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Providing low-budget estimations of carbon sequestration and greenhouse gas emissions in agricultural wetlands

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Abstract

The conversion of wetlands to agriculture through drainage and flooding, and the burning of wetland areas for agriculture have important implications for greenhouse gas (GHG) production and changing carbon stocks. However, the estimation of net GHG changes from mitigation practices in agricultural wetlands is complex compared to dryland crops. Agricultural wetlands have more complicated carbon and nitrogen cycles with both above- and below-ground processes and export of carbon via vertical and horizontal movement of water through the wetland.

This letter reviews current research methodologies in estimating greenhouse gas production and provides guidance on the provision of robust estimates of carbon sequestration and greenhouse gas emissions in agricultural wetlands through the use of low cost reliable and sustainable measurement, modelling and remote sensing applications. The guidance is highly applicable to, and aimed at, wetlands such as those in the tropics and sub-tropics, where complex research infrastructure may not exist, or agricultural wetlands located in remote regions, where frequent visits by monitoring scientists prove difficult.

In conclusion, the proposed measurement-modelling approach provides guidance on an affordable solution for mitigation and for investigating the consequences of wetland agricultural practice on GHG production, ecological resilience and possible changes to agricultural yields, variety choice and farming practice.

Keywords: low-budget, carbon sequestration, greenhouse gases, agriculture, wetlands, remote sensing, measurement, modelling

1. Introduction

Agricultural wetlands considered in this paper include not only those wetlands that have been converted to agricultural activities (e.g. rice paddies) or support agricultural activities (such as reed beds, mangroves) but also those wetlands, either natural or agricultural, that may produce enhanced greenhouse gas (GHG) emissions following the addition of fertilizer products from adjacent agricultural land. Wetlands that may be converted to agriculture through drainage are also considered, as well as dryland that may be converted to agricultural wetlands by flooding.

While such wetlands are part of the global wetland biome, agricultural wetlands in Europe, North America and other developed regions are currently both researched and monitored by organizations able to supply adequate financial support and expertise to enable long term and sophisticated measurements of GHG emissions and develop complex models and Earth Observation (EO) sensors and platforms. This paper is not aimed at this community but utilizes the advances made by these organizations to provide the ability to measure and monitor GHG emissions where either expensive research facilities are absent or the agricultural wetlands are remote and not easily and frequently visited by research scientists.

The biophysical processes in wetlands are the most complex of all biomes in terms of GHG production and carbon balance as they involve equally important above and below ground dynamic interactions between carbon dioxide (CO_2), methane (CH_4) and highly mobile microbial communities in an often mobile liquid environment. Wetland agriculture, as in dryland agriculture, has the capacity, through its management, to control its production of GHGs (e.g. Lloyd 2006 (wetland management), Robertson *et al* 2000 (dryland agriculture)). This is especially true for rice paddies, which not only provide a vital food commodity, but are also potentially very important in either increasing or mitigating global GHG production. Equally, measuring and monitoring carbon balances and GHG production in agricultural systems is challenging due to changing and mixed vegetation cover, mechanical soil turnover and the often mosaic nature of many agricultural systems (e.g. rice paddies, especially terraced rice paddy systems, and recession agriculture in floodplain wetlands). Such a changing and fragmented environment poses measurement difficulties for methods that rely on extensive areas of monoculture for the correct interpretation of measurements including eddy covariance and remote sensing methods.

The past decade has seen major advances in the linkage between ground measurements, modelling, satellite remote sensing and Geographic Information Systems (GIS), especially for large scale international research programmes (e.g. semi-arid Niger: HAPEX-Sahel Goutorbe *et al* 1994, Amazonia: LBA (http://earthobservatory.nasa.gov/Features/LBA/), West Africa: AMMA (www.amma-international.org)). These major International experiments demanded intensive planning and involved huge funding—the LBA experiment had annual budgets of between USD12–15 million during each of the years 1998–2004 (The Encyclopedia of Earth 2008) while the AMMA programme cost a total of Euro 50 million. In order to make efficient and cost-effective use of the facilities available through such programmes, as well as other much smaller programmes, collaboration between individual field scientists, modellers and EO groups has to be encouraged, organized and implemented at regional and local levels. Such collaboration between researchers from different organizations and countries is evident through programmes such as the ALSO Kyoto and Carbon Initiative (Rosenqvist *et al* 2007). Further, the application of established models and remote sensing data (along with *in situ* calibration and validation measurements) to the carbon balance issue in terrestrial biomes would provide a cheaper route than field experimentation and the development of new models. The latter also provide opportunities to engage the knowledge and expertise of resident scientists as well as providing low cost and low risk training opportunities for less experienced local staff.

As the experience of scientists in recent large-scale experiments (e.g. AMMA in west Africa; Redelsperger *et al* 2006) have highlighted the operational and technical problems that arise during the placement and long-term operation of expensive and sophisticated experimental equipment in remote or climatically inhospitable locations, we have concentrated on methods and measurements that have a better chance of successfully providing long-term estimates of changing carbon balances in wetlands at relatively low cost in regions that are either isolated or difficult to access, such as wetlands in many tropical and sub-tropical areas. The priorities are affordability over the long term and the provision of accurate and scalable estimates provided by local scientific organizations.

This letter reviews the complex interaction of processes in wetlands, an understanding of which requires intensive and often expensive research facilities. However, the present understanding of these processes and the models that have been developed from this understanding is sufficiently well-advanced to allow simple low-budget measurements combined with available well-tested models and remote sensing data to provide robust estimates of carbon balance and GHG production in agricultural wetlands and remote regions. The proposed scheme, with its accent on affordability and robustness, could provide the network of carbon balance estimates that are currently lacking in many parts of the world, especially agricultural wetlands, where management practice can have an important effect upon GHG production.

2. Measurement methods

2.1. Background

Much research has proceeded in the last few decades to identify and measure the production of GHGs and the changing carbon stocks due to global warming (e.g. Post *et al* 1990, Matthews *et al* 1991, Shaver *et al* 2000, Grace 2004, Lal 2004 and references therein). Measurements, methodologies, models and predictions have largely centred around regions of the developed world for many reasons including the close proximity to major research organizations of the most endangered biomes such as forests and peatlands; the close relationship between research groups and manufacturers of cutting-edge measurement sensors and the provision of large funding amounts by National and International government agencies for this highly expensive area of scientific investigation. The large carbon stocks in northern peatlands and in temperate and boreal forests were identified as potentially large source and sinks of both CO_2 and CH_4 as the Earth warmed and possibly dried during global warming (Gorham 1991, Price *et al* 1997, Kurz *et al* 2008). In the early stages of accounting carbon balances, when measurements required expensive equipment and mains power, relatively close proximity to the research sites allowed research to proceed on a continuous basis and to provide annual and inter-annual budgets for the carbon balance and measurements to provide insight into the processes governing the production and assimilation of CO_2 (e.g. Harazono *et al* 1998, Lindroth *et al* 1998, Urbanski *et al* 2007). Until quite recently, the measurement of CH_4 production from terrestrial surfaces was very expensive even for well-resourced research organizations, was labour and skill intensive, and could only provide isolated temporal snapshots of CH_4 production. In many ways this hampered research into carbon measurements in wetlands, compounded by the complex biophysical processes that occur in wetlands and which influence the cycling of carbon in these ecosystems (Rydin and Jeglum 2006, van der Valk 2006).

This letter does not review the methodological details of the instruments, models and remote sensing applications applicable to agricultural wetlands. The processes of carbon sequestration in wetlands have been identified, measured and modelled for more than fifty years. Eddy covariance methods of estimating the exchange of energy balance terms over terrestrial surfaces were routinely being used from the 1970s and CO_2 exchange was added to the eddy covariance methodology a few years later. Concurrently, large-scale monitoring and measurement of the Earth's surface by remote sensing began with the launch of Landsat 1 in 1972.

The following decades saw the development of more sophisticated ground sensors, requiring less power, less supervision and lower purchase cost, while ecosystem models were being constructed from the individual process models and many more satellites, often with specific purposes, were launched. While there are many processes that are particular to wetlands, most of the instruments, models and satellite sensors that are used routinely to investigate and understand terrestrial surfaces are applicable to wetlands. More detailed information regarding terrestrial surface measurement, modelling and monitoring is available (for example, see Baldocchi *et al* (1996), Aubinet *et al* (2000), Raupach *et al* (2005), Heinsch *et al* (2006), Baldocchi (2008)).

2.2. Wetland carbon balance measurements

In wetlands, below-ground biochemical and physical processes are as important and dynamic as those processes occurring above ground (Zhang *et al* 2002, Adhikari *et al* 2009). Physical, biological and chemical quantities below ground in both dryland and wetland biomes can be highly heterogeneous with properties only metres or centimetres apart being radically different (Fang *et al* 1998). Transport and mixing of these quantities can be slow compared to similar quantities above ground where the turbulent air provides rapid mixing. This has repercussions in both the ability to provide representative measurements of anything larger in scale than the immediate area surrounding the measurement, and in the representation of these processes in models. Such difficulties are reflected in the fact that wetland measurements and modelling has lagged behind the progress seen in dryland research. It can be observed that many validated soil–vegetation–atmosphere transfer (SVAT) models have only recently had 'wetland' tagged onto the existing code (Zhang *et al* 2002, Zhuang *et al* 2004).

In many instances, the difficulties described above are compounded by the expense and technical expertise required to operate the current sophisticated measurement systems for long periods, particularly in climatically difficult and remote regions. Initial purchase of equipment may not seem expensive but the ability to maintain a working system requires ready access to backup equipment and repair facilities which are costly over the long term.

Below-ground activities are also not as readily measured, either directly or by proxy, as those above ground by remote sensing platforms. Not only do the remote sensing instruments need to look beyond the above-ground vegetation and processes, but also need to actively penetrate into the soil structure to gain information. Wetlands that are not open water rely on microwave measurements of soil moisture to both identify and analyse inter- and intra-annual ephemeral vegetation/water surface changes (Finlayson *et al* 1999, Lehner and Döll 2004, Reichle *et al* 2007, Bartsch *et al* 2008, Mackay *et al* 2009). Such satellite platforms (e.g. ESA Living Planet Programme SMOS satellite—see www.esa.int/esaLP/LPsmos.html) have only recently become operational.

Long-term field-scale time-average measurement of higher concentration GHGs (CO_2 and water vapour) in non-wetland terrestrial surfaces has become routine over the past two decades. The development of estimation methodologies for GHGs has largely centred around extensive monocultures (e.g. conifer forests, cereal crop fields) in areas of the developed world. International collaborations (e.g. CarboEurope (www.carboeurope.org), AmeriFlux (http://ameriflux.ornl.gov)) have organized and produced datasets of multi-annual carbon and energy balances from most of the European and north American terrestrial biomes (temperate and boreal forest, grasslands, agricultural crops such as wheat, maize, etc). These organizations and others have also been instrumental in extending the measurement methodologies to investigate seasonal and long-term carbon balances in tropical rainforests (LBA-Amazon (http://daac.ornl.gov/LBA/lba.shtml)) and semi-arid zones (HAPEX-Sahel; Goutorbe *et al* 1994, AMMA). These methodologies are now being extended to wetland and fragmented agricultural situations e.g. rice and peatlands/oil palm plantations and to other wetland environments (e.g. in African papyrus wetlands: Jones and Humphries 2002; Saunders *et al* 2012).

Many national and international experiments have relied heavily on one measurement technique—eddy covariance. Eddy covariance is a statistical measurement where high frequency (typically 20 Hz) instantaneous measurements of the velocity of the vertical vector of near surface wind is combined with instantaneous measurements of gas concentration (water vapour and CO_2) to provide overall Energy Balance estimates of Latent and Sensible heat fluxes and Net Ecosystem Exchange (NEE) estimates of the carbon balance. For CO_2, this method avoids the need to measure the individual components of the carbon balance (e.g. stomatal and soil CO_2 exchanges). Typical eddy covariance sensor systems can be found at any of the websites of the major manufacturers of these instruments. The method is not without operational and analytical difficulties, some of which concern the correct interpretation of the fluxes from the upwind area from which the eddies originate—termed the flux footprint. More detailed aspects of the eddy covariance methodology can be found in Lee *et al* (2004) and details of the flux footprint in Schmid and Oke (1990) and Schmid and Lloyd (1999). Analysis of eddy covariance data is further complicated where agricultural practice results in fragmented mosaic fields. These situations may eliminate eddy covariance as a viable method or require careful placement of the instrumentation and analysis of the resultant data.

Deployment of eddy covariance measurement systems is expensive in initial component purchase. The instruments are robust but sensor failure and recalibration over time needs to be included in the budget. Equally, these instruments require expert operation and data analysis if the measurements are to be representative and indicative of the carbon and energy balance of the studied terrestrial surface. In non-wetland terrestrial areas, the carbon balance is largely contained and exchanged in the above-ground vegetation. Organic carbon in non-wetland soils is often a minor constituent of the soil structure and percentage change in this carbon stock is usually slow and can often be discounted.

The application of these methodologies for full carbon balance appreciation in wetlands has only recently been implemented. In wetlands, CO_2 and water vapour fluxes have been measured using eddy covariance for many years—but the production of CH_4 by wetlands and its low atmospheric concentration has posed problems for measurement scientists. Eddy covariance methods to measure the emission of CH_4 and other low concentration GHG's have included Gas Chromatography (GC) and tunable diode laser (TDL) techniques. Both of these sensor systems are expensive and were difficult to run for any period greater than a few weeks, required mains power and other facility provision (liquid nitrogen) that tended to restrict their general deployment to non-remote regions of the world. More recently, the development of a normal temperature low-power open-path laser sensor for CH_4 (Licor LI-7700, Licor Environmental, Lincoln, NE, USA) has overcome some of these restrictions—although the measurement of CH_4 using this sensor is not without its own problems including frequent and dedicated maintenance schedules to maintain instrument accuracy. Other laser instruments, including the Quantum Cascade Laser Absorption Spectrometer (QCLAS—Aerodyne Research Inc.; www.aerodyne.com) and the Los Gatos Research (LGR) Fast Greenhouse Gas Analyser (FGGA) using Cavity Ringdown Spectroscopy (CRDS) (Los Gatos Research Inc.; www.lgrinc.com), have improved both the sensitivity and robustness of CH_4 measurements in field applications but these remain expensive and require dedicated expert scientists to run them.

Alternative measurements of GHG emissions from wetlands include chamber measurements (manual and automatic) which measure the change in GHG concentration over a small area of the wetland surface over a specified time period (Burrows *et al* 2005). Manual measurement methods include gas sampling of the air inside the chamber using syringes or similar sampling procedures, while automatic measurements require mechanized opening and closing of the chamber top together with either pumped air transport to a local GC or InfraRed Gas Analyser (IRGA), all of which require substantial power, maintenance, redundant capacity and local expertise to keep running. In wetlands, these latter methods have problems with flotation, leakage at the interface between the chamber and the wetland surface and horizontal movement of carbon and energy fluxes below the chamber (Goulden and Crill 1997).

Although there is a constant exchange of greenhouse gases between the soil, vegetation and atmosphere, the only mid to long-term storage for GHGs such as CO_2 are trees and soil carbon. Simple and inexpensive methods to assess the long-term assimilation of carbon into these stores include allometric relationships for trees and soil core analysis for soils (e.g. Chave *et al* 2005). There are problems in each of these methods. Allometric relationships become less reliable the further away in age, location and species the tree in question is from the original research findings. Soil corings suffer from heterogeneity demanding many samples from one area to reduce the sampling error (see Schumacher 2002). Soils are also not of constant depth so the ability to assess carbon storage over depth is difficult to establish without some form of mapping of the soil horizon—or again, extensive soil core sampling. Changes in soil carbon may be very small and trends might not be visible for several years. In wetlands, the changing water table and its effect upon below-surface plant density adds a further complication to assessing changing carbon stocks.

In agricultural wetlands, carbon is often exported via harvest of agricultural or cattle production. While these exports ultimately return their carbon—in the form of CO_2 or CH_4—during digestion, this is often some distance from the production wetland. It is thus vitally important to estimate the size of the export in terms of carbon stock—and to incorporate these estimates into the overall carbon balance of the wetland agricultural site (Byrne *et al* 2007).

2.3. Wetland carbon balance modelling

Understanding the many interrelated processes, both above- and below-ground in wetlands has complicated the analytical and empirical description of these processes and caused the incorporation of these processes into models to lag behind the modelling of other terrestrial biomes. Figure 1 shows the carbon cycle in wetlands and illustrates the varied and interrelated processes that occur below the soil surface. This is in contrast to non-wetland biomes where the processes below the soil surface play a more limited role in the carbon and energy balance. Natural wetlands have a certain predictability regarding their overall carbon balance governed largely by temperature and moisture controls. In agricultural wetlands, this predictability is often upset by the differing farming

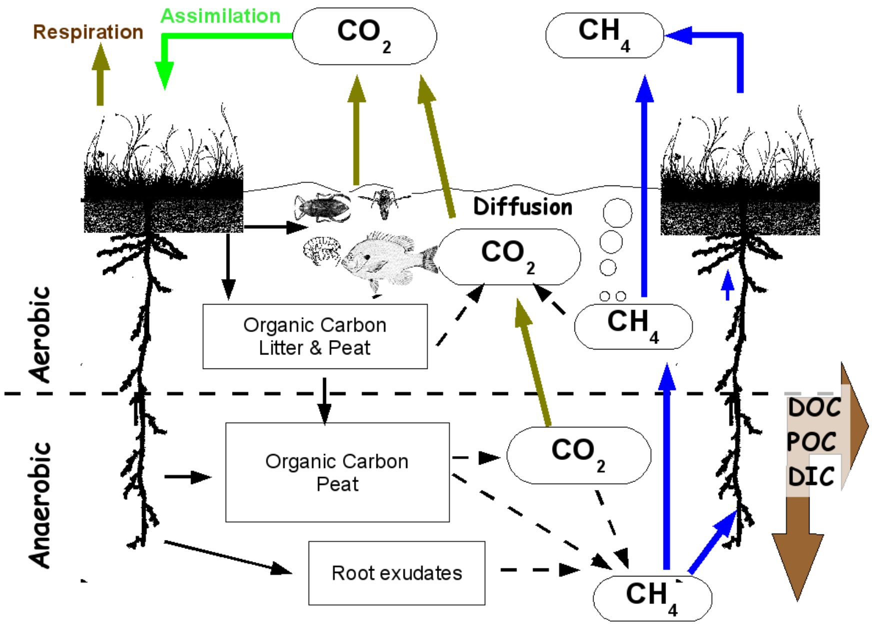

Figure 1. A representation of the carbon cycle in wetlands (redrawn from van der Valk 2006). DOC/POC (dissolved/particulate organic carbon), DIC (dissolved inorganic carbon).

practices that occur from season to season, many of which have a marked effect upon the microbiological communities that contribute to greenhouse gas production. The change from natural to agricultural wetland will also impact upon the inherent processes that may be difficult to predict.

Because of the complex nature of wetland hydrological, biological, chemical and physical interactions, the ability to simulate wetland GHG production and uptake has lagged behind the modelling of the carbon balance in other regions of the natural environment. Many well-established soil–vegetation–atmosphere transfer (SVAT) models (e.g. DNDC, Li *et al* 2000; LPJ, Sitch *et al* 2003) have only recently attached a wetland component in an attempt to simulate wetland carbon balance processes. The conceptual structure of the Wetland-DNDC model is shown in figure 2.

However, models are now being developed that are primarily designed to include wetland processes (e.g. McGill Wetland Model (MWM), St-Hilaire *et al* (2008), and PEATLAND-VU, van Huissteden *et al* (2009)). A useful register of ecological models, methodology and data sources exists at http://ecobas.org/www-server/index.html. The database currently contains over 50 models that have some form of CO_2 modelling, but only 4 models currently model CH_4, with just one (DNDC) that models both CO_2 and CH_4. The register entries contain information regarding the input requirements and output parameters so that models can be assessed against current or future measurement schemes.

Deterministic or process modelling provides the ability to simulate the physical, chemical and biological processes that comprise the exchange of greenhouse gases between the atmosphere, vegetation and soil. Such SVAT models, through their mechanistic approach, are transportable and thus models developed for one biome or one location can be used to simulate other biomes in other regions provided appropriate characteristic parameters are chosen when running the model.

These SVAT models typically use a suite of driving variables that are the major controllers of the biophysical processes. These variables include incoming solar radiation, albedo, wind speed, air humidity, air and soil temperatures, as well as vegetation parameters such as ground level normalized difference vegetation index (NDVI).

In wetlands, these models need to be extended to include microbial activity processes responsible for CH_4 production, water table depth and seasonal changes in wetland expanse. However, the models have been developed and validated over many decades and provide an inexpensive option for assessing carbon exchange in developing countries provided there is provision to install, maintain and analyse data from simple and again, relatively inexpensive (compared to eddy covariance or GC systems) automatic weather stations (AWS). These low-power systems, that have sensors measuring the driving data for the above SVAT models, have been used in all the large-scale national and international programmes to provide the long-term local climate data needed to both run and validate models, eddy covariance results and satellite remote sensing data.

The defining drivers for reliable and long-term assessment of the carbon balance in agricultural wetlands, many of which are in remote or difficult to access areas, are cost and expertise. What level of instrumentation is affordable to install, run and maintain over the long-term? What level of expertise is necessary to run this equipment properly—this includes not only the general maintenance in the collection of data but also the ability to recognize sensor failure or partial failure. Is this expertise available locally to check, maintain and collect data from the chosen systems at a weekly or monthly frequency? What expertise is available to analyse the data taken? This expertise need not be local to the measurements, but needs to be available and deployed at

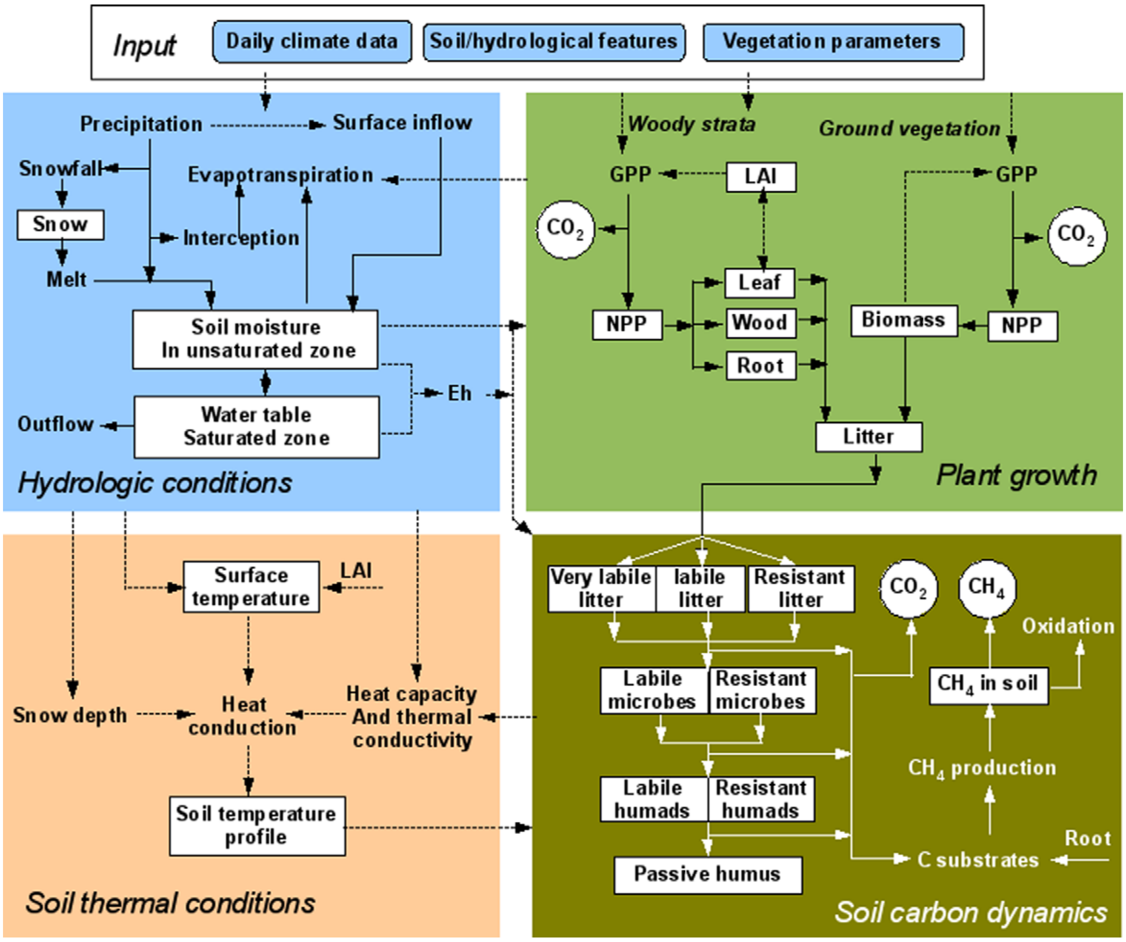

Figure 2. The conceptual structure of the Wetland-DNDC model. Redrawn from Zhang *et al* (2002).

the same frequency as the data collection otherwise errors and malfunctions may be overlooked for several months or longer. These considerations are applicable to all carbon balance or greenhouse gas exchange programmes—not just agricultural wetlands. Often overlooked in deploying instrumentation is the question of security. Modern measurement systems increasingly rely on solar panels, wind generators and batteries for power provision. These are desirable items and some provision to secure the instrumentation or guard sites is usually necessary.

Such considerations tend to rule out the eddy covariance, GC, IRGA, automated chamber techniques that are prevalent in European, north American and other similar studies. However, a network of AWS climate stations providing local climate data for input to computer models coupled to simple validation measurements and remote sensing data could be cost-effective in both agricultural wetlands and remote areas with the ability to measure, evaluate and understand national emissions and carbon balances.

The choice of measurement package, modelling strategy and remote sensing data retrieval is not a simple one. Different models require different sensor measurements as driving and parameter data. The frequency at which the model is run can be a major factor. It's an unfortunate truth that some models require measurements that are routinely impossible to provide. The major cost of the exercise proposed in this paper is the provision, maintenance and running of the ground measurement system. Creating a list of the instruments that an organization can afford to run will define the models that can adequately give the estimates required.

Table 1 lists the major measurements that are regularly operated by a solid-state battery driven AWS. The measurements marked as important encompass the most common measurements providing driving data for models and for validation and linkage to satellite measurements.

The above discussion has highlighted the possible and varied instrumentation and models that are currently being used to estimate GHG balances from terrestrial surfaces including wetlands. Comparisons of relevant instrumentation has been done in the past (Marshall and Woodward 1985, Brock and Richardson 2001, Lee *et al* 2004, Monteith and Unsworth 2008) but a lot of the content of these books have been left behind by the recent rapid development of eddy covariance and other sensors. Drexler *et al* (2004) provided a review of both models and methods for wetland evaporation, but a companion review for wetland GHG balances is much needed. Moncrieff *et al* (1997) and Baldocchi and Meyers (1998) both address some of the factors involved in any reasonable comparison for wetlands.

Table 1. List of important or useful measurement sensors to be deployed on an AWS.

Measurement	
Incoming global shortwave radiation	Important
Reflected shortwave radiation	Important
Net radiation	Important
Incoming longwave radiation	Useful
Outgoing longwave radiation	Useful
NDVI	Useful
Rainfall	Important
Atmospheric pressure	Useful
Air temperature	Important
Air humidity	Important
Wind speed	Important
Wind direction	Important
CO_2 concentration	Useful
Soil temperature profile	Important
Soil moisture	Useful
Water depth pressure transducers	Important

Any measurement scheme needs to be able to provide the accompanying model with the correct driving data (e.g. air temperature, incoming radiation) and state variable values (e.g. initial depth of carbon stock, biome type). It is therefore imperative that measurements and models complement each other—so that models do not require data that is lacking from the measurement scheme. In the absence of available local data, modellers often revert to using parameter look-up tables that may or may not be appropriate for that biome, region or climate. The provision of even simple local climate and biome data can assist modelling greatly, and the increasing provision of satellite data aimed specifically at wetland carbon balance issues is providing models with much-needed large-scale data.

2.4. Remote sensing of wetlands

Remote sensing data are critical to understanding and quantifying global budgets of CO_2, CH_4, and nitrous oxide (N_2O) and frequently provide the model inputs described in the previous section. Atmospheric concentrations cannot generally be remotely observed with sufficient resolution or the accuracy needed to determine rates of change or spatial distribution[4] and therefore cannot link these to specific processes occurring on the ground. Instead, various correlates of GHG exchanges are measured from remote sensing, including those related to surface climate, vegetation health and condition, terrestrial land cover and land cover change, frequency, intensity and areal extent of biomass burning, and frequency, duration and areal extent of inundation (King 1999).

While the extent and boundaries of relatively static biomes such as forests and dryland agricultural crops are generally easily identified from EO sensors, it has historically been a problem to identify and measure the type and extent of some wetlands, in particular those that can dynamically change with season or even on a daily basis, e.g. agricultural wetlands. The increasing spatial resolution and overpass frequency of EO platforms is beginning to address this issue of wetland extent, which is a significant factor in estimating the GHG production. However, long-term uncertainties in the data for global extent of wetlands and the amount of carbon stored therein still exist and have been much discussed (Mitre *et al* 2005).

In this paper, remote sensing or EO has been limited to dealing with aspects of land surface processes, which can contribute to the quantification of GHG emissions from wetlands used for agriculture. The use of satellites to determine atmospheric concentrations of GHGs is not discussed although it is recognized that this could provide a link between surface and boundary layer fluxes.

The IPCC (2007) report showed that data describing the total area of wetlands, the area of human impacted wetlands, and effects on GHGs are largely unknown for many regions, the difficulties compounded by the use of different datasets and definitions of what constitutes a wetland. While satellite data provides the best means for identifying, mapping and monitoring the distribution and dynamics of wetlands in a consistent manner and over large scales there are associated constraints (Mackay *et al* 2009). High spatial resolution data are needed to accurately capture the range of different wetland types, while high temporal resolution data are needed to characterize the dynamics of these ecosystems, and to accurately represent their extent. In the absence of a constellation of high resolution sensors which together provide frequent (e.g. daily) global coverage, practitioners are limited to using either high spatial resolution data (which may not capture the seasonal dynamics) or high temporal resolution data (which may have an insufficient spatial resolution to accurately identify wetland extent), neither of which are ideal for mapping wetlands at the regional to global scale. Unsurprisingly, an up-to-date, high/moderate spatial resolution map of global wetland extent and type does not exist. Those that are available have too low a resolution (e.g. Papa *et al* 2010) to represent significant differences in the emission rates of GHGs from individual ecosystems (Zhuang *et al* 2009). It is therefore critical that the development of accurate global wetland datasets which describe the extent, type, and inundation dynamics of wetlands continues, in order to provide the data needed to characterize ecosystem processes at the regional to global scale.

Understanding and quantifying the effects of agricultural activities in wetlands on GHG emissions requires information on areal conversion by wetland type, along with net changes in GHG emissions (IPCC 2007). Remote sensing can contribute directly to the former, and analyses of remote sensing datasets along with ground surveys at individual sites and at regional scales have produced valuable contributions to national inventories. Such studies are typically most successful when a combination of both optical and radar datasets are used with reported accuracies greater than 80% (Costa and Telmer 2007, Bwangoy *et al* 2010, Rebelo 2011). As Synthetic Aperture Radar (SAR) data provides information on the ground or canopy structure and the data can be acquired irrespective of cloud cover, while optical sensors

[4] Spatial distribution of CH_4 columns in the atmosphere can be determined from remote sensing.

characterize the spectral properties, the two sensor types are complementary (Rosenqvist *et al* 2007). With an archive of Landsat data available from the early 1970s at high resolution (∼30 m), and MODIS since 2000 at a moderate spatial resolution (250 m, 500 m, 1 km depending on data product) both available at no cost, it is possible to identify changes which have occurred to wetland ecosystems. These data have been used extensively, often in combination with various radar datasets to identify changes which have occurred. Bwangoy *et al* (2010) for example, have used Landsat mosaics for the 1990s and 2000s along with MODIS data and JERS −1 SAR data (acquired over the tropical belt between 1995 and 1996 and also available at no cost) to produce a detailed wetland map of the Congo Basin.

2.5. Remote sensing of above-ground biomass

Remote sensing data supported by ground observations are increasingly being used to quantify above-ground biomass (AGB) and carbon stocks of terrestrial biomes over large areas. Methods which are typically applied to both optical and radar data sources can be split into two main categories; those where direct statistical relationships are derived between AGB and remote sensing variables, and those where the data is classified into land cover type with each cover type assigned an AGB value (Mitchard *et al* 2012). Various detailed reviews of available remote sensing datasets and appropriate methods for estimating carbon stocks are available; Lu (2006) reviews the potential and challenge of various remote sensing datasets for biomass estimation, Gleason and Im (2010) review remote sensing of forest biomass, focusing on advances and applications over the last decade, Ghasemi *et al* (2011) look specifically at estimation methods using SAR data, and Wulder *et al* (2008) discuss approaches for large area biomass estimation. The former concludes that a combination of spectral responses (from optical data) and image textures (radar data) improves the estimation of biomass, but that the data and procedure used will depend on the need of the user, the scale of the study area and the availability of economic support. While very high resolution optical data (e.g. Ikonos or Quickbird) or aerial photos can be used to identify individual trees and their canopies accurately, the cost of acquiring data over large areas is extremely high. Landsat data has proved popular (e.g. Samimi and Kraus 2004, Lu 2005, Powell *et al* 2009), as has PALSAR L-band SAR data (e.g. Lucas *et al* 2010, Cartus *et al* 2010), the former often due to the long, and now freely available data archive. Limitations include saturation of both optical and radar over sites with high biomass or complex stand structures, the effects of topography on radar data, and the presence of cloud affecting the availability of optical data.

Due to the various limitations, an increasing number of studies have focused on the use of LiDAR (Light Detection and Ranging) data which does not suffer from saturation issues and provides more robust biomass estimates. A review of the different types of airborne LiDAR data available is provided by Lu *et al* (2012). LiDAR data is captured by sending a pulse of laser light from either an airborne of spaceborne platform, the response of which can be analysed to provide information on canopy height with accuracy of the order of mm; this and other LiDAR derived metrics have been shown to be highly correlated to biomass, with no saturation at high levels (Lefsky *et al* 2005, Mitchard *et al* 2012). However, as biomass is not solely dependent on canopy height information on vegetation species composition and density are also required (Lu *et al* 2012). More robust estimates may thus be derived through a combination of data from LiDAR and optical sensors. Although it does not suffer from saturation, airborne LiDAR data are expensive to acquire even over small areas. Data from the ICESat GLAS, a spaceborne LiDAR, are available for the years 2003–2009; no spaceborne LiDAR sensors are currently in operation.

While efforts to estimate carbon stocks have focused predominantly on high biomass ecosystems such as tropical forests, AGB has also been successfully quantified from remote sensing data for various wetland ecosystems. Fatoyinbo *et al* (2008) have quantified the biomass of mangroves at the national scale (Mozambique) using Landsat ETM+ combined with topography information from Shuttle Radar Topography Mission (SRTM) data and for the whole of Africa using radar interferometry, ICESat GLAS and field data (Fatoyinbo and Simard 2013). Accuracies are 83% for the area of mangrove mapped, and an overall root mean square error of 3.55 m for canopy height. Wang and Liao (2009) have estimated the biomass of wetland vegetation at a single site (Poyang Lake, China) using Landsat TM and Envisat ASAR, and Whitcomb *et al* (2008) have used ALOS PALSAR and JERS SAR to look at decadal changes in biomass (as well as other parameters) in Arctic wetlands.

2.6. Remote sensing of land surface processes in agricultural wetlands

At higher latitude wetlands, soil and air temperature are dominant factors in controlling rates of methanogenesis, length of growing season and surface area of wetlands through surface evaporation. However, in the tropics, processes relative to hydrology, such as rainfall controlling water table depth and regional wetland area, are believed to be the dominant driver of wetland CH_4 emissions (Bousquet *et al* 2011, Ringeval *et al* 2010). Although spatial datasets of inundation fraction derived from multi-source remote sensing datasets (Papa *et al* 2010) have been used to estimate emissions and carbon cycling from natural wetlands at the global scale (Bousquet *et al* 2011), the coarse spatial resolution (∼25 km) does not allow for the accurate quantification of emissions from individual wetlands, or provide an understanding of the impact of changing land use and management on emission factors. Information on inundation dynamics and the impact of management decisions on the dynamics is essential to the quantification of GHGs from agricultural wetlands.

Rice production covers an area of approximately 80 m ha globally, contributing to 11% of the total CH_4 flux to the atmosphere (Scheehle and Kruger 2006, Salas *et al* 2007). While there are large uncertainties in the current estimation of CH_4 emissions from rice paddies (Huang *et al* 2004; IPCC 2007), it is understood that emissions from rice are dependent on both local biophysical conditions and management practices. Process-based biogeochemical models are typically used to simulate GHG emissions from paddies (and other ecosystems), to understand the impacts of management practices on emissions, and to extrapolate site level data on fluxes to larger scales. These models require accurate spatial information on the extent and characteristics of rice production systems at different inundation states. This information is increasingly being provided by satellite remote sensing datasets. SAR data from a range of sensors have successfully been used to map rice paddies at varying flood levels (Salas *et al* 2007, Torbick *et al* 2011) and are typically chosen over optical data for this purpose due to several reasons. These are described in detail by Salas *et al* (2007), but their suitability is primarily due to the strong correlation between the backscatter signal and various growth parameters of rice, and due to the fact that SAR data are acquired independently of the meteorological conditions which affect optical data (i.e. cloud cover).

Forested wetlands are an important terrestrial carbon pool due to both above and below-ground biomass. Peatlands, for example, are estimated to cover approximately 3% of the earth's surface, covering a total area of 400 m ha, and storing a large proportion of terrestrial carbon (Murdiyarso *et al* 2010). In Southeast Asia conversion of peatlands to agricultural plantations (typically palm oil) has large implications for carbon and GHG emissions due to removal of forest biomass and peat drainage and decomposition. While emissions from perturbed peatlands are determined by a range of complex biophysical and management processes (e.g. rates of peat decomposition and compaction, soil moisture and water table levels), remote sensing can provide critical information on the nature, extent and rate of conversion. High spatial resolution optical data from satellites such as the Landsat series (30 m) can provide sufficient detail to identify change, however in tropical areas acquisition will be limited by cloud cover. Clearance and drainage of peatlands in preparation for agricultural use is usually achieved through burning. This results in the release of CO_2, CH_4 and N_2O. Murdiyarso *et al* (2010) have estimated that 25% of the total carbon loss associated with the conversion of peat to oil palm in Southeast Asia is released immediately due to fire. While exact figures are difficult to quantify, remote sensing can be used to provide information on the extent of burning in peatlands and other wetland ecosystems. These data are essential to quantify the loss of carbon stocks, as well as to estimate emissions due to burning. High resolution optical data has been used frequently to map burned areas at individual sites (Cassidy 2007, Boschetti *et al* 2010, Sedano *et al* 2012), and a monthly global burned area product, based on daily data, is produced from MODIS data with a resolution of 500 m (Roy *et al* 2005). Palacios-Orueta *et al* (2005) provide a review of remote sensing data and models used to quantify the emission of these due to burning.

2.7. Combining the different approaches

Measurements, modelling and remote sensing can all operate at varying overlapping scales from the micrometre to the global. Each has their advantages and disadvantages. In the context of this paper, it is necessary to combine the advantages (and limit the disadvantages) of each to achieve a viable, affordable long-term estimation of carbon sequestration and GHG emissions in agricultural wetlands.

The questions of scale and upscaling, validation and validation data, accuracy and precision cannot be treated in isolation—they are interrelated and optimizing one of these factors will inevitably have impacts on one or more of the other factors.

For measurements, the focus is on affordable long-term monitoring of pivotal parameters that control carbon sequestration and GHG production over scales that integrate easily with current models and remote sensing data. Models used need to be proven and sufficiently general to only require easily obtainable data from both measurement and remote sensing platforms running at time-steps that link with both measurement and remote sensing acquisition time-frames. Remote sensing also needs to provide long-term data at spatial scales and temporal resolutions that provide both validation and calibration data for the large-scale outcomes of the models and for their own calibration and validation from the ground-based measurements.

At the measurement level, precision and accuracy is a question of both a sensor's ability to measure accurately (calibration accuracy) and the ability to measure accurately the field application—which is dependent upon many other factors such as correct deployment, good maintenance and objective analysis. Validation of field measurements are often provided through independent measurements of the same parameter(s) e.g. using radiation energy balance data to validate eddy covariance latent and sensible heat fluxes. For carbon sequestration and GHG production, fully independent validation is generally not available except between similar measurement systems that often will disagree because their different spatial locations create different flux footprints.

Models can generally be tested internally by identifying the parameters that have the largest impact on outcomes through sensitivity analysis. This procedure can identify the important parameters that need to be measured, either as driving data or as validation data. Simple statistical testing of model runs will produce an estimate of the models accuracy against validation datasets. As an example, Lloyd (2001) used surface data obtained from an Automatic Weather Station at a high Arctic site in Svalbard to initially calibrate an existing model of carbon exchange and through sensitivity analysis to identify the important parameters in the model. Error analysis was also performed on the model outcomes. The calibrated model was subsequently run without modification using the following years AWS data and the model outcomes successfully compared to independent eddy covariance data. EO sensors are subject to the same precision and accuracy concerns as ground-based measurement systems—internal sensor accuracy and applied sensor accuracy—how close to surface reality is this sensor able to measure. An example of using remote sensing data to calibrate SVAT models is given by Ridler *et al* (2012).

It is imperative that long-term datasets of observation relating to GHG emission and carbon sequestration are obtained for developing countries. But it is equally important to ensure that the data and the analyses are capable of indicating and predicting the effect of agricultural management on GHG production. An agriculture that is highly fragmented with small field sizes and a mosaic of crops poses problems for both measurements and models. Measurements in one field can be 'contaminated' through mixing of entities, e.g. soil water, atmospheric fluxes of water vapour, CO_2 from adjacent fields. Models are predominantly organized vertically, from soil through vegetation into the atmosphere, and advection modelling that accounts for horizontal movement of entities is still in its infancy. The accuracy with which agricultural areas can be mapped decreases as the size of the mosaic field approaches the size of the sensor pixel when again, contamination by adjacent pixels becomes a problem. It is therefore extremely important that areas chosen as characteristic agricultural wetlands are of a size that minimizes spatial scale errors in ground and EO measurement and, modelling while allowing the effects of management practice to be perceived and analysed. This may be of the order of 10 hectares.

An illustration of the ability of combined ground measurement and modelling to provide management guidance in an agricultural wetland was shown by Lloyd (2006) where a change to the flooding management practice could reduce the production of CO_2 sufficiently to stop the loss of soil carbon. This was developed further by Acreman *et al* (2011) to include all ecosystem services pertinent to the studied wetland. Verma and Negandhi (2011), and Jenkins *et al* (2010) in the Mississippi basin, used wetland modelling to understand ecosystem dynamics to provide a toolkit for wetland management to help planners and policy makers. There are many such studies providing mitigation scenarios in response to changes in wetland agricultural practice. But, as Voldseth *et al* (2009) point out in their North American prairie pothole study, there often exists few empirical data to verify the results of these land-use change simulations. Attempting to mitigate the effects of climate change through land-use change based on non-verified modelling scenarios is probably worse than doing nothing at all. It is therefore imperative that there is relevant and up-to-date data available to enable sensible statements to be made from mitigation modelling.

The ability of the combined measurement-modelling-remote sensing approach to provide guidance on mitigation can be illustrated using rice paddies as an example. Rice paddies are probably the largest agricultural wetland system and expected, unlike many other wetlands, to grow by 2025 by 50–70% from 1997 levels to meet expected demand. (Pingali *et al* 1997). This increase in production is to be achieved through both increased yields as well as expansion of the cultivated area. There are four major rice paddy agronomies; upland, rainfed, deepwater and irrigated with irrigated being the largest and expected to be the major growth area (IRRI 2002). There are marked differences in agricultural practices with each agronomy leading to important differences in their carbon balances and production of GHGs.

Rice paddies account for approximately 15–20% of global annual total CH_4 emissions (Sass and Fisher 1997) but these emissions are highly variable (Kumaraswamy *et al* 2000, Lu *et al* 2000, Wassman *et al* 2000). But they are also highly managed and have a history, through research into the hydrological (Bouwman 1991) and greenhouse gas processes, of improvement to rice cultivars (Gogoi *et al* 2008) and optimizing agronomic practices (Kumaraswamy *et al* 2000, Lu *et al* 2000) to reduce CH_4 levels. Through extensive monitoring of the seasonal and inter-annual changes in rice production area and hydrological and physical changes to the agronomic practice with basic measurements, models and remote sensing, organizations have the tools to begin to predict the effects of mitigating management practices on the production of GHGs in a changing climate.

3. Conclusion

Tools are currently available that would provide developing countries with the ability to monitor their carbon sequestration and GHG emissions from agricultural wetlands at affordable levels in terms of instrumentation, data and expertise. This paper has illustrated what is available and what is affordable. The paper proposes that it is more productive to use low-budget, robust and readily available measurement, modelling and EO products over sustainable timescales that will show the effects of mitigation through changing agricultural management practice than to attempt to utilize leading edge measurements, modelling schemes and EO sensors. The latter may provide more accurate estimations—but the costs in terms of equipment, data collection and analysis, and the high probability of failure to capture sufficient data to provide an informed appraisal of mitigation and agricultural practice on wetlands in developing countries need to be critically examined. Lloyd (2001) illustrated the potential of the proposed method. An Automatic Weather Station operating largely unattended in the high Arctic for two years provided data for simple energy and GHG exchange models. Short-term (2–3 days) eddy covariance data was used to calibrate the model during pivotal periods of the first year. The calibrated model was then run for the second year and tested successfully against eddy covariance data.

A combination of local climate stations at characteristic agricultural wetland sites, providing the common driving data for SVAT models and validation data for remote sensing products, together with proven readily available SVAT models to extend estimations to the landscape and regional scale constrained and validated by EO data is proposed as an affordable solution. The combination of basic ground-level climate data and EO data would provide models with the necessary input and validation data to make sensible predictions from mitigation studies involving current and future land-use change.

The indication that such combination schemes were being implemented would be of great interest to the International research fraternity. The linkage of such proposed or existing developing country schemes to the wider international global carbon community would benefit both parties—as developing country research groups gain expertise and possible externally funded research programmes made possible by the established infrastructure and data sets available.

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References

Acreman M C, Harding R J, Lloyd C, McNamara N P, Mountford J O, Mould D J, Purse B V, Heard M S, Stratford C J and Dury S J 2011 Trade-off in ecosystem services of the Somerset Levels and Moors wetlands *Hydrol. Sci. J.* **56** 1543–65

Adhikari S, Bajracharaya R M and Sitaula B K 2009 A review of carbon dynamics and sequestration in wetlands *J. Wetlands Ecol.* **2** 42–6

Aubinet M *et al* 2000 Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology *Adv. Ecol. Res.* **30** 113–75

Baldocchi D 2008 Breathing of the terrestrial biosphere: lessons learnt from a global network of carbon dioxide flux measurement systems *Aust. J. Bot.* **56** 1–26

Baldocchi D and Meyers T 1998 On using eco-physiological, micrometerological and biogeochemical theory to evaluate carbon dioxide, water vapor and trace gas fluxes over vegetation: a perspective *Agric. For. Meteorol.* **90** 1–25

Baldocchi D, Valentini R, Running S, Oechel W and Dahlman R 1996 Strategies for measuring and modelling carbon dioxide and water vapour fluxes over terrestrial ecosystems *Glob. Change Biol.* **2** 159–68

Bartsch A, Pathe C, Scipal K and Wagner W 2008 Detection of permanent open water surfaces in central Siberia with ENVISAT ASAR wide swath data with special emphasis on the estimation of methane fluxes from tundra wetlands *Hydrol. Res.* **39** 89–100

Boschetti M, Stroppiana D and Brivio P A 2010 Mapping burned areas in a mediterranean environment using soft integration of spectral indices from high-resolution satellite images *Earth Interact.* **14** 1–20

Bousquet P *et al* 2011 Source attribution of the changes in atmospheric methane for 2006–2008 *Atmos. Chem. Phys.* **11** 3689–700

Bouwman A F 1991 Agronomic aspects of wetland rice cultivation and associated methane emissions *Biogeochemistry* **15** 65–88

Brock F V and Richardson S J 2001 *Meterorological Measurement Systems* (New York: Oxford University Press)

Burrows E H, Bubier J L, Mosedale A, Cobb G W and Crill P M 2005 Net ecosystem exchange of carbon dioxide in a temperate poor fen: a comparison of automated and manual chamber techniques *Biogeochemistry* **76** 21–45

Bwangoy J R B, Hansen M C, Roy D P, Grandi G D and Justice C O 2010 Wetland mapping in the Congo basin using optical and radar remotely sensed data and derived topographical indices *Remote Sens. Environ.* **114** 73–86

Byrne K A, Kiely G and Leahy P 2007 Carbon sequestration determined using farm scale carbon balance and eddy covariance *Agric. Ecosyst. Environ.* **121** 357–64

Cartus O, Kellndorfer J M, Walker W S, Goetz S J, Laporte N, Bishop J, Cormier T and Baccini A 2010 Large-area mapping of forest cover and biomass using ALOS PALSAR *American Geophysical Union, Fall Meeting 2011* Abstract #IN22A-06

Cassidy L 2007 Mapping the annual area burned in the wetlands of the Okavango panhandle using a hierarchical classification approach *Wetlands Ecol. Manag.* **15** 253–68

Chave J *et al* 2005 Tree allometry and improved estimation of carbon stocks and balance in tropical forests *Oecologia* **145** 87–99

Costa M and Telmer K H 2007 Mapping and monitoring lakes in the Brazilian Pantanal wetland using synthetic aperture radar imagery *Aquat. Conserv.* **17** 277–88

Drexler J Z, Snyder R L, Spano D E I and Paw U K T 2004 A review of models and micrometeorological methods used to estimate wetland evaporation *Hydrol. Process.* **18** 2071–101

Fang C, Moncrieff J B, Gholz H L and Clark K L 1998 Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation *Plant Soil* **205** 135–46

Fatoyinbo T E and Simard M 2013 Height and biomass of mangroves in Africa from ICESat/GLAS and SRTM *Int. J. Remote Sens.* **34** 668–81

Fatoyinbo T E, Simard M, Washington-Allen R A and Shugart H H 2008 Landscape-scale extent, height, biomass, and carbon estimation of Mozambique's mangrove forests with Landsat ETM+ and Shuttle Radar Topography Mission elevation data *J. Geophys. Res.* **113** G02S06

Finlayson C M, Davidson N C, Spiers A G and Stevenson N J 1999 Global wetland inventory—status and priorities *Mar. Freshwater Res.* **50** 717–27

Ghasemi N, Sahebi M and Mohammadzadeh A 2011 A review on biomass estimation methods using synthetic aperture radar data *Int. J. Geomatics Geosci.* **1** 776–88

Gleason C J and Im J 2010 A review of remote sensing of forest biomass and biofuel: options for small scale applications *GIScience Remote Sens.* **48** 141–70

Gogoi N, Baruah K K and Gupta P K 2008 Selection of rice genotypes for lower methane emission *Agron. Sustainable Dev.* **28** 181–6

Gorham E 1991 Northern peatlands: role in the carbon cycle and probable responses to climatic warming *Ecol. Appl.* **1** 182–95

Goulden M L and Crill P M 1997 Automated measurements of CO_2 exchange at the moss surface of a black spruce forest *Tree Physiol.* **17** 537–42

Goutorbe J-P *et al* 1994 HAPEX-Sahel: a large scale study of land–atmosphere interactions in the semi-arid tropics *Ann. Geophys.* **12** 53–64

Grace J 2004 Understanding and managing the global carbon cycle *J. Ecol.* **92** 189–202

Harazono Y, Yoshimoto M, Mano M, Vourlitis G L and Oechel W C 1998 Characteristics of energy and water budgets over wet sedge and tussock tundra ecosystems at North Slope in Alaska *Hydrol. Process.* **12** 2163–83

Heinsch F A *et al* 2006 Evaluation of remote sensing based tereestrial productivity from MODIS using regional tower eddy flux network observations *IEEE Trans. Geosci. Remote Sens.* **44** 1908–25

Huang Y, Zhang W, Zheng X, Li J and Yu Y 2004 Modeling methane emission from rice paddies with various agricultural practices *J. Geophys. Res.* **109** D08113

Intergovernmental Panel on Climate Change 2007 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 500–90

IRRI (International Rice Research Institute) 2002 *Rice Almanac: Source Book for the Most Important Economic Activity on Earth* ed J L Maclean, D C Dawe, B Hardy and G P Hettel (Wallingford: CABI Publishing)

Jenkins W A, Murray B C, Kramer R A and Faulkner S P 2010 Valuing ecosystem services from wetlands restoration in the Mississippi Alluvial Valley *Ecol. Econom.* **69** 1051–61

Jones M B and Humphries S W 2002 Impacts of the C4 sedge Cyperus papyrus L. on carbvon and water fluxes in an African wetland *Hydrobiologia* **488** 107–13

King M D 1999 *EOS Science Plan: The State of Science in the EOS Program* (Greenbelt, MD: NASA, Goddard Space Flight Centre) (available at: http://eospso.gsfc.nasa.gov/science_plan/SciencePlan.pdf)

Kumaraswamy S, Rath A K, Ramakrishnan B and Sethunathan N 2000 Wetland rice soils as sources and sinks of methane: a review and prospects for reasearch *Biol. Fertil. Soils* **31** 449–61

Kurz W A, Stinson G and Rampley G 2008 Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? *Phil. Trans. R. Soc. Lond.* B **363** 2261–9

Lal R 2004 Soil carbon sequestration impacts on global climate change and food security *Science* **304** 1623

Lee X, Massman W and Law B (ed) 2004 *Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis* (Dordrecht: Kluwer Academic)

Lefsky M A, Harding D J, Keller M and Cohen W B 2005 Estimates of forest canopy height and aboveground biomass using ICESAT *Geophys. Res. Lett.* **32** L22S02

Lehner B and Döll P 2004 Development and validation of a global database of lakes, reservoirs and wetlands *J. Hydrol.* **296** 1–22

Li C *et al* 2000 A process-oriented model of N_2O and NO emission from forest soils, 1. Model development *J. Geophys. Res.* **105** 4369–84

Lindroth A, Grelle A and Morén A-S 1998 Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity *Glob. Change Biol.* **4** 443–50

Lloyd C R 2001 The measurement and modelling of the carbon dioxide exchange at a high Arctic site in Svalbard *Glob. Change Biol.* **7** 405–26

Lloyd C R 2006 Annual carbon balance of a managed wetland meadow in the Somerset Levels, UK *Agric. For. Meteorol.* **138** 168–79

Lu D 2005 Aboveground estimation using Landsat TM data in the Brazilian Amazon basin *Int. J. Remote Sens.* **26** 2509–25

Lu D 2006 The potential and challenge of remote sensing-based biomass estimation *Int. J. Remote Sens.* **27** 1297–328

Lu D, Chen Q, Wang G, Moran E, Batistella M, Zhang M, Laurin G V and Saah D 2012 Aboveground forest biomass estimation with Landsat and LiDAR data and uncertainty analysis of the estimates *Int. J. For. Res.* **2012** 436537

Lu W F, Chen W, Duan B W, Guo W M, Lu Y, Lantin R S, Wassman R and Neue H U 2000 Methane emissions and mitigation options in irrigated rice fields in southeast China *Nutr. Cy. Agroecosyst.* **58** 65–73

Lucas R *et al* 2010 An evaluation of the ALOS PALSAR *L*-Band backscatter-above ground biomass relationship Queensland, Australia: impacts of surface moisture condition and vegetation structure *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **3** 576–93 Part 2

Mackay H, Finlayson C M, Fernández-Prieto D, Davidson N, Pritchard D and Rebelo L-M 2009 The role of Earth Observation (EO) technologies in supporting implementation of the Ramsar Convention on Wetlands *J. Environ. Manag.* **90** 2234–42

Marshall B and Woodward F I (ed) 1985 *Instrumentation for Environmental Physiology* (Cambridge: Cambridge University Press)

Matthews E, Fung I and Lerner J 1991 Methane emission from rice cultivation geographic and seasonal distribution of cultivated areas and emissions *Glob. Biogeochem. Cycles* **5** 3–24

Mitchard E T A *et al* 2012 Mapping tropical forest biomass with radar and spaceborne LiDAR: overcoming problems of high biomass and persistent cloud *Biogeosciences* **9** 179–91

Mitre S, Wassmann R and Vleck P L G 2005 An appraisal of global wetland area and its organic carbon stock *Curr. Sci.* **88** 25–35

Moncrieff J, Valentini R, Greco S, Seufert G and Ciccioli P 1997 Trace gas exchange over terrestrial ecosystems: methods and perspectives in micrometerorlogy *J. Exp. Bot.* **48** 1133–42

Monteith J L and Unsworth M 2008 *Principles of Environmental Physics* 3rd edn (Oxford: Academic, Elsevier)

Murdiyarso D, Hergoualc'h K and Verchot L V 2010 Opportunities for reducing greenhouse gas emissions in tropical peatlands *Proc. Natl Acad. Sci.* **107** 19655–60

Palacios-Orueta A, Chuvieco E, Parra A and Carmona-Moreno C 2005 Biomass burning emissions: a review of models using remote sensing data *Environ. Monit. Assess.* **104** 189–209

Papa F, Prigent C, Jimenez C, Aires F and Rossow W B 2010 Interannual variability of surface water extent at global scale, 1993–2004 *J. Geophys. Res.* **115** D12111

Pingali P L, Hossain M and Gerpacio R V 1997 *Asian Rice Bowls—the Returning Crisis?* (Wallingford: CAB International)

Post W M, Peng T H, Emanuel W R, King A W, Dale V H and DeAngelis D L 1990 The global carbon cycle *Am. Sci.* **78** 310–26

Powell S L, Cohen W, Healey S, Kennedy R, Moisen G, Pierce K and Ohmann J 2009 Quantification of live aboveground forest biomass dynamics with Landsat time-series and field inventory data: a comparison of empirical modelling approaches *Remote Sens. Environ.* **114** 1053–68

Price D T, Halliwell D H, Apps M J, Kurz W A and Curry S R 1997 Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit *Can. J. For. Res.* **27** 2005–16

Raupach M R, Rayner P J, Barrett D J, DeFries R S, Heimann M, Ojima D S, Quegan S and Schmullius C C 2005 Model-data synthesis in terrestrial carbon observation: methods, data requirements and data uncertainty specifications *Glob. Change Biol.* **11** 378–97

Rebelo L-M 2011 Eco-hydrological characterization of inland wetlands in Africa using *L*-band SAR *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **3** 554–9

Redelsperger J L, Thorncroft C, Diedhiou A, Lebel T, Parker D J and Polcher J 2006 African Monsoon Multidisciplinary Analysis (AMMA): an international research project and field campaign *Bull. Am. Meteorol. Soc.* **87** 1739–46

Reichle R H, Koster R D, Liu P, Mahanama S P P, Njoku E G and Owe M 2007 Comparison and assimilation of global soil moisture retrievals from the advanced microwave scanning radiometer for the earth observing system (AMSR-E) and the scanning multichannel microwave radiometer (SMMR) *J. Geophys. Res.* **112** D09108

Ridler M E, Sandholt I, Butts M, Lerer S, Mougin E, Timouk F, Kergoat L and Madsen H 2012 Calibrating a soil–vegetation–atmosphere transfer model with remote sensing estimates of

soil temperature and soil surface moisture in a semi arid environment *J. Hydrol.* **436** 1–12
Ringeval B N, Ciais P, Bousquet P, Prigent C, Papa F and Rossow W B 2010 An attempt to quantify the impact of changes in wetland extent on methane emissions on the seasonal and interannual time scales *Glob. Biogeochem. Cycles* **24** GB2003
Robertson G P, Paul E A and Harwood R R 2000 Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere *Science* **289** 1922
Rosenqvist A, Finlayson C M, Lowry J and Taylor D 2007 The potential of long-wavelength satellite borned radar to support implementation of the Ramsar Wetlands Convention *Aquat. Conserv.* **17** 229–44
Roy D P, Jin Y, Lewis P E and Justice C O 2005 Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data *Remote Sens. Environ.* **97** 137–62
Rydin H and Jeglum J 2006 *The Biology of Peatlands* (Oxford: Oxford University Press)
Salas W, Boles S, Li C S, Babu Y, Xiao X, Frolking S and Green P 2007 Mapping and modelling of greenhouse gas emissions from paddies with satellite radar observations and the DNDC biogeochemical model *Aquat. Conserv.: Mar. Freshwater Ecosyst.* **17** 319
Samimi C and Kraus T 2004 Biomass estimation using Landsat-TM and -ETM+. Towards a regional model for southern Africa? *GeoJournal* **59** 177–87
Sass R L and Fisher F M 1997 Methane emissions from rice paddies: a process study summary *Nutr. Cycl. Agroecosyst.* **49** 119–27
Saunders M J, Kansiime F and Jones M B 2012 Agricultural encroachment: implications for carbon sequestartion in tropical African wetlands *Glob. Change Biol.* **18** 1312–21
Scheehle E A and Kruger D 2006 Global anthropogenic methane and nitrous oxide emissions *Energy J.* **22** (Special Issue 3) 33–44
Schmid H P and Lloyd C R 1999 Spatial representativeness and the location bias of flux footprints over inhomogeneous areas *Agric. For. Meteorol.* **93** 195–209
Schmid H P and Oke T R 1990 A model to estimate the source area contributing to turbulent exchange in the surface layer over patchy terrain *Q. J. R. Meteorol. Soc.* **116** 965–88
Schumacher B A 2002 *Methods for the Determination of Total Organic Carbon (TOC) in Soils and Sediments (Report for the Ecological Risk Assessment Support Centre (ERASC) of the US Environmental Protection Agency (US EPA)* EPA/600/R-02/069 (Washington, DC: US Environmental Protection Agency)
Sedano F, Kempeneers P, Strobl P, McInerney D and San Miguel J 2012 Increasing spatial detail of burned scar maps using IRS-AWiFS data for mediterranean Europe *Remote Sens.* **4** 726–44
Shaver G R *et al* 2000 Global warming and terrestrial ecosystems: a conceptual framework for analysis *Bioscience* **50** 871–82
Sitch S *et al* 2003 Evaluation of ecosystem dynamic, plant geography and terrestrial carbon cycling in the LPJ dynamic vegetation model *Glob. Change Biol.* **9** 161–85
St-Hilaire F, Wu J, Roulet N T, Frolking S, Lafleur P M, Humphreys E R and Arora V 2008 McGill Wetland Model: evaluation of a peatland carbon simulator developed for global assessments *Biogeosci. Discuss.* **5** 1689–725
The Encyclopedia of Earth 2008 *Large-Scale Biosphere-Atmosphere Experiment in Amazonia* (www.eoearth.org/article/Large_Scale_Biosphere-Atmosphere_Experiment_in_Amazonia)
Torbick N, Salas W A, Hagen S and Xiangming X 2011 Monitoring rice agriculture in the Sacramento Valley, USA with multitemporal PALSAR and MODIS imagery *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **4** 451–7
Urbanski S, Barford C, Wofsy S, Kucharik C, Pyle E, Budney J, McKain K, Fitzjarrald D, Czikowsky M and Munger J W 2007 Factors controlling CO_2 exchange on timescales from hourly to decadal at Harvard Forest *J. Geophys. Res.* **112** G02020
van der Valk A G 2006 *The Biology of Freshwater Wetlands* (Oxford: Oxford University Press)
van Huissteden J, Petrescu A M R, Hendriks D M D and Rebel K T 2009 Sensitivity analysis of a wetland methane emission model based on temperate and arctic wetland sites *Biogeosciences* **6** 3035–51
Verma M and Negandhi D 2011 Valuing ecosystem services of wetlands—a tool for effective policy formulation and poverty alleviation *Hydrol. Sci. J.* **56** 1622–39
Voldseth R A, Johnson W C, Guntenspergen G R, Gilmanov T and Millett B V 2009 Adaptation of farming pracvtices could buffer effects of climate change on northern prairie wetlands *Wetlands* **29** 635–47
Wassman R, Neue H U, Lantin R S, Makarim K, Chareonsilp N, Buendia L V and Rennenberg H 2000 Characterisation of methane emissions from rice fields in Asia II differences among irrigated, rainfed and deepwater rice *Nutr. Cycl. Agroecosyst.* **58** 13–22
Wang Q and Liao J 2009 Estimation of wetland vegetation biomass in the Poyang Lake area using Landsat TM and Envisat ASAR data *Proc. SPIE* **7841** 78411D
Whitcomb J B, Moghaddam M, McDonald K, Podest E and Chapman B 2008 Decadal change in Northern Wetlands based on analysis of ALOS/PALSAR and JERS SAR data *American Geophysical Union, Fall Meeting 2008* Abstract #B13A-0419
Wulder M, White J, Richard F, Luther J and Magnussen S 2008 Spatially explicit large area biomass estimation: three approaches using forest inventory and remotely sensed imagery in a GIS *Sensors* **8** 529–60
Zhang Y, Li C, Trettin C C, Li H and Sun G 2002 An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems *Glob. Biogeochem. Cycles* **16** 1061
Zhuang Q, Melack J M, Zimov S, Walter K M, Butenhoff C L and Khalil M A K 2009 Global methane emissions from wetlands, rice paddies, and lakes *EOS Trans. Am. Geophys. Union* **90** 37–44
Zhuang Q, Melillo J M, Kicklighter D W, Prinn R G, McGuire A D, Steudler P A, Felzer B S and Hu S 2004 Methane fluxes between terrestrial ecosystems and atmosphere at northern high latitudes during the past century: a retrospective analysis with a process-based biogeochemistry model *Glob. Biogeochem. Cycles* **18** GB3010