that organic carbon inputs, correctly applied, improve milkfish yields in fishponds. For example milkfish net production was found to average 320 kg/ha/90-day crop in inorganically fertilised ponds, 545 kg/ha/90-day crop for cow manure and 820 kg/ha/90-day crop in duckweed-fertilised ponds (Ogburn and Ogburn 1994).

A conventional technique for milkfish production in the Philippines involves the application of organic carbon inputs, typically animal manures, to the pond bottom prior to the stocking of fish fry. This is done to stimulate the growth of cyanobacterial algal mats, locally termed *lab lab*, a favoured food of milkfish. However, acid sulphate soils, which are present in approximately 60% of the area converted to milkfish ponds in the Philippines (Tang 1979) are a major factor limiting national production yields in traditional milkfish pond systems (Chong et al. 1984). Successful long-term remediation programmes involve the tillage of the pond surface (<10 cm depth) sediments with significant organic carbon enrichment.

Remediation consequently needs large quantities of cheap and locally available animal manures or other suitable organic carbon inputs to sustainably and profitably increase milkfish production yields in these saline fishponds. In order to directly address the need for organic carbon inputs to improve production yields from a 200 ha milkfish farm operation at Sycip Plantation located in Negros Oriental, Philippines (see Figure 1) an integrated system of crop and livestock production coupled to bio-processing of animal waste for production of natural milkfish feed developed in the mid 1980s (Ogburn et al. 1986). The system is illustrated in Figure 2.

2.2. *Challenges and opportunities in a developing rural environment*

At the time the integrated farming project commenced in 1983, the Sycip Plantation was facing bankruptcy due to low world sugar prices. Sugar provided over 90% of the farm income. Dire poverty existed in the surrounding community with a local workforce of almost 2000 workers the majority (85%) of whom had been recently displaced because of the introduction of tractors for ploughing the sugarcane fields. It was thus imperative to address the deficiencies and capitalise on local opportunities.

The deficiencies included:

(1) Rangeland feeding on unimproved "grasslands" in the surrounding hills was haphazard;
(2) Dry-season weight loss of rangeland cattle was occurring due to deficient feed;
(3) Burning of the sugarcane crop prior to harvesting was a routine practice;
(4) Cane-tops were not being processed for fodder storage;
(5) Low fishpond yields due to acid sulphate soils and huge deficiencies in organic carbon; this organic carbon was previously supplied to the natural ecosystem by inter-tidal mangrove habitat;

Figure 1. Sycip plantation fish pond location on Bais Bay, Negros Oriental, Philippines.

(6) Massive levels of un-employment, acute poverty and major nutritional deficiencies for poor families in the region.

The opportunities included:

(1) Sugarcane was the predominant crop and highly suitable in poorly developed tropical high rainfall regions because it is relatively low technology and low input, low maintenance and low risk, productive with high biomass yield, reliable and robust crop;
(2) Identification of local crops, by-products and other materials available locally that were suitable for cattle feeding;
(3) Manual harvesting of unburnt cane at a premium price was supported by the workers and enabled silaging of cane-tops;
(4) Opportunity for locally constructing purpose built feed processing machinery;
(5) Development of cheap silaging methodology and storage systems;

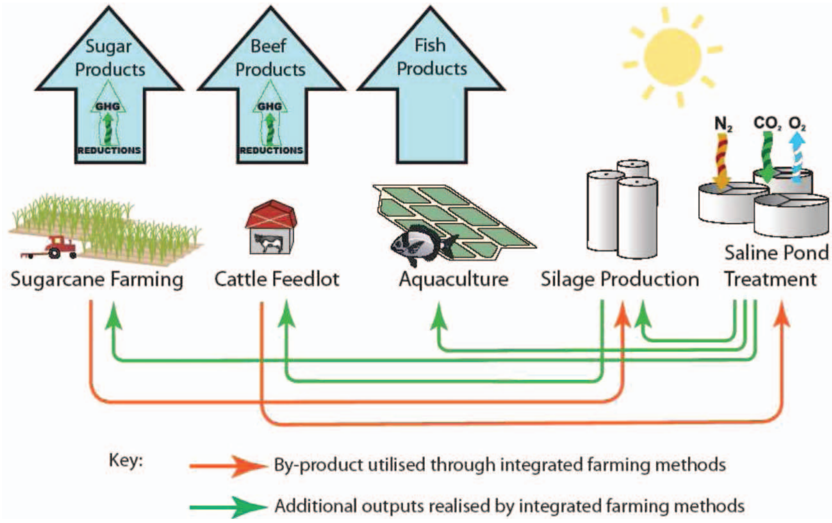

Figure 2. Schematic of the integrated farming system to improve saline fish pond yields and lower GHG from extensive grazing systems in tropical and subtropical regions.

(6) Development by the author of algorithms for computer programme for linear least cost feed formulations of concentrates for poultry and cattle;
(7) Development of egg laying poultry system using local products;
(8) Poultry manure provided a high-level nitrogen source for silaging and concentrate ingredient for cattle;
(9) Large areas of marine fish ponds requiring large amounts of organic fertiliser and providing evaporative cooling and enhanced biosecurity to livestock enclosures;
(10) Cheap and abundant labour and market for cheaper protein products such as eggs.

2.3. Animal production and greenhouse gas emissions

Life cycle assessments for GHG emissions from beef livestock systems attempt to quantify the important environmental impacts of all processes involved in a production system (Peters et al. 2010). Published estimates vary for CO_2-e per kg of beef. A review of life cycle assessments for beef production under a range of feedlot and grazing conditions around the developed world found that published estimates varied from 19 to 46 kg CO_2-e per kg of beef with an average of 32 kg CO_2-e per kg of beef in live weight terms (Peters et al. 2010). The association between feed characteristics and feed intake is pivotal to the effects of general nutrition on methane emissions (Beauchemin et al 2008). Slow growth rates of cattle due to forage feeds with poor digestibility (low metabolisable energy) greatly affect the overall efficiency of the system in terms of GHG emissions per kg of meat produced. It is also well established that increasing the level of concentrate in the diet reduces the proportion of dietary energy converted to methane (Blaxter and Clapperton 1965) and also improves animal performance (Beauchemin et al. 2008). The reduction in methane production with increasing level of intake above maintenance levels is associated with decreasing rumen residence time and decreased ruminal fermentation (Mathison et al. 1998).

3. Methods

3.1. Methods used in the integrated farming system

A cattle feedlot trial (Figure 3) was established adjacent to an existing tidal saline milkfish pond system at Sycip Plantation Inc., and run for two cycles, each of 1 year duration. A schematic of the system is shown in Figure 2. This farm consisted of approximately 200 ha of milkfish ponds converted from mangrove wetlands in the 1960s; 500 ha of productive coastal sugarcane lands and an additional 400 ha of crop and grazing land in the adjoining hills. Cattle were sourced from range lands in the hinterland of the plantation early in the dry season (December) before the onset of rate of weight-gain loss, typical of extensive tropical livestock production systems (Landers 2007). The beginning of the dry season coincides with the start of the sugarcane harvesting season. The feedlot operated on complete harvest of cattle, shut-down for maintenance and cleaning, followed by complete restocking at one time to enhance biosecurity measures. Cattle were weighed individually at the beginning and end of the trial.

The feedlot required large quantities of cane-top based silage for the 30 cattle involved in each feed-lot trial. Cane was manually harvested green and the cane-tops sent directly to the silage processing site. Ferro-cement silos were constructed for proper storage of silage, adjacent to the feedlot. Silage production of cane-tops required discontinuing burning of sugarcane as part of the cane harvest procedures; this was a major step in the history of the plantation and the region. Negotiations were undertaken with cane cutters to contract harvest at a premium price. Green harvest provided opportunity for additional employment in the harvesting and processing job steps. Other ingredients used in the silage process included corn stalks, molasses, duckweed (Ogburn and Ogburn 1994), chicken manure and urea.

A variety of traditional and novel local products were also evaluated for suitability in cattle concentrate mix. This included poultry manure, rapidly dried to

Figure 3. Trial feedlot for cattle at Sycip Plantation.

reduce nitrogen losses, from the egg layer project built over fishponds; cerithid snails which were an abundant pest in the fishponds; cassava and copra from plantings at the edge of the sugarcane fields; corn bran as a by-product of corn grits for human consumption; molasses from the local sugar mill.

Feedlot cattle were fed silage (approx. 63% moisture) and supplemented with a concentrate mix. Feed formulation was balanced to optimise nutrient density with a calibrated cost-benefit weight gain computer model. Cattle were fed a daily concentrate ration based on estimated body weight; silage was fed to satiation. The weight of concentrate and approximate weight by volume of silage fed each day were recorded throughout the trial. Mass balance estimates were used to establish dry-weight equivalent of waste coming from the feedlot.

The feedlot stalls were washed daily with seawater and all liquid and solid wastes were discharged directly to a saline waste processing pond (SWPP). The SWPP formed part of a 20 ha integrated fishpond system (Jumalon and Ogburn 1987). Water depth in the pond was approximately 0.5 m deep. Seawater was added tidally to the SWPP as required during high evaporation periods. Salinity in the pond was generally above 60 ppt and pH was always above 8.0 (Jumalon and Ogburn 1987). There was no discharge from the SWPP, except surface run-off of freshwater during high rain periods. Finfish were completely absent from the SWPP and naturally recruited zooplankton (and *Artemia* sp) assisted in maintaining a clear water column.

In the saline pond bio-processing system used here, benthic microbial mats are formed by filamentous entangled micro-organisms that regularly lift off the sediment in large coherent pieces less than 5 mm thick (Figure 4). These mats consist of dense micrometre scale communities in which the full plethora of microbial metabolism can be present (Stal 2000). The predominant metabolism is oxygenic photosynthesis, using the sun's light source as energy, water as an electron donor and CO_2 as carbon source (Stal 2000). However, light is strongly attenuated in the surface layer of the mat. As a consequence all species of cyanobacteria in microbial mats are capable of fermentation. This is essential for life in microbial mats in which environmental conditions strongly fluctuate (Stal 2000). Acetate and other products formed during

Figure 4. Daily production of '*lab lab*' from the waste processing pond.

fermentative degradation of the organic matter may therefore also undergo anaerobic oxidation in the lower strata of the mat, by several genera of sulphate-reducing bacteria (Pfennig and Widdel 1982) as indicated by the presence of black iron monosulphide on the bottom of the mats.

Floating microbial mats of *lab lab* were harvested daily from the downwind corner of the SWPP (Figure 4) by scoop nets and loaded in woven baskets for transport. The material was used as feed in adjoining fish ponds and surrounding fish farms. Daily volume of the harvested *lab lab* was recorded as number of baskets and computed in terms of dry-weight equivalent. Proximate analysis of the feedlot waste and the *lab lab* was undertaken periodically during the trial.

3.2. Cyanobacteria-sulphate reduction pathway

In the saline pond bio-processing system described here, benthic microbial mats are formed by filamentous entangled micro-organisms that regularly lift off the sediment in large coherent pieces less than 5 mm thick. These mats consist of dense micrometre scale communities in which the full plethora of microbial metabolism can be present (Stal 2000). The predominant metabolism is oxygenic photosynthesis, using the sun's light source as energy, water as an electron donor and CO_2 as carbon source (Stal 2000). However, light is strongly attenuated in the surface layer of the mat. As a consequence all species of cyanobacteria in microbial mats are capable of fermentation. This is essential for life in microbial mats in which environmental conditions strongly fluctuate (Stal 2000). Acetate and other products formed during fermentative degradation of the organic matter may therefore also undergo anaerobic oxidation in the lower strata of the mat, by several genera of sulphate-reducing bacteria (Pfennig and Widdel 1982) as indicated by the presence of black iron monosulphide on the bottom of the mats.

Overall, two moles of organic carbon are oxidised to carbon dioxide for every mole of sulphate reduced (Jorgensen 1977). The mineralisation of other elements in organic matter is stoichiometrically related to the mineralisation of carbon at pH less than 7:

$$SO_4^{2-} + 2(CH_2O) + 2H^+ = H_2S + 2CO_2 + 2H_2O\,. \tag{1}$$

The use of seawater in the treatment pond, its pH above 8, and the consumption of hydrogen ions in Equation (1) mean that the CO_2 produced in this reaction will be mostly present as bicarbonate. In freshwater environments, sulphate concentrations are usually much lower than in saline water and this often limits the rate of sulphate reduction in freshwater aquatic sediments. In the absence of sulphate, methanogenesis is the dominant process of organic matter degradation in anoxic sediments. Methane is also rapidly oxidised in the presence of sulphate. The net result is that methane fluxes from sediments are inversely correlated with sulphate concentrations in aquatic environments. As a correlative, flooded freshwater rice paddies are major sources of methane to the world's atmosphere (Miyata et al. 2000).

Cyanobacteria, particularly *Oscillatoria* sp., are the principal primary producers in the microbial mats in the system studied here. The dense mass of cyanobacteria in the upper photic zone of the microbial mats results in high rates of photosynthesis and on a surface basis the productivity we have reported for the bio-processing system, approximately 62 kg C/ha/day, within the organic matter produced, is similar to the high rates reported by Stal (2000) in naturally occurring saline cyanobacteria mats. This rate is double the productivity reported for tropical rainforests (Malhi et al. 1998), considered as the most productive ecosystems on Earth. In addition we report that over 63% dry weight of the microbial mat consists of $CaCO_3$, indicating additional carbon sequestration of approximately 21 kg C/ha/day in the process.

Cyanobacteria use a variety of nitrogen sources including ammonia, several amino acids, nitrite and nitrate. They can also use nitrogen directly. All steps of the nitrogen cycle may be present in the microbial mat in which cyanobacteria play a particularly important role (Stal 2000). Non-heterocystous aerobic nitrogen fixing cyanobacteria such as *Oscillatoria* sp. are capable of inducing nitrogenase activity under anoxygenic conditions. Stal (2000) reports that saline cyanobacteria mats typically demonstrate a temporal separation of nitrogen fixation and photosynthesis activity over night and day respectively. Our results, based on mass-balance computations, demonstrate that nitrogen fixation is occurring in the system.

Microbial mats, when conditions allow, precipitate minerals, mainly calcite (Stal 2000) as has been found here. In the presence of dissolved iron, common in seawater, sulphate reduction is buffered by the precipitation of iron sulphide and this ensures alkaline conditions prevail. Iron sulphide is deposited on the pond bottom as a consequence of sulphate reduction. As a consequence, conditions are suitable for calcium carbonate precipitation within the microbial mat and this is demonstrated here by the high-calcium carbonate content of the harvested microbial mat.

3.3. *Calculation of GHG emissions*

The Intergovernmental Panel on Climate Change (IPCC) publishes internationally accepted inventory methodologies that serve as a basis for GHG inventories, ensuring that they are comparable and understandable (IPCC 2006). The development of guidelines for consistent methodology in calculating life cycle GHG emissions of goods and services has been a major international objective (British Standards (BSI) 2008). However, an objective of this study is not to present a life cycle GHG emissions inventory for whole of farm processes but to identify the potential GHG emissions savings that the system described here can potentially achieve, using first principles stoichiometry and a mass balance approach in the absence of available emission factors, to show the benefits of a closed loop approach which uses agricultural wastes from one part of a farming landscape as inputs to a

Table 1. Indicative unitised values for each phase of the integrated production system showing the annualised inputs and outputs in the system.

Unit	Input	Output	Net increase
Sugarcane (1 ha)	N.A.	8.5 tonnes cane-tops	
Silage unit	N.A.	8.4 tonnes	
Cattle[a] (4 head)	860 kg (live wt.)	1640 kg (live wt.)	780 kg (live wt.)
SWPP pond[a] (0.13 ha) – Biomass	4800 kg	13920 kg	9120 kg
SWPP pond – $CaCO_3$	17.2 kg	10161 kg	10143 kg
SWPP pond – Nitrogen	84.5 kg	307.2 kg	222.7 kg

Notes: Values in dry weight unless specified and unitised to SWPP of 0.13 ha.
[a]SWPP pond operational for 300 days.

Table 2. Indicative unitised values for each phase of the integrated production system functional unit showing the potential GHG emission savings.

Phase	Unit	Annual GHG emission savings (tonne CO_2-e)
Green cut sugarcane	1 ha	34
Feedlot cattle	4 head	5
SWWP pond	0.13 ha	12.5
Fish	3.3 tons	–

subsequent phase of the integrated farming system. Consequently the computation of GHG that are mitigated or sequestered in the integrated farm system included only the following components:

- GHG emissions from pre-harvest burning of sugarcane include CO_2, CH_4 and N_20 and are estimated to be an average of 33 tonne CO_2-e./ha/yr (Weier 1998)
- GHG emissions for manure are estimated using beef stocker estimates for methane and N_20 from manure of 6.5 kg CO_2-e./kg live weight gain (IPCC 1996; Phetteplace et al. 2001)
- Computations for carbon sequestered in *lab lab* were based on harvest records and proximate analysis.

The basis for this integrated system analysis, called the ''functional unit'' (FU), is defined in the following relationship:

$$\text{FU} = \text{Area of sugarcane: Per nos. of cattle: per area of SWPP.} \tag{2}$$

The trials were conducted to quantitatively determine the relationship of this FU.

4. Results

Cane production on the plantation averaged approximately 90 tonne/ha with additional 30 tonnes/ha of cane-tops. Average weight of feedlot cattle at the start of the trial was 215 kg. The cattle consumed approximately 4 kg dry weight material/100 kg body weight per day during the 300 day feedlot trial. This included an approximate average of 3.5 kg/day of concentrate and 15 kg/day (wet weight) of silage. Weight gain was approximately 0.65 kg/day and the target average weight of the cattle at the end of the trial was 410 kg.

The SWPP received feedlot waste at approximately 100 kg dry weight/ha of pond/day. Feedlot waste had an average dry basis proximate composition of 11% crude protein, 35% crude fibre, 2.5% ether extract, 12% ash and 39.5% nitrogen free extract. The microbial mat harvested daily from the SWPP averaged 2.2 tonne wet-weight; 290 kg dry weight; 73% ash (predominantly $CaCO_3$) and approximately 40 kg of protein on a dry weight and ash-free basis (Ogburn et al. 1986). Input–output ratios for the process demonstrated more than a three-fold increase in crude protein output.

Fish production from ponds receiving the harvested *lab lab* in the livestock production trials resulted in an annual average of 3300 kg/ha compared to an average 700 kg/ha in the inorganic fertilised ponds (Ogburn et al. 1986; Ogburn and Ogburn 1994).

The quantitative relationship of the FU defined in Equation (2) was:

$$FU = 1 \text{ ha sugarcane: 4 head of cattle: 0.13 ha SWPP.} \tag{3}$$

The gross input and output results for the FU are presented as weights in Table 1.

The functional unit was used to calculate estimated GHG emission savings for each component of the FU, presented in Table 2, using data from:

- mitigation of GHG emissions from sugarcane by harvesting green (Weir 1998)
- mitigation of GHG emissions from cattle manure due to SWPP (IPCC 1996)
- sequestered GHG in the SWPP computed by analysis of organic matter and $CaCO_3$.

The resultant estimated mass balance of GHG emission saving for the FU is 51.5 tonne CO_2-e for each cycle of the feedlot. This can also be calculated as 12.9 tonne CO_2-e head of cattle exiting the feedlot with a target weight of 410 kg.

5. Discussion

As discussed earlier the fish ponds at Sycip Planatation were built in an area that had previously been an intertidal mangrove area and the soils were identified as largely acid sulphate. Remediation and improved yields of fish required large quantities of suitable organic carbon inputs on an ongoing basis. The large biomass residue available from the annual harvest of sugarcane was a key driver in developing this integrated system to provide an organic carbon source for fishponds. Methods for storing cane-tops by silaging were introduced to enable year-round cattle feedlot operations.

Advances in silage manufacture and microbiology (e.g. Mühlbach 1999; Park et al. 2005) coupled with cheap and portable low-cost plastic-wrap baling methods offer significant scope for process engineering improvements in silage manufacture and storage in developing countries. Ruminants consuming forage can only eat more if the rate at which feed is cleared from the rumen increases. This is a rate limiting phenomenon known as "rumen-fill" (Hegarty 2001). In the system described above, the feed was chopped and pre-processed as silage, to increase digestion and facilitate rapid passage through the rumen. The silage process also improves digestibility and overall nutrient content. Consequently, composition of the feedlot diet can be tailored to minimise "rumen-fill" as a rate limiting process. In the operation we describe, the economics of the whole system was considered in tailoring the composition of the diet.

As discussed earlier, the objective of this study is to show the benefits of a closed loop approach to farming which uses agricultural wastes from one part of a farming landscape as inputs to a subsequent phase of the integrated farming system. An important and enabling linking feature of the integrated system described here is the bio-processing features of the SWPP component of the FU. Pollution from feedlot wastes is largely eliminated through its use in fish pond preparation and the SWPP. The ponds used for milkfish production in this system are typical of fertile extensive earthen aquaculture ponds in having a net positive gross oxygen production (Szyper and Rosenfeld 1992) and hence have not been considered in the calculation of GHG emissions.

The production of cyanobacteria mats (*lab lab*) prior to the stocking of milkfish ponds is considered a pre-requisite for success in extensive milkfish pond-production systems in the Philippines. Large amounts (up to 3 tonne/ha) of organic matter are required to ensure this occurs. However during the latter stages of the pond production cycle, standing stock of *lab lab* in the growing pond is often diminished. Supplemental feeding of *lab lab* at this stage further ensures that good growth of milkfish is maintained until harvest. The integrated system described here provides an organic fertiliser source (manure) for fish pond preparation and also a supplemental source of *lab lab* harvested from the SWPP.

Additional benefits in the process we describe include:

(1) The nitrogenous compounds in feedlot waste are conserved. Ammonia volatisation is minimised and denitrification, leading to emissions of the potent GHG nitrous oxide (N_20), is largely eliminated.
(2) Our measurements of the system process suggest a three-fold increase, based on mass-balance calculations, in nitrogen content arising from the resultant solid material harvested from the saline pond. This suggests that direct atmospheric fixation of N_2 by cyano-bacteria in the *lab lab* microbial mat complex is occurring.
(3) Additional sequestration of carbon is achieved in the system via the facilitation of cyanobacteria-induced precipitation of calcium carbonate, aided by the buffering effect of sulphide precipitation with iron present in the SWPP.

The use of silage as a major portion of cattle feedlot ration is a major step in improving sugarcane crop production practices by conserving carbon in organic solid form and consequently reducing GHG that occur when cane is burnt prior to harvesting. Appropriate feed-lotting processes, using moderate energy-dense feeds sourced from crop residues can also directly tackle landscape impacts including deforestation, erosion, land degradation and loss of biodiversity all of which can adversely impact GHG levels.

This integrated system can improve economics and efficiency of livestock production systems in tropical developing countries where much of the anticipated increase in livestock production during the next decades is expected to occur (Steinfeld et al. 2006). The system is also available at low capital cost using local materials. It is not complex and the technology can be readily implemented in suitable seasonally dry-land areas where saline water (including inland aquifers) is available. Additional benefits in the system include improved hygiene in the feedlot with daily washing using saline water; minimal use of freshwater; minimal odour problems; reduction in ammonia volatisation; improved biosecurity features particularly in relation to sanitation, rodents, venomous species and a range of potential pathogenic carriers. In addition, co-location of feedlots with a pond system enables architectural designs that enhance evaporative cooling effects within the feedlot enabling the animals to remain relatively cool in a tropical climate and protected from adverse climate conditions.

6. Conclusions

The system described in this article presents a novel integrated approach for livestock and crop production and saline pond aquaculture using a closed loop utilising agricultural wastes from one component of the system as inputs to another component. It has broad potential application and future opportunity for adaptation and refinement and is particularly suited to developing countries in tropical regions such as those widely distributed across Asia-Pacific, the Americas and Africa. Its great advantage lies in providing a very significant incentive for increasing farm productivity and profitability while achieving reductions in GHG emissions over traditional farming systems. Importantly, it also provides an important social contribution by providing a range of income generating opportunities for poor rural communities.

Collection and use of the floating microbial mat produced in the SWPP may require engineering improvements where labour costs are a significant factor. Alternative uses for *lab lab*, apart from fish farm food also need to be considered. This includes possible use as a soil amendment for crops or in the silage production process. The material offers an enriched nitrogen and lime source for enhancement of the ensilage process. Periodic maintenance procedures for the SWPP bottom, to deal with accumulation of iron sulphide and other materials, also need to be considered.

In addition to its potential for livestock production, the system provides remote rural communities with technology that can directly and effectively address key GHG emission issues facing the sector. The estimated total cumulative annual GHG emission savings amount to 12.9 tonne CO_2-e per head of cattle passed through the feedlot for 300 days. The system is not limited to coastal areas but could be implemented in areas where artesian reserves of saline water, with adequate sulphate and iron content for on-going sulphate reduction and iron sulphide production, occur.

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