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A Framework for Estimating Greenhouse Gas Emissions from Brazil's Amazonian Hydroelectric Dams

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Abstract Estimating the greenhouse-gas emissions from hydroelectric dams is important as an input to the decision-making process on public investments in the various options for electricity generation and conservation. Amazonian dams often have large drawdown zones on which soft easily-decomposed vegetation grows quickly when the water level in the reservoir falls. This vegetation decomposes each year at the bottom of the reservoir when the water level rises, producing methane. The methane from drawdown-zone vegetation represents a permanent source of this greenhouse gas, unlike the large peak of emission from decomposition of initial stocks of carbon in the soil and in the leaves and litter of the original forest. The turbines and spillways draw water from below the reservoir's thermocline, releasing a large part of the dissolved methane to the atmosphere. Carbon dioxide from decay of the above-water portions of trees in the forest that is flooded represents another significant greenhouse gas emission source in the early years after reservoir formation.

KEY WORDS: Amazonia, Brazil, Global warming, Greenhouse-gas emissions, Hydroelectric dams, Methane, Reservoirs

Hydroelectric Dams and Greenhouse-Gas Emissions

Decision-making on energy development requires a comprehensive assessment of the environmental costs and benefits of each alternative. While the benefit of hydroelectric dams in displacing fossil fuels burned by thermoelectric plants is widely known, their emission of greenhouse gases has received relatively little attention. Greenhouse-gas emissions are particularly high in tropical forest areas.

Hydroelectric dams in tropical areas such as Brazilian Amazonia emit carbon dioxide (CO₂) from above-water decay of trees that are left standing when the reservoirs are filled, and release methane (CH₄) from decay under anaerobic conditions near the bottom of the reservoir. Methane is released by various pathways, including surface bubbling and diffusion and release from water passing through the turbines and spillways. Soft, easily decomposed vegetation quickly grows in the drawdown zones of reservoirs. When the water level subsequently rises, this biomass decays on the bottom of the reservoir, producing methane.

Reservoirs are thermally stratified, with a boundary (thermocline) typically located at 2-3 m depth. The water temperature abruptly decreases below the thermocline, and water trapped below this layer does not mix with the surface water. This deep water (the hypolimnion) quickly becomes anoxic, and the soft vegetation from the drawdown zone that decomposes under these conditions produces methane (CH₄) rather than carbon dioxide (CO₂). A ton of CH₄ has 21 times more impact on global warming than a ton of CO₂ using the conversion factor (global warming potential, or GWP) adopted by the Kyoto Protocol (Schimel and others 1996), or 23 times more if the most recent value calculated by the Intergovernmental Panel on Climate Change (IPCC) is used (Ramaswamy and others 2001, p. 388). Per metric ton (megagram = Mg) of carbon released in each form, CH₄ has 7.6 times more impact than CO₂ when calculated using the GWP of 21.

The wood in the submerged trees is not believed to be a significant carbon source for methane production because lignified plant tissue (wood) decays extraordinarily slowly under anaerobic conditions. Trees are still usable as timber after several decades if they remain continually submerged, as is shown by the experience at Tucuruí, which was filled in 1984 and 20 years later is still the scene of disputes between various claimants engaged in exploiting the underwater timber stock. In contrast, soft, green vegetation decomposes quickly, thus releasing its carbon stock in the form of gases, some of which are released to the atmosphere.

The regrowth of vegetation in the reservoir's drawdown zone each year removes carbon dioxide from the atmosphere through photosynthesis, and re-emits the carbon in the form of methane when the vegetation is flooded. The reservoir therefore acts as a virtual methane factory, continually converting CO₂ to CH₄. The carbon source from the annual flooding of the drawdown zone is permanent, unlike the carbon from the original-forest leaves and leaf litter and labile soil organic carbon. These carbon pools decay over the first few years after the reservoir is filled. Macrophytes (water weeds), another source of easily decomposed biomass, decline to lower levels when the fertility of the water reaches a lower equilibrium after the initial nutrient flush that follows a reservoir filling. Hydroelectric-dam emissions are much higher during the first few years, both from CH₄ generated from underwater decay of soft biomass in the reservoir

and from CO₂ from decay of the above-water portions of the original forest trees left standing in the reservoir. Nevertheless, the continual supply of soft biomass from the drawdown zone and from macrophytes guarantees a certain level of permanent emission.

Previous estimates of greenhouse-gas emissions from Amazonian reservoirs have generally calculated emissions at a single point in time, such as 1990—the standard baseline year for national inventories of greenhouse gases under the United Nations Framework Convention on Climate Change (UN-FCCC) (Fearnside 1995, 2003, 2005a,b). One study has included the time path of emissions from decay of the original forest biomass (Fearnside 1997a). Methane emissions estimates have generally relied on the assumption that a directly measured concentration at one dam can be extrapolated to others of similar age. An explicit model of carbon stocks and degradation is needed in order to estimate emissions over time in a given reservoir and at reservoirs with different ages, water management and other characteristics. The model developed for this purpose is described in the following sections. In a separate paper, this model is applied to the specific case of the proposed Belo Monte (formerly Kararaô) and Altamira (formerly Babaquara) dams on the Xingu River (Fearnside manuscript). The information presented in the present paper is applicable to dams throughout the Brazilian Amazon and to other tropical regions with similar environmental conditions. The characteristics of each dam, however, will determine the amounts of greenhouse gases emitted by each pathway, and the net impact or benefit once fossil fuel displacement has been taken into account.

Carbon sources and Greenhouse-Gas Release Pathways

Methane

Methane produced by underwater decay can be released in various ways. One is by bubbling and diffusion through the reservoir surface. Bubbling, which allows CH₄ to pass through the barrier of the thermocline, is highly dependent on the depth of the water at each point in the reservoir, bubbling emissions being much greater at shallower depths. Diffusion is important in the first year, but not thereafter; this is because bacterial populations in the surface water (epilimnion) then increase, with the result that any methane diffusing through this layer is oxidized to CO₂ before it reaches the surface (Dumestre and others 1999, Galy-Lacaux and others 1997). The surface emissions are also higher in the first years after filling because the leaves and leaf litter from the original forest and the labile portion of the soil carbon is being released from the bottom of the reservoir as methane. These initial carbon stocks will decline as they are progressively exhausted and, in later years, carbon will only be available from renewable carbon sources such as macrophytes and the drawdown zone regrowth (as well as soil carbon entering the reservoir from upstream erosion).

Studies to quantify the relative role of different carbon sources are lacking. At the Petit Saut reservoir in French Guiana, Galy-Lacaux and others (1999) believe that soil carbon is the principal source in the first years. The stock of labile soil carbon is large relative to the other stocks of easily degraded carbon. The present calculation uses the labile (hydrolysable) soil carbon stock of 54 Mg C/ha measured in the top 60 cm of a typical Amazonian Ultisol (Trumbore and others 1990, p. 411). Assumptions

regarding the rate of decay of the stocks produce a theoretical total for the carbon released into the water as CH₄. Considering the dilution effect of inflows to the reservoir, the amount of anaerobically decomposed carbon per billion cubic meters of water can be calculated. This calculated amount has been derived for two existing tropical-forest reservoirs (Petit Saut and Tucuruí) and related to the CH₄ concentration in the water at a standardized depth (30 m) in the same reservoirs.

The amount of carbon decayed anaerobically is the sum of the portions decayed of original leaves and leaf litter, labile soil carbon, unbeached macrophytes and flooded drawdown vegetation. The amount of water is the reservoir volume at the end of the month plus the inflows during the month and the previous month. The relation of the amount of carbon decayed anaerobically (calculated according to the assumptions given above) to CH₄ concentration at 30 m depth is shown in Figure 1; concentration data are from Petit Saut (Galy-Lacaux and others 1999), with the exception of the point at the far left with 6 mg CH₄/liter at 30-m depth, which is from Tucuruí (J. G. Tundisi, cited by Rosa and others 1997, p. 43). The range of values for the amount of carbon decayed anaerobically is divided into three segments for calculation of CH₄ concentration at 30 m depth (equations 1-3).

[Figure 1 here]

For anaerobic decay ≤ 684.4 Mg C/billion m³ of water:

$$Y = 0.00877 X \quad (\text{eq. 1})$$

For anaerobic decay 684.5 – 15,000 Mg C/billion m³ of water:

$$Y = 0.000978 X + 6 \quad (\text{eq. 2})$$

For anaerobic decay $> 15,000$ Mg C/billion m³ of water:

$$Y = 20 \quad (\text{eq. 3})$$

Where: X = anaerobic decay (Mg C/billion m³ of water)

Y = CH₄ concentration at 30 m depth (mg/liter)

The ratio of the methane concentration at different depths to the concentration at 30 meters depends on the age of the reservoir, since the relationship changes over time as the bacterial populations in the surface waters become more capable of degrading methane to carbon dioxide. Data from the Samuel reservoir when five months old (J.G. Tundisi, cited by Rosa and others 1997, p. 43) are used to represent reservoirs up to 12 months after filling; data from Petit Saut (Galy-Lacaux and others 1999) are used to represent reservoirs from the 13th to the 36th month, and data from Tucuruí collected 44 months after filling (J.G. Tundisi, cited by Rosa and others 1997, p. 43) are used to represent reservoirs after month 36. The ratios are calculated using the equations in Table 1.

[Table 1 here]

Bubbling and diffusion emissions can be related to the concentration at the standardized depth of 30 m. Table 2 presents equations for these emissions for areas with different water depths. These relationships have been derived from the measurements at Petit Saut (Galy-Lacaux and others 1999). The predicted CH₄ concentration at 30 m depth is closely related to the observed bubbling emissions in each depth range in the Petit Saut data (0-3 m, 4-6 m and 7-8 m) (Figure 2a, b and c). Diffusion emissions at Petit Saut, independent of depth, are also closely related to the predicted CH₄ concentration at 30 m (Figure 2d).

[Table 2 and Figure 2 here]

For each month over a 50-year period a calculation is made of the area of drawdown zone that has remained exposed for one month, two months, and so forth up to one year, and a separate category is maintained for area of drawdown exposed for over one year. The area that is submerged in each age class is calculated for each month. This allows a calculation of the amount of soft biomass that is flooded, based on assumptions regarding the growth rate of the vegetation in the drawdown zone. The category for vegetation over one year old contains less soft biomass, as growth after the first year would be largely allocated to producing wood rather than more soft material (the leaf biomass of the forest is used for this category).

Macrophytes are an important source of soft, easily decomposed biomass. The populations of these aquatic plants explode to cover a substantial part of a new reservoir, as occurred at Brokopondo in Surinam (Paiva 1977), Curuá-Una in Pará (Junk and others 1981), Tucuruí in Pará (de Lima 2002), Balbina in Amazonas (Walker and others 1999), and Samuel in Rondônia (Fearnside 2005a). LANDSAT satellite imagery indicates that at Tucuruí macrophytes covered 40% of the reservoir surface two years after filling, subsequently declining to 10% a decade later (de Lima and others 2002). Based on monitoring at Samuel and Tucuruí, Ivan Tavares de Lima (2002) developed an equation (eq. 4) to describe the path of macrophyte cover, which is used in the present analysis:

$$Y = 0.2 X^{-0.5} \quad (\text{eq. 4})$$

where:

X = Years since flooding

Y = The fraction of the reservoir covered by macrophytes.

Macrophytes die at a given rate in the reservoir and the dead biomass sinks to the bottom. In *várzea* (floodplain) lakes, macrophyte death results in a turnover of the biomass 2-3 times per year (Melack and Forsberg 2001, p. 248); the midpoint of this range (4.8 months) implies that 14.4% of the macrophyte biomass dies each month. This rate has been adopted for macrophyte mortality in the reservoirs. In addition to this mortality, a part of the macrophyte biomass is beached when the water level falls. Because the prevailing winds (which blow from east to west) push the floating macrophytes against one shore, a part of the carpet of floating of plants is necessarily positioned where it will be beached whenever the water level descends. The quantities involved are impressive, as is evident at Tucuruí (see Fearnside 2001). Because macrophytes concentrate along only one shore of the reservoir, only half of the drawdown zone is considered in computing areas of beached macrophytes. When

beached, the macrophytes die and decay aerobically. However, if the water level rises again before the decay process is complete, the remaining carbon stock in beached macrophytes is added to the pool of underwater carbon that can produce methane. Here it is assumed that, if an area is exposed for only one month, then half of the beached macrophytes will still be present when these areas are re-flooded.

The macrophyte cover in Amazonian reservoirs undergoes a regular sequence of species succession, beginning with *Eichhornia* and ending with *Salvinia*, as occurred at Curuá-Una (Vieira 1982) and Balbina (Walker and others 1999). *Eichhornia* and other species that predominate in the early years have significantly greater biomass per hectare than *Salvinia*. At Balbina the replacement of higher-biomass macrophytes by *Salvinia* occurred between the seventh and eighth year after filling (Walker and others 1999, p. 252). The shift to *Salvinia* is assumed to occur seven years after reservoir filling. Floating macrophytes such as *Eichhornia* and *Salvinia* are most common in reservoirs, but some rooted species also occur.

For the first six years, the biomass of macrophytes is assumed to be 11.1 Mg/ha dry weight, based on an *Eichhornia* mat measured at Lago Mirití, a *várzea* lake near Manacapuru, Amazonas (P. M. Fearnside, unpublished data). For comparison, *Oryza* species (a rooted grass) in *várzea* lakes, had 9-10 Mg/ha of dry weight, while *Paspalum* had 10-20 Mg/ha (T. R. Fisher, D. Engle and R. Doyle, unpublished data cited by Melack and Forsberg 2001, p. 248). In another measurement in *várzea* lakes (where nutrient availability is greater than in many Amazon tributaries), nine measurements of rooted macrophytes in the *várzea* after approximately three months of growth averaged 5.7 Mg/ha (SD=1.7, range=3.2-8.7) (Junk and Piedade 1997, p. 170). The value of 11.1 Mg/ha is similar to values for floating and submerged macrophyte biomass in other parts of the world. For example, the submerged macrophyte load in Lake Biwa, Japan has 7-10 Mg/ha of dry biomass (Ikusima 1980, p. 856).

After the transition to *Salvinia* takes place the biomass per hectare of macrophytes is lower. The biomass value used in the calculation is 1.5 Mg/ha dry weight, which is the biomass of mats of *Salvinia auriculata* in *várzea* lakes (Junk and Piedade 1997, p. 169).

The methane in the water that is trapped below the thermocline will be exported from the reservoirs in the water drawn by the turbines and the spillway. This is a feature of hydroelectric dams that is completely different from natural water bodies such as *várzea* lakes, which are globally significant sources of CH₄ from surface emissions alone. Opening the intakes for the turbines and spillway is like pulling the plug in a bathtub—the water is drawn from the bottom, or at least from the bottom portion (hypolimnion) of the reservoir. Below the thermocline the concentration of CH₄ increases steadily as one descends through the water column. An important observation from Petit Saut is that, within a reservoir, the CH₄ concentration at a given point in time is approximately constant at any given depth below the surface—regardless of the depth to the bottom at the location in question (Galy-Lacaux and others 1997). The present analysis tracks the depth below the water surface of the spillway and turbine intakes in order to calculate the corresponding CH₄ concentration in the water released through these structures.

As one descends through the water column, the pressure increases and the temperature decreases. Both effects act to increase the concentration of CH₄ at greater depths. By Henry's Law, the solubility of a gas is directly proportional to the pressure, while Le Chatelier's Principle holds that gas solubility is inversely proportional to temperature. While both effects are important, the effect of pressure predominates (Fearnside 2004). At the proposed Altamira (Babaquara) Dam, for example, the pressure is almost five atmospheres at the 48-m turbine intake depth at the normal operating level. When the water emerges from the turbines, the pressure instantly drops to one atmosphere. Dissolved gases are released when the pressure drops, just as bubbles of CO₂ emerge immediately when one opens a bottle of Coca Cola. The pressure drop when a bottle of Coca Cola is opened is much less than the pressure drop when water emerges from the turbines of a hydroelectric dam, thus making the degassing even more immediate. The ease with which each gas comes out of solution is determined by the Henry's Law constant of the gas. This constant is higher for CH₄ than for CO₂, so the methane would also be released more readily than the bubbles from a bottle of Coca Cola for this reason. At Petit Saut, for example, the water entering the turbines in 1995 had a ratio of dissolved CO₂ to CH₄ of 9:1, but in the plume immediately below the dam the ratio was 1:1, meaning that proportionally much more of the dissolved methane had been released (Galy-Lacaux and others 1997).

Carbon dioxide

Unlike methane, carbon dioxide is removed from the atmosphere through photosynthesis when plants grow. The CO₂ released from decay of soft biomass that has grown in the reservoir and its drawdown zone therefore cannot be counted as a global-warming impact, as this is merely being cycled repeatedly between the biomass and the atmosphere. The biomass in the forest trees that were killed when the reservoir was created is a different matter, and the CO₂ it releases constitutes a net impact on global warming. Only the above-water portion of this biomass decays at an appreciable rate.

Above-water wood biomass is modeled in some detail, based on what is known from the experience at Balbina (which filled over the 1987-1989 period). Trees break off just above the high-water mark. By eight years after flooding, approximately 50% of the trees ≥ 25 cm in diameter and 90% of the trees < 25 cm in diameter had broken (Walker and others 1999). In addition, branches continually fall from the standing trees. Approximately 40% of *terra firme* (upland) trees float in water (see Fearnside 1997b). The trees that sink stay where they fall, either in the permanently flooded zone or in the shallower areas that are periodically exposed as the drawdown zone. Those that float are pushed by wind and waves to the shore and will be exposed to aerobic decay in the drawdown zone when the water level descends. The stocks and decay rates in each category are calculated. Aerobic decay contributes to the CO₂ emissions from above-water biomass. Parameters for the dynamics and aerobic decay of above-water biomass are given in Table 3.

[Table 3 here]

Another source of emissions is from trees near the edge of the reservoir that are killed when the water table rises and reaches their roots. At Balbina, a band of dead trees is evident all around the edge of the reservoir (Walker and others 1999). Because

the format of the shoreline is exceedingly tortuous and includes the edges of many islands created by the reservoir, this band of forest dieback encompasses a significant area. The dead trees decay, releasing CO₂, and over a period of decades secondary forest develops (with an attendant absorption of carbon). The present analysis assumes that mortality is 90% within 50 m of the reservoir edge and 70% if 50-100 m from the edge. Decay follows the same course as in areas felled for agriculture, while secondary forests are presumed to grow at the same rate as those in shifting-cultivation fallows (Fearnside 2000).

Pre-Dam Ecosystem Emissions

The emissions of ecosystems present before the dams were built must be deducted from the dams' emissions in order to have a fair evaluation of the net impact of the hydroelectric development. The idea that the forests flooded by the reservoir have large natural emissions of greenhouse gases has been a major component of the attack that the hydropower industry has mounted against studies indicating high emissions from hydroelectric dams. When early studies indicated that the Balbina Dam emitted more than would be released by producing the same amount of electricity from fossil fuels (Fearnside 1995), the US National Hydropower Association (USNHA) reacted with the statement:

“It’s baloney and it’s much overblown ... Methane is produced quite substantially in the rain forest and no one suggests cutting down the rain forest.”

This statement by Karolyn Wolf (spokesperson for USNHA) illustrates the vehemence with which this subject has been resisted (see IRN 2002). Hydro-Québec even went so far as to assert that large emissions from floodplain ecosystems in the areas flooded by hydroelectric dams could make the net impact of these projects a “zero-sum issue” (Gagnon 2002). Unfortunately, a closer examination of these arguments points instead to a major net emission from hydroelectric dams.

The parameters for methane emissions by unflooded forest are given in Table 4. These indicate a minimal effect on methane, with a small sink coming in the soil being lost to flooding. Nitrous oxide (N₂O) emissions from unflooded forest soil are small: 0.0087 Mg gas/ha/year (Verchot and others 1999, p. 37), or 0.74 Mg/ha/year of CO₂-equivalent carbon considering the global warming potential of 310 (Schimel and others 1996, p. 121). Nitrous oxide calculations for unflooded forest and flooded areas are given in Table 5. The calculations include the effect of temporary ponding on *terra firme* during periodic heavy rainfall events (Table 5).

[Tables 4 and 5 here]

For flooded areas, the assumption is made that each flooded point is submerged for an average of two months per year. Of course some parts of the area would be submerged for longer and some for shorter times, depending on the altitude of each point. The value used for emissions per hectare (103.8 mg CH₄/m²/day, SD=74.1, range=7-230) is the mean of five studies in white-water *várzea* forest reviewed by Wassmann and Martius (1997). A similar value of 112 mg CH₄/m²/day while flooded (n=68, sd=261) was found in blackwater flooded forests (*igapós*) along the Jaú River, a tributary to the Rio Negro Basin. In the *igapó* forests in the Jaú basin studied by

Rosenqvist and others (2002, p. 1323) the rate of methane emission from the flooded areas is much higher during the short period when the water level is falling than it is during the remainder of the time that the area is under water. This would tend to make the annual emission somewhat independent of the time period that the areas are flooded, and makes the result relatively robust for extrapolation to other river basins in Amazonia if expressed in terms of emission per flooding cycle (rather than per day flooded).

Uncertainties

The magnitude of the high seasonal peaks of CH₄ depend on the relationship between the amount of degradable carbon and the CH₄ stock (and concentration) when these variables were at high levels in the early years at Petit Saut (*i.e.*, data from Galy-Lacaux and others 1997, 1999). The nature of the carbon source at Petit Saut during this time was different (believed to be primarily soil carbon). The true amount of carbon degraded anaerobically at Petit Saut during this time is unknown, and the scaling that lends confidence to the results for the initial years after reservoir filling, when the carbon sources were of the same type, does not lend so much confidence to these results in later years. Quantifying the relationship between the amount of decay of soft biomass (such as macrophytes and especially drawdown-zone vegetation) and CH₄ production should be a top research priority. However, the general result, namely that drawdown vegetation produces a large and renewable pulse of dissolved CH₄ in reservoirs, is not in doubt. A case in point is the experience at the Três Marias Dam in the state of Minas Gerais, where a 9-m vertical fluctuation in water level results in exposure and periodic flooding of a large drawdown zone, with a subsequent large peak of surface emissions of methane (Bodhan Matvienko, personal communication 2000). Even at the very advanced age of 36 years, the Três Marias reservoir emits methane through bubbling in amounts that greatly exceed the surface emissions of all other Brazilian reservoirs that have been studied, including Tucuruí, Samuel and Balbina (Rosa and others 2002, p. 72).

Conclusions

The relationships derived here provide a framework for assessing the greenhouse-gas emissions of existing and planned hydroelectric dams in Brazilian Amazonia. Much of the information can also be applied to other tropical areas, although both the uncertainties and the need for additional location-specific information will be greater. The framework proposed here allows calculation of net emissions from major emissions pathways, such as methane from surface bubbling and diffusion and from turbine and spillway flows, and carbon dioxide from above-water decay of original forest biomass. These calculations indicate significant releases of greenhouse gases. Greenhouse gas emissions are greatest in the first years after reservoir formation, but continued carbon inputs such as annual decay of soft vegetation in the flooded drawdown zone mean that an appreciable level of emissions will be sustained over the long term.

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1-3620) provided financial support. An earlier version of these calculations will appear in Portuguese as part of the ongoing Brazilian debate concerning the Xingu River dams (Sevá forthcoming).

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FIGURE LEGENDS

Figure 1. Methane concentration at 30 m depth versus carbon decayed anaerobically. Concentration data are from Petit Saut (Galy-Lacaux and others 1999), with the exception of the point at the far left with 6 mg CH₄/liter at 30-m depth, which is from Tucuruí (J. G. Tundisi, cited by Rosa and others 1997, p. 43).

Figure 2. Bubbling and diffusion emissions versus predicted methane concentration at 30 m depth. Emissions data are from Petit Saut (Galy-Lacaux and others 1999). A.) Bubbling for locations 0-3 m in depth; B.) Bubbling emissions for 4-6 m depth; C.) Bubbling emissions for 7-8 m depth; D.) Diffusion emissions for all depths.

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Table 3: Parameters for reservoir emission from above-water biomass

Table 4: Avoided methane flux from forest loss

Table 5: Avoided nitrous oxide emission from forest loss

Fig. 1

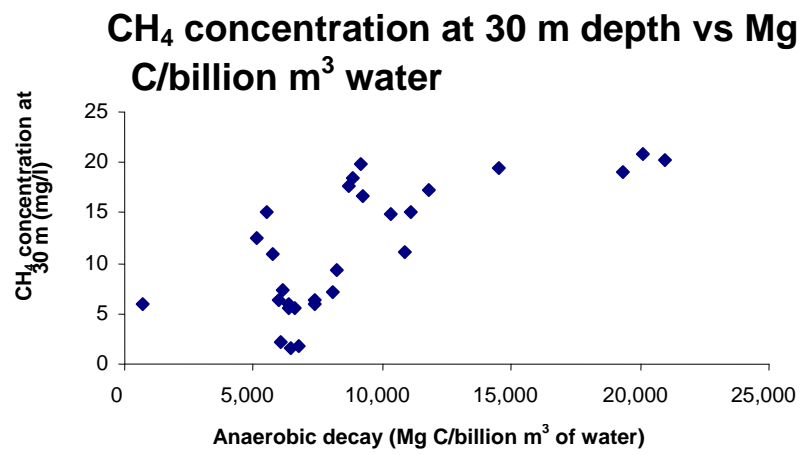


Fig. 2a.

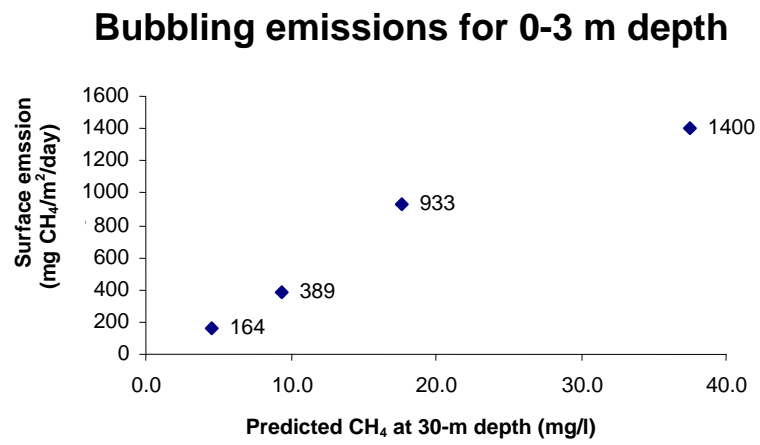


Fig 2b.

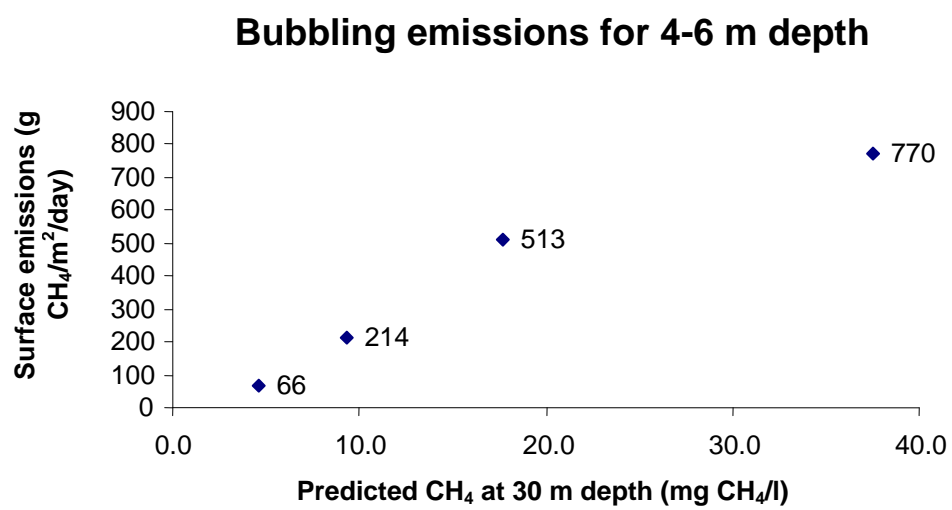


Fig. 2c.

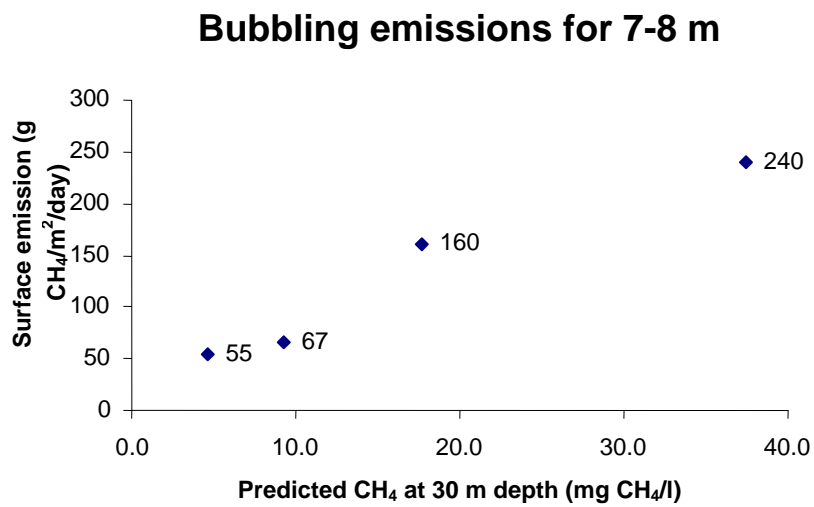


Fig. 2d.

