AKUNTANSI KARBON SEBAGAI *PERSPECTIVE* BARU DALAM AKUNTANSI LINGKUNGAN

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SURABAYA

2010

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TUGAS AKHIR MAKALAH
Diajukan kepada
FAKULTAS EKONOMI
UNIVERSITAS KATOLIK WIDYA MANDALA SURABAYA
untuk Memenuhi Sebagian Persyaratan Memperoleh Gelar Sarjana
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TUGAS AKHIR MAKALAH

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Judul Makalah : Akuntansi Karbon Sebagai *Perspective* Baru Dalam Akuntansi Lingkungan

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“Tak Ada Yang Istimewa Yang Pernah Dicapai Kecuali Oleh Mereka-Mereka Yang Berani Percaya Bahwa Ada Sesuatu Di Dalam Dirinya Yang Lebih Unggul Dibandingkan Keadaan." – Bruce Barton

"Untuk Menyelesaikan Sesuatu Hal Yang Besar, Kita Tidak Hanya Harus Bertindak, Tapi Juga Bermimpi; Tidak Hanya Merencanakan, Tapi Juga Yakin." – Alexander Graham Bell

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KATA PENGANTAR

Dengan memanjatkan syukur kehadirat Tuhan Yesus Kristus, yang berkat rahmat-Nya maka penulis dapat menyelesaikan makalah tugas akhir ini dengan baik. Makalah ini disusun untuk memenuhi salah satu syarat guna memperoleh gelar sarjana Ekonomi di Fakultas Ekonomi Universitas Katolik Widya Mandala Surabaya.

Penulis menyadari bahwa terwujudnya makalah tugas akhir ini tidak terlepas dari kerja sama, dorongan dan bantuan dari pihak lain. Oleh karena itu penulis ingin mengucapkan terima kasih yang sebesar-besarnya kepada:

1. Ibu Dr. Chr. Whidya Utami, MM, selaku Dekan Fakultas Ekonomi Unika Widya Mandala Surabaya.
2. Bapak Yohanes Harimurti, SE., M.Si., Ak., selaku Ketua Jurusan Akuntansi yang telah memberikan banyak petunjuk-petunjuk berharga dengan penuh kesabaran dalam proses penyusunan makalah tugas akhir ini.
3. Ibu Marini Purwanto, SE., M.Si., Ak, selaku dosen pembimbing yang telah memberikan petunjuk dan bimbingan bagi penulis sehingga tersusunnya makalah ini.
4. Seluruh staf dan pengajar di Fakultas Ekonomi Unika Widya Mandala Surabaya yang telah mendidik penulis selama kuliah.
5. Seluruh staf perpustakaan Unika Widya Mandala Surabaya yang telah membantu pada penyediaan literatur.
6. Orang tua dan saudara yang memberikan dorongan dan doa.

7. Agatha Christiana, Irena Tjandra, Kartono Wibowo, Megawati Mintaredja, Nia Anastasia Setiawan, semua sahabat dan teman-teman yang telah memberikan banyak dukungan selama pembuatan makalah ini.
8. Seluruh rekan dan semua pihak yang telah memberikan bantuan.

Penulis menyadari bahwa makalah ini masih jauh dari sempurna dan banyak kekurangan, untuk itu penulis dengan segala kerendahan hati dan penuh rasa terima kasih akan menerima segala kritik dan saran demi kesempurnaan makalah ini.

Akhirnya penulis berharap semoga makalah ini dapat bermanfaat bagi pembaca.

Surabaya, Juli 2010

Penulis

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UNIVERSITAS KATOLIK WIDYA MANDALA SURABAYA

AKUNTANSI KARBON SEBAGAI *PERSPECTIVE* BARU DALAM AKUNTANSI LINGKUNGAN

ABSTRAK

Peningkatan tingkat karbon dioksida di atmosfer telah diidentifikasikan sebagai penyebab utama pemanasan global. Protokol Kyoto menetapkan target pengurangan kolektif emisi gas rumah kaca negara-negara industri sebesar 5% tiap tahunnya, ketentuan dalam Protokol Kyoto akan memungkinkan pengurangan emisi gas rumah kaca. Akuntansi karbon hadir sebagai pelengkap dari Protokol Kyoto, yang diharapkan mampu memperhitungkan efek gas yang dihasilkan oleh kegiatan produksi perusahaan. Akuntansi karbon adalah bentuk baru dalam ilmu akuntansi yang merupakan bagian dalam akuntansi lingkungan sebagai bentuk pertanggungjawaban perusahaan terhadap lingkungan yang dalam hal ini mengurangi emisi gas yang dihasilkan oleh kegiatan produksi perusahaan.

Kata kunci: Akuntansi Karbon, Protokol Kyoto, Gas rumah kaca.

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CARBON ACCOUNTING AS NEW PERSPECTIVE IN ENVIRONMENT ACCOUNTING

ABSTRACT

Increasing levels of carbon dioxide in the atmosphere has been identified as the main cause of global warming. The Kyoto Protocol set a target of collective reduction of greenhouse gas emissions of industrialized countries by 5% each year, the provisions in the Kyoto Protocol will allow the reduction of greenhouse gas emissions. Carbon Accounting comes as a complement for the Kyoto Protocol, Which is expected to take into account the effects of the gas produced by the company's production activities. Carbon accounting is a new form of science in accounting that is part of environmental accounting as a form of corporate responsibility towards the environment which in this case to reduce greenhouse gas emissions generated by the company's production activities.

Key words: Carbon Accounting, Kyoto Protocol, greenhouse gas

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PENDAHULUAN

Pada dasarnya tujuan perusahaan adalah memproduksi produk atau jasanya secara maksimal dan mendapatkan keuntungan yang sebanyak-banyaknya. Tetapi banyak perusahaan di Indonesia yang tidak memperhatikan dan bahkan tidak memperdulikan efek yang dihasilkan dari kegiatan produksinya. Sehingga lingkungan dan masyarakat disekitarnya yang mendapatkan efek buruk dari kegiatan produksi perusahaan tersebut. Sumber daya manusia yang rendah dan ditambah lagi dengan hukum yang tidak tegas, membuat banyak perusahaan tidak memperdulikan efek dari kegiatan produksinya. Efek terburuk yang paling berpengaruh dalam kehidupan manusia dewasa ini adalah pemanasan global oleh gas rumah kaca.

Dewasa ini, isu lingkungan menjadi komoditas global yang berkaitan dengan eksploitasi ekonomi. Banyak hasil riset yang menyimpulkan bahwa bumi sekarang makin panas. Perubahan iklim di negeri kita telah dirasakan dalam beberapa tahun terakhir ini. Musim kemarau dengan panas yang sangat menyengat, di sisi lain hujan terlambat datang, dan jika tiba curahnya yang sangat tinggi menimbulkan banjir.

Pemanasan global menjadi perhatian utama bagi seluruh Negara di dunia. Pemanasan global yang berasal dari penimbunan gas rumah kaca di atmosfer terjadi karena ulah manusia. Gas rumah kaca itu sendiri mengalir hanya ke dua tempat: laut dan sistem terestrial (termasuk tanah dan tumbuh-tumbuhan). Pemanasan Global bukanlah sekedar masalah lingkungan, pemanasan global berdampak pada berbagai sisi kehidupan baik di negara-negara maju maupun di negara-negara berkembang. Mencegah pemanasan global yang membahayakan merupakan tugas penting bagi umat manusia di seluruh dunia. Selain pemanasan global, perdagangan karbon merupakan isu yang cukup hangat di perbincangkan saat ini, ada pro dan kontra. Banyak persepsi dan perbedaan pendapat anatara pendukung keduanya.

Akuntansi karbon lahir sebagai pelengkap dari diresmikannya Perjanjian Kyoto. Akuntansi karbon adalah proses akuntansi yang dilakukan untuk mengukur jumlah karbondioksida setara yang tidak akan dilepaskan ke atmosfer sebagai hasil dari proyek-proyek Mekanisme Fleksibel di bawah Perjanjian Kyoto. Perjanjian Kyoto sendiri adalah sebuah amandemen terhadap Konvensi Rangka Kerja PBB tentang perubahan iklim, sebuah persetujuan internasional mengenai pemanasan global. Negara-negara yang meratifikasi protokol ini berkomitmen untuk mengurangi emisi atau pengeluaran karbondioksida dari gas rumah kaca. Akuntansi karbon merupakan suatu kebutuhan yang penting bagi perusahaan karena kepedulian perusahaan terhadap lingkungan tergolong sangat minim untuk saat ini.

Peluang Indonesia untuk berpartisipasi dalam mereduksi emisi gas rumah kaca dan ikut dalam perdagangan karbon terbuka lebar. Mengingat peran signifikan Indonesia dalam Protokol Kyoto sebagai negara yang memiliki kekayaan hutan terbesar sudah sepantasnya kita menjaga hutan kita sebagai pereduksi emisi karbon. Di sinilah paradigma pembangunan berkelanjutan perlu terus dikampanyekan dan diimplementasikan dalam setiap kegiatan pembangunan. Saatnya kebijakan yang lebih sistematis mengenai keberlanjutan ekologi harus diwujudkan sebagai tempat hidup kita. Hal itu dapat terlaksana melalui upaya penyelamatan keutuhan hutan dan lingkungan yang ada dan mempertahankan keanekaragaman hayati yang masih ada di alam. (Harian Pikiran Rakyat, Rabu 22 April 2009).

Makalah ini membahas tentang akuntansi karbon (*carbon accounting*) dalam hal ini : pengertian, sejarah, dan manfaat dari akuntansi karbon. Diharapkan makalah ini mampu memperkenalkan akuntansi karbon sebagai bentuk ilmu baru dari akuntansi yang membahas tentang kepedulian perusahaan terhadap emisi gas yang dihasilkan, serta pengendalian perdagangan karbon oleh negara-negara maju terhadap negara-negara berkembang.

PEMBAHASAN

1. Teori yang Mendasari Akuntansi Karbon (*Carbon Accounting)*

Akuntansi Lingkungan (*Environment Accounting*)

Menurut Shapiro *et.al*., 2000 definisi Akuntansi Lingkungan adalah penggabungan informasi manfaat dan biaya lingkungan ke dalam macam-macam praktek-praktek akuntansi. Sedangkan menurut (EPA742-R-97-003, 1997) Akuntansi Lingkungan adalah identifikasi, prioritisasi, kuantifikasi, atau kualifikasi, dan penggabungan biaya lingkungan ke dalam keputusan-keputusan bisnis.

Praktek-praktek akuntansi tradisional seringkali melihat biaya lingkungan sebagai biaya mengoperasikan bisnis, meskipun biaya-biaya tersebut signifikan, meliputi : biaya sumberdaya, yaitu mereka yang secara langsung berhubungan dengan produksi dan mereka yang terlibat dalam operasi bisnis umum, pengolahan limbah, dan biaya pembuangan, biaya reputasi lingkungan, dan biaya membayar premi asuransi resiko lingkungan.

Dalam banyak kasus, biaya-biaya lingkungan seperti yang berkaitan dengan sumberdaya alam (energi, udara, air) dimasukkan ke dalam satu jalur biaya operasi atau biaya administrasi yang diperlakukan independen dengan proses produksi. Juga biaya lingkungan sering didefinisikan secara sempit sebagai biaya yang terjadi dalam upaya pemenuhan dengan atau kaitan dengan hukum atau peraturan lingkungan. Hal ini karena sistem akuntansi cenderung berfokus pada biaya bisnis yang teridentifikasi secara jelas bukan pada biaya dan manfaat pilihan alternatif.

Akuntansi Lingkungan adalah mengenai secara spesifik mendefinisikan dan menggabungkan semua biaya lingkungan ke dalam laporan keuangan perusahaan. Bila biaya-biaya tersebut secara jelas teridentifikasi, perusahaan akan cenderung mengambil keuntungan dari peluang-peluang untuk mengurangi dampak lingkungan.

2. Akuntansi Karbon (*Carbon Accounting)*

Menurut keputusan PBB dalam perjanjian Kyoto 2005 definisi akuntansi karbon adalah proses akuntansi yang dilakukan untuk mengukur jumlah karbondioksida setara yang akan dilepas ke atmosfer sebagai hasil dari proyek-proyek mekanisme fleksibel dibawah perjanjian Kyoto. Akuntansi karbon merupakan bagian baru dari akuntansi lingkungan y merupakan pelengkap dengan memberikan laporan mengenai emisi karbon gas yang dihasilkan perusahaan selama proses produksi.

Akuntansi Karbon di perlukan untuk: mengukur emisi karbon gas rumah kaca, memenuhi persyaratan pelaporan internasional, dan memenuhi kebutuhan potensial pasar. Tujuan akuntansi karbon adalah: untuk memberikan kemampuan pemantauan emisi gas rumah kaca, untuk membentuk suatu referensi yang kredibel tentang tingkat emisi gas rumah kaca, untuk mendukung pengembangan kebijakan dan pedoman GHG (*Greenhouse Gas*), dan mengurangi ketidakpastian dalam perkiraan emisi gas.

Indonesia akan segera mengimplementasikan sistem akuntansi karbon untuk membantu memerangi pemanasan global. Dikembangkan di Australia, *National Carbon Accounting System* telah dirancang untuk menyediakan neraca yang menunjukkan tingkat pencemaran atmosfer yang disebabkan oleh kegiatan pengelolaan lahan seperti kehutanan, pembukaan lahan dan pertanian. Sistem ini akan menghitung jumlah karbon yang dipancarkan ke atmosfir dengan jumlah karbon yang ditangkap oleh *biomassa*, seperti: pepohonan.

3. Perdagangan Karbon

Perdagangan karbon adalah mekanisme berbasis pasar untuk membantu membatasi peningkatan CO2 di atmosfer. Pasar perdagangan karbon terdiri dari para penjual dan pembeli yang mempunyai posisi sejajar dalam peraturan perdagangan yang sudah distandarisasi. Pembeli adalah pemilik industri yang menghasilkan CO2 ke atmosfer dan memiliki ketertarikan atau diwajibkan oleh hokum untuk menyeimbangankan emisi yang mereka keluarkan melalui mekanisme karbon, sedangkan penjual adalah pemilik yang mengelola hutan atau lahan pertanian bisa melakukan penjualan karbonnya berdasarkan akumulasi karbon yang terkandung dalam pepohonan di hutan mereka. (Perdagangan Karbon di Hutan Aceh, 2008)

Perdagangan karbon adalah mekanisme pendanaan yang diberikan oleh Negara-negara maju kepada Negara yang melestarikan hutannya atau Negara yang memberikan jasa lingkungan dengan menjaga hutannya melalui sebuah mekanisme yang telah diatur. Dalam kesepakatan Perjanjian Kyoto yang dimaksud denagn Negara-negara pembeli karbon adalah Negara-negara yang masuk ke dalam Annex 1 atau negara maju yang memiliki industri besar yang menghasilkan emisi dalam sekala besar, sementara hutannya telah habis. Sedangkan yang dimaksud penjual karbon adalah negara-negara yang masih memiliki tutupan hutan atau Negara ketiga yang berkomitmen untuk mempertahankan tutupan hutannya dari ancaman konversi. (Perdagangan Karbon di Hutan Aceh, 2008)

Saat ini mekanisme yang digunakan adalah mekanisme CDM (*Clean Development Mecanism*) atau Mekanisme Pembangunan Bersih yang merupakan hasil dari kesepakatan Kyoto tahun 1997. Sedangkan untuk mekanisme Non-Kyoto antara lain; *Bio-Carbon Fund, Community Development Carbon Fund, Special Climate Change Fund, Adaptation*

Fund, Prototype Carbon Fund, CERUPT, GEF, Private Carbon Fund. Secara prinsip program-program tersebut digunakan untuk mencegah deforestrasi lahan yang menyebabkan lepasnya carbon di atmosfer. Untuk mekanisme non-kyoto atau dikenal dengan pasar sukarela carbon baru dapat diakses pasca berakhirnya kesepakatan Protokol Kyoto atau setelah tahun 2012, sehingga dapat disimpulkan bahwa, masuknya berbagai dana karbon non-kyoto kepada negara ketiga atau negara berkembang, termasuk Indonesia merupakan sebatas isu dan wacana. Sedangkan mekanisme CDM (*Clean Development Mecanism*) hanya dapat diakses oleh corporasi atau industri yang bersedia menurunkan emisinya.

4. Protokol Kyoto

Protokol Kyoto adalah sebuah amandemen terhadap Konvensi Rangka Kerja PBB tentang Perubahan Iklim (UNFCCC), sebuah persetujuan internasional mengenai pemanasan global. Negara-negara yang meratifikasi protokol ini berkomitmen untuk mengurangi emisi/pengeluaran karbon dioksida dan lima gas rumah kaca lainnya, atau bekerja sama dalam perdagangan emisi jika mereka menjaga jumlah atau menambah emisi gas-gas tersebut, yang telah dikaitkan dengan pemanasan global. Nama resmi persetujuan ini adalah *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. Dinegosiasikan di Kyoto pada Desember 1997, ditandatangani pada 16 Maret 1998 dan ditutup pada 15 Maret 1999. Persetujuan ini mulai berlaku pada 16 Februari 2005 setelah ratifikasi resmi yang dilakukan Rusia pada 18 November 2004.

Menurut rilis pers dari Program Lingkungan PBB: Protokol Kyoto adalah sebuah persetujuan sah di mana negara-negara perindustrian akan mengurangi emisi gas rumah kaca mereka secara kolektif sebesar 5,2% dibandingkan dengan tahun 1990. Tujuannya adalah untuk mengurangi rata-rata emisi dari enam gas rumah kaca - karbon dioksida, metan, nitrous oxide, sulfur heksafluorida, HFC, dan PFC - yang dihitung rata-rata selama masa lima tahun antara 2008-12. Target nasional berkisar dari pengurangan 8% untuk Uni Eropa, 7% untuk AS, 6% untuk Jepang, 0% untuk Rusia, dan penambahan yang diizinkan sebesar 8% untuk Australia dan 10% untuk Islandia.

Pada saat pemberlakuan persetujuan pada Februari 2005, Protokol Kyoto telah diratifikasi oleh 141 negara, yang mewakili 61% dari seluruh emisi di dunia. Negara-negara tidak perlu menanda tangani persetujuan tersebut agar dapat meratifikasinya, penanda tanganan hanyalah bentuk simbolis saja. Menurut syarat-syarat persetujuan protokol, Protokol Kyoto mulai berlaku pada hari ke-90 setelah tanggal saat di mana tidak kurang dari 55 Pihak Konvensi, termasuk Pihak-pihak dalam Annex I yang bertanggung jawab kepada setidaknya 55 persen dari seluruh emisi karbon dioksida pada 1990 dari Pihak-pihak dalam Annex I, telah memberikan alat ratifikasi mereka, penerimaan, persetujuan atau pemasukan. Dari kedua syarat tersebut, 55% dicapai pada 23 Mei 2002 ketika Islandia meratifikasi. Ratifikasi oleh Rusia pada 18 November 2004 memenuhi syarat 55% dan menyebabkan pesetujuan itu mulai berlaku pada 16 Februari 2005.

Hingga 3 Desember 2007, sebanyak 174 negara telah meratifikasi protokol tersebut, termasuk Kanada, Tiongkok, India, Jepang, Selandia Baru, Rusia dan 25 negara anggota Uni Eropa, serta Rumania dan Bulgaria. Ada dua negara yang telah menanda tangani namun belum meratifikasi protokol tersebut: Amerika Serikat (tidak berminat untuk meratifikasi) dan Kazakstan. Pada awalnya AS, Australia, Italia, Tiongkok, India dan negara-negara berkembang telah bersatu untuk melawan strategi terhadap adanya kemungkinan Protokol Kyoto II atau persetujuan lainnya yang bersifat mengekang. Namun pada awal Desember 2007 Australia akhirnya ikut seta meratifikasi protokol tersebut setelah terjadi pergantian pimpinan di negera tersebut.

5. Peran Indonesia Dalam Protokol Kyoto

Indonesia menjadi Negara ke 124 yang meratifikasi Perjanjian Kyoto melalui pengesahan Undang-Undang Nomor 17 Tahun 2004, tanggal 28 Juli 2004 tentang ratifikasi Perjanjian Kyoto. Dengan demikian, Indonesia bersama-sama negara berkembang lainnya harus mempersiapkan diri menyongsong ajakan *stakeholder* asing bertransaksi dalam projek mereduksi emisi atau perdagangan karbon di sektor energi dan kehutanan sebagai dua sektor utama penyokong projek ini. Kegiatan-kegiatan perdagangan karbon, contohnya penggunaan energi terbarukan, efisiensi energi, reforestasi, dan pengelolaan sampah secara terpadu dan berkesinambungan.

Komitmen politik untuk mengurangi emisi telah dilakukan hampir semua negara dengan mengurangi emisinya sebesar 6% (sampai 2005 produksi emisinya masih berkutat pada angka 8,1%). Negara-negara anggota Uni Eropa menargetkan pengurangan emisi 8%, tapi kenyataannya sampai dengan 2003 baru mampu mengurangi 1,7%. AS sebagai penyumbang emisi terbesar diharapkan mengurangi jumlah emisinya 7%. Sampai dengan 2003, emisi negeri adikuasa itu mencapai 13%. Manusia menghasilkan gas rumah kaca baru seperti klorofluorokarbon (CFC) dan karbondioksida.

Upaya lain dilakukan Forum Energi dan Lingkungan Berkelanjutan dengan mengusahakan pemanfaatan energi terbarukan melalui riset terpadu. Melalui riset, forum itu mendorong peningkatan penggunaan energi baru terbarukan seperti energi air, angin, panas bumi, gelombang laut, sinar matahari, dan biomassa. Target yang dicanangkan sampai dengan 2030 sebesar 50%. Indonesia baru bisa memanfaatkan energi terbarukan seperti air, panas bumi, dan sumber lain 4,4%. Selebihnya bergantung pada sumber minyak bumi, gas alam, dan batubara. (sumber: Harian Pikiran Rakyat, Rabu 22 April 2009).

6. Implementasi Akuntansi Karbon (*Carbon Accounting)*

Pemanasan global yang terjadi saat ini disebabkan semakin banyaknya gas rumah kaca yang dilepaskan ke atmosfer bumi. Ada dua kelompok gas rumah kaca yaitu kelompok gas rumah kaca yang berpengaruh langsung dan kelompok gas rumah kaca yang berpengaruh secara tidak langsung terhadap pemanasan global. Gas rumah kaca yang berpengaruh langsung adalah CO_2 (karbon dioksida), CH_4 (Metana), N_2O (Nitro oksida), PFCs (Perfluorocarbons) dan HFCs (Hydrofluorocarbons). Gas rumah kaca yang berpengaruh secara tidak langsung adalah SO_2, NOx, CO dan NMVOC.

Dari semua jenis gas rumah kaca tersebut, gas CO_2 menempati urutan pertama penyebab pemanasan global. Banyak sumber yang menjadi penyebab dilepaskannya gas CO_2 ke udara, diantaranya kegiatan pertanian, peternakan, kehutananan, industri, kendaraan bermotor dan lain-lain. Kegiatan-kegiatan yang berbasis lahan atau tanah di Indonesia menyumbangkan emisi gas rumah kaca lebih besar dibandingkan sektor industri. Saat ini Indonesia belum memiliki standar sistem penghitungan emisi karbon yang digunakan secara nasional, skala regional ataupun areal tertentu, khususnya penghitungan emisi karbon berbasis lahan. Penghitungan emisi karbon nasional berbasis lahan di Indonesia menjadi sangat penting karena :

- Untuk mengetahui emisi karbon nasional maupun regional berbasis lahan
- Untuk mengetahui stok karbon nasional maupun regional
- Untuk mengetahui perubahan emisi akibat penggunaan lahan
- Untuk mendapatkan kompensasi internasional dalam peranannya mengatasi emisi karbon dunia
- Dapat melakukan pengontrolan kegiatan-kegiatan berbasis lahan yang menyebabkan emisi karbon, dan lain-lain.

A. Sistem Akuntansi Karbon Nasional (*National Carbon Accounting System)*

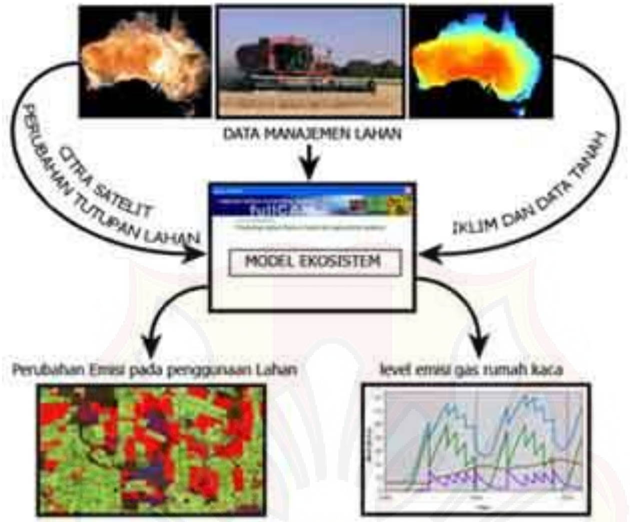
Salah satu sistem penghitungan karbon nasional yang sudah diakui oleh UNFCCC (konvensi PBB untuk perubahan iklim) adalah sistem penghitungan karbon nasional di Australia, lebih dikenal dengan istilah NCAS (*National Carbon Accounting System*). NCAS adalah sebuah sistem terdepan yang digunakan untuk menghitung emisi gas rumah kaca berbasis lahan. Emisi-emisi gas rumah kaca yang bersumber pada aktifitas-aktifitas berbasis lahan dan pelepasan gas rumah kaca ke atmosfer membentuk sebagian besar emisi gas rumah kaca di Australia. Sebanyak 27 persen gas rumah kaca di Australia dihasilkan oleh aktifitas masyarakat dalam hal peternakan, penanaman tanaman produksi, pembukaan lahan dan kehutanan.

NCAS didirikan pada Tahun 1998 dengan maksud untuk menyediakan sistem akutansi, prakiraan dan perencanaan mengenai emisi gas rumah kaca yang disebabkan oleh aktifitas-aktifitas masyarakat di Australia dalam penggunaan lahan. NCAS telah dikembangkan melalui beberapa tahapan pembangunan dengan penerapan atau pelaksanaannya sebagian besar didorong oleh kebijakan Pemerintah Australia dan isu internasional mengenai perubahan iklim.

Sistem NCAS pada saat ini telah menjadi referensi dan memiliki kemampuan sebagai berikut: baseline untuk Kyoto Protocol dan Inventarisasi Gas Rumah Kaca Nasional pada Konvensi PBB mengenai perubahan iklim (*UNFCCC*), pelacakan dan penghilangan emisi gas rumah kaca yang berasal dari sektor berbasis lahan, proyeksi dan arah tren emisi di masa depan, memiliki kapasitas untuk melacak emisi akibat afforestasi (konversi dari areal penggunaan lain menjadi hutan) dan reboisasi, memiliki kemampuan dalam menilai potensi keberhasilan kebijakan dan mengukur pencapaian dalam pengurangan emisi gas rumah kaca, pengembangan kerangka program dan data yang kuat yang mendukung kemampuan menghitung gas2 diluar CO_2.

NCAS dibangun tidak hanya memperhatikan satu sektor saja, akan tetapi merupakan sistem akuntansi terpadu yang menggabungkan unsur-unsur lahan secara menyeluruh di dalam proses penghitungannya. Unsur-unsur tersebut adalah sebagai berikut :

- *Remote Sensing* (Penginderaan Jauh) terhadap perubahan tutupan lahan. Data penginderaan jauh di Australia diperoleh dari ribuan citra satelit yang diperoleh sejak tahun 1970, sehingga diperoleh secara lengkap data perubahan tutupan lahan dari tahun dimaksud sampai sekarang.
- Data manajemen penggunaan lahan
- Iklim dan data tentang tanah
- Program penghitungan emisi gas rumah kaca dan
- Model ekosistem sementara dan tata ruang
- Berikut adalah diagram alir sistem NCAS di Australia :



Gambar 1

Diagram Alir NCAS di Australia

Sumber : http://www.baligreen.org/mengenal-ncas-perhitungan-karbon-nasional-di-australia.html

Program NCAS yang ada pada saat ini sebenarnya sudah mengalami beberapa tahap pengembangan. Adapun tahapan proses pengembangan programnya adalah sebagai berikut :

- Tahap awal (Akhir Tahun 1997 - 1999). Pada tahap ini merupakan tahapan pembentukan sistem dan arahan program strategis yang akan dibangun
- Tahap 1 (Pertengahan Tahun 1999 - 2002), meliputi pengembangan penelitian tertarget dan pengembangan kapasitas sistem.

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- Tahap transisi (Pertengahan Tahun 2002 – 2003) bertujuan untuk menguatkan persyaratan-persyaratan sistem yang teruji.
- Tahap 2 (dimulai pertengahan Tahun 2003 sampai sekarang), bertujuan untuk menyediakan kemampuan akuntansi secara lengkap yang mendukung Kyoto Protocol, perbaikan-perbaikan dalam penilaian terhadap perubahan tutupan lahan dan pengembangan lebih lanjut dalam peningkatan program NCAS.

NCAS dibangun dengan sistem model pengoperasian pada skala yang kecil (25 m). Model ini dapat menentukan perubahan stok karbon pada tingkat spasial yang baik. Pada akhirnya unit spasial 25 meter ini akan membentuk inventori gas rumah kaca skala nasional. NCAS merupakan kumpulan program-program yang secara pararel menginformasikan sekumpulan model terintegrasi membentuk model FullCAM (*full carbon accounting model*). Model FullCAM tersebu bisa digunakan untuk mengestimasi emisi dari perubahan penggunaan lahan secara menyeluruh. Program-program pararel terintegraris tersebut meliputi : perubahan tutupan lahan, manajemen tata guna lahan, input iklim, parameter pertumbuhan tanaman dan pohon, kenaikan pertumbuhan dan stok biomasa, parameter pohon, parameter hutan, karbon tanah dan kerangka model.Dalam melakukan penghitungannya, program NCAS menggunakan layer-layer data. Layer-layer datanya adalah sebagai berikut :

- Layer perubahan tutupan lahan (Diperoleh dari citra satelit dengan resolusi piksel 25 meter (terdapat 16 piksel per hektar).

Australia menggunakan data citra bulanan dari Tahun 1972 sampai sekarang)

- Layer perubahan peruntukan lahan (Berisi data-data penyebab terjadinya perubahan tutupan lahan dan mencakup aktifitas-aktifitas perubahan lahan).
- Layer tipe tanah (Merupakan karakteristik-karakteristik tanah dalam satu unit lahan).
- Layer tipe hutan (Merupakan tipe hutan dalam suatu unit lahan, diidentifikasi dari layer peta)
- Layer manajemen (merupakan rentang waktu terjadinya perubahan tutupan lahan, lokasi, tipe tanah dan lain-lain dalam suatu unit lahan).
- Layer iklim (data iklim bulanan untuk suatu unit lahan, diperoleh dari peta iklim)
- Layer pertumbuhan biomasa (penghitungan biomasa saat panen, pertumbuhan pohon, regenerasi pohon)
- Layer input sampah (sampah-sampah yang terdapat di dasar hutan, sampah sisa panen, pergantian alam dan unsur manajemen)
- Layer pemodelan (laporan karbon bulanan meliputi stok karbon, proses pembentukan dan proses emisi karbon terhitung)

Tingkat perubahan level karbon berbasis lahan setelah terjadinya perubahan penggunaan lahan bervariasi tergantung pada variasi penggunaan lahan, manajemen penggunaan lahan dan sifat alami tanah. Program manajemen dan penggunaan lahan pada NCAS menjelaskan tentang penggunaan lahan dan sistem manajemen yang dipakai, hal ini mempengaruhi level karbon tanah setelah terjadinya deforestasi. Tipe tanah informasinya dikumpulkan dari masing-masing daerah, termasuk didalamnya tipe tanaman dan tipe pengelolaan berdasarkan waktu. Hasil kajian diperoleh bahwa di Australia terdapat 141 perbedaan dalam hal sistem tanam dan sistem penggembalaan. Informasi yang diperoleh dikumpulkan selama rentang waktu yang direncanakan, hasilnya dijadikan sebuah model FullCAM database relasional.

Laju perubahan stok karbon dari waktu ke waktu juga dipengaruhi oleh iklim yang berlaku pada masing-masing unit lahan. Pada program *climate input* (salah satu program tentang iklim yang terintegrasi pada NCAS), curah hujan minimum, curah hujan maksimum, rata-rata temperatur, penguapan air dan tingkat kekeringan harian selama periode waktu tertentu diperoleh dari Biro meteorology Australia. Data stasiun meteorologi ini memberikan prakiraan cuaca yang mencerminkan pengaruh cuaca pada suatu tempat dan menghasilkan peta iklim bulanan dengan resolusi 1 kilometer.

Karbon yang tersimpan dalam biomasa tanaman perlu dilakukan penghitungan sebagai stok karbon. Karbon biomasa akan memperngaruhi tingkat perubahan dalam karbon di dalam tanah, tanaman dan sistem tanaman untuk peternakan. Pada Program parameter pertumbuhan tanaman dan pohon memberikan data relevan mengenai hasil panen, alokasi variasi pertumbuhan dari masing-masing komponen tanaman, pengguguran material pohon secara alami dan proses pembusukan, semuanya berpengaruh pada kedua hal yaitu stok karbon tanah dan stok karbon sampah. Data yang telah dikumpulkan untuk masing-masing daerah biogeografis berdasarkan tipe tanah, tipe tanaman dan sistem penanaman dari waktu ke waktu, dimasukan ke dalam database relasional yang mendukung model FullCAM.

Baik UNFCCC maupun Protokol Kyoto mensyaratkan untuk menghitung hilangnya karbon biomasa sebagaimana cara karbon dipisahkan pada saat pertumbuhan kembali atau regenerasi hutan. Pada program input stok biomasa, tahapan pertumbuhan, parameter pohon dan parameter tanaman memberikan peta perkiraan biomasa pada saat pohon atau tanaman menjadi dewasa. Pada program input ini juga memberikan gambaran mengenai sejarah gangguan, tingkat pertumbuhan kembali, pengguguran alamiah, pembusukan dan pengaruh-pengaruh dari suatu sistem pengelolaan lahan. Sehingga pada akhirnya dapat diperkirakan jumlah stok karbon yang tersimpan dalam tanaman, batang pohon, daun, akar, sampah hutan dan membentuk sebuah model perubahan stok karbon.

B. NCAT (*National Carbon accounting Toolbox)*

Program NCAS yang telah dibangun saat ini telah memenuhi standar untuk menghitung emisi karbon berbasis lahan untuk tingkat nasional dan tingkat internasional. Program NCAS juga dapat digunakan untuk penghitungan karbon pada tingkat proyek atau wilayah kecil, yaitu dengan menggunakan program turunannya yang dikenal dengan program NCAT (National Carbon Accounting Toolbox).

Dengan program NCAT memungkinkan untuk melakukan penghitungan karbon dari aktifitas-aktifitas penggunaan lahan pada tingkat lebih rendah, seperti halnya tingkat desa, tingkat kecamatan, tingkat kabupaten ataupun wilayah tertentu. Program NCAT sendiri disediakan secara gratis di Australia dan dapat digunakan oleh pengguna untuk menghitung dan menghilangkan emisi karbon dioksida menggunakan data dan model yang sama dengan yang digunakan untuk skala nasional. Sebenarnya untuk kepentingan pembelajaran di Indonesia, program NCAS dan program NCAT beserta contoh-contoh datanya dapat diperoleh dengan meminta secara resmi ke pemerintah Australia.

Program NCAS dan NCAT secara berkesinambungan terus dilakukan pengembangan dan peningkatan kemampuan dan kegunaan sistem. Hal ini dilakukan agar kedua program tersebut dapat digunakan untuk menghitung emisi berbasis lahan dari gas-gas rumah kaca lainnya disamping gas karbon dioksida (CO_2), seperti halnya gas CH_4 (metana) dan N_2O (nitro oksida). Pengembangan program juga dilakukan dalam rangka memberikan biaya lebih rendah pada penggunaan penghitungan gas rumah kaca di tingkat proyek atau skala kecil.

Keberadaan sistem NCAS dalam lingkup internasional diantaranya yaitu digunakan dalam pendekatan kolaborasi oleh *Clinton Climate Initiative*. Pada proyek *Clinton Climate Initiative* program NCAS digunakan sebagai dasar untuk mengembangkan sistem pemantauan karbon global yang dapat membantu dalam pembangunan kehutanan berkelanjutan dan reboisasi dalam pasar karbon global.

NCAT (*National Carbon Accounting Toolbox*) dalam CD programnya berisi hal berikut : Satu set alat untuk melakukan pelacakan emisi gas rumah kaca dan perubahan stok karbon akibat pengaturan dan penggunaan lahan, model fullcam (Full Carbon Accounting Model) yang berasal dari Sistem akuntansi karbon nasional (NCAS), dokumentasi atau referensi teknis yang mudah diakses. Persyaratan teknis komputer untuk dapat menggunakan program NCAS maupun NCAT adalah sebagai berikut :

- Sistem operasi Win2000/NT4SP6/XP sp2
- CPU-Pentium 233MHz atau lebih cepat
- Memori minimal 256MB
- Hard Disk 120MB
- Resolusi tampilan minimal 800x600 dengan true colour
- CD Room
- Program browser Internet eksplorer 5 atau diatasnya

Program NCAS dan NCAT juga disediakan data satelit dalam bentuk DVD dan dikenal dengan istilah Data Viewer. Data Viewer tersebut berisi panduan penggunaan dan image satelit. Data image satelit yang ada diberikan yaitu selama 30 tahun terakhir. Dengan menggunakan snapshot, dari data satelit tersebut kita dapat melihat suatu wilayah dan dilakukan perbesaran, membandingkan perubahan suatu wilayah dari tahun ke tahun, membandingkan data iklim dan statistik tutupan lahan.

Data viewer juga dengan fasilitas *property* atau *regional scale* dapat menilai hal berikut: tempat dimana tutupan atau tajuk pohon berubah, daerah mana saja yang paling efektif dalam penanaman pohon, daerah mana saja yang menjadi target reboisasi, daerah mana saja yang mengalami kekeringan.

SIMPULAN

Akuntansi Karbon (*Carbon Accounting)* ternyata dapat mengurangi emisi gas CO_2 (karbondioksida), CH_4 (Metana), N_2O (Nitro oksida), PFCs (Perfluorocarbons), HFCs (Hydrofluorocarbons), SO_2, NOx, CO dan NMVOC yang dihasilkan oleh perusahaan dan dapat mengakibatkan pemanasan global yang berdampak dalam kehidupan umat manusia di seluruh dunia dengan cara mendeteksinya terlebih dahulu dan memberikan laporan emisi gas yang dihasilkan kepada perusahaan. Dengan demikian, perusahaan dapat mengantisipasi dengan cara perdagangan karbon atau dengan membatasi pengeluaran gas yang dihasilkan dari proses produksi perusahaan. Indonesia sendiri sudah meratifikasi Protokol Kyoto yang merupakan perjanjian internasional tentang pengurangan gas karbondioksida melalui pengesahan Undang-Undang Nomor 17 Tahun 2004, tanggal 28 Juli 2004 tentang Ratifikasi Protokol Kyoto. Selain itu Indonesia juga bekerja sama dengan Australia dan Cina dalam perdagangan karbon, tetapi sayangnya pemerintah belum mengimplementasikannya ke setiap perusahaan yang ada di Indonesia. Hal ini dikarenakan hukum dan SDM di Indonesia yang tergolong rendah.

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SURABAYA

Eco-Carbon Accounting for Evaluating Environmental Impacts and Co-benefits of Combined Carbon Management Projects: Application and Case Studies

Paper presented at the 3rd Annual Conference on Carbon Sequestration,
Alexandria, USA, 3-6 May 2004

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1. Introduction

As a consequence of the Kyoto Protocol, a large number of carbon management projects dealing with land use (in particularly forestry), renewable energy, and waste management are currently being developed and analyzed. Considering that carbon management practice is relatively sparse, it is not surprising that there exist a number of problems. Three shortcomings are of particular importance for the argument pursued in this article:

First, there is a discernible lack of integration and linkage of forestry projects and bio-energy projects utilizing wood wastes with other carbon management project types, such as those aiming at carbon reductions and removals through efficiency improvements in industry and power generation, renewable energy technologies, or waste management.

Furthermore, the separation of the certification and carbon credit evaluation procedures between these different project types could reduce the incentives for implementing these projects, for example under the Clean Development Mechanism (CDM) and Joint Implementation (JI) schemes.

Finally, although recommended, the evaluation of socio-environmental (SE) impacts and co-benefits is not integrated in a comprehensive way with the central carbon accounting process. Although carbon management projects affect local communities with socio-environmental impacts, and provide them with benefits, the need for corresponding quantitative impact/benefit assessment during the project planning and design phases has often been overridden by the perceived importance of economic analysis. In our view, however, all types of analysis should accompany and thus complement each other, in order to provide a richer picture for decision-making.

There are a number of studies in the literature pointing at possible ways to overcome these shortcomings. The Institute of Environmental Physics, Energy and Climate at the Swiss Federal Institute of Technology (2003) and the CarboEurope (2002) project have come up with methods and sets of criteria that aim at evaluating sustainable projects under the Clean Development Mechanism (CDM). Moreover, some ecological-economic analyses and environmental management studies, (for example Scott and Bilyard et al. 1998, and De Groot et al. 2002) address causal relations between human activities and SE impacts/co-benefits, and suggest a typology for the valuation of ecosystem functions.

In order to make inroads in terms of achieving a consistent and comprehensive carbon management framework, it is clearly necessary to first clarify and better understand the relations between project activities and SE impacts/co-benefits, and as well to develop approaches that can more holistically evaluate these impacts/benefits, and thus assist project managers and policy makers.

In order to achieve this objective, we propose several measures: First, carbon management practice should look at projects in integration, by linking the projects' accounts and evaluating their performance as one system. Based on such an evaluation, impacts can be minimised, and benefits be maximised in a coordinated, synergistic way.

To meet this end, we are developing a method which we term 'Eco-Carbon Accounting' (ECA), and which is designed to deal with carbon reduction effects and SE impacts/co-benefits. This method fulfils two basic functions: 1) the identification of relations between project activities, and carbon and socio-environmental impacts/benefits, and 2) the holistic evaluation of these impacts/benefits. The method is flexible in a spatial sense, since it can be applied at both an international project level (for example CDM) and a regional level (for example in a domestic strategic project).

In the following, we will first give a detailed outline of Eco-Carbon Accounting. In Section 3 we will present two case studies: one CDM project and one regional forestry project in Japan. The article is concluded in Section 4.

2. Eco-Carbon Accounting

An ECA task proceeds in two stages: First, a graphical model is set up, with compartments representing activities and impacts/benefits, and arrows linking these compartments representing causal links (see Fig. 1 and Section 2.1). In parallel, a numerical representation of the graph is compiled in form of an interactions matrix. At present, this model is created with the help of expert interviews, however a statistical approach is envisaged for future applications. Second, SE impacts/co-benefits and costs are evaluated quantitatively, based on the graphical model, using cash-flow and environmental-economic analysis. These techniques will be explained in detail in Section 2.2.

2.1. Graphical model

During the course of developing our accounting method, we found it helpful to express the causal model underlying our application in graphical form. This facilitates both clarity for the analyst in understanding the complexity of interactions, and visualisation for decision-makers. In designing the graphical model, we initially followed a simple cause-and-effect logic, but because of the nature of many carbon management projects, we subsequently saw the need to insert an intermediate layer (Fig. 1).

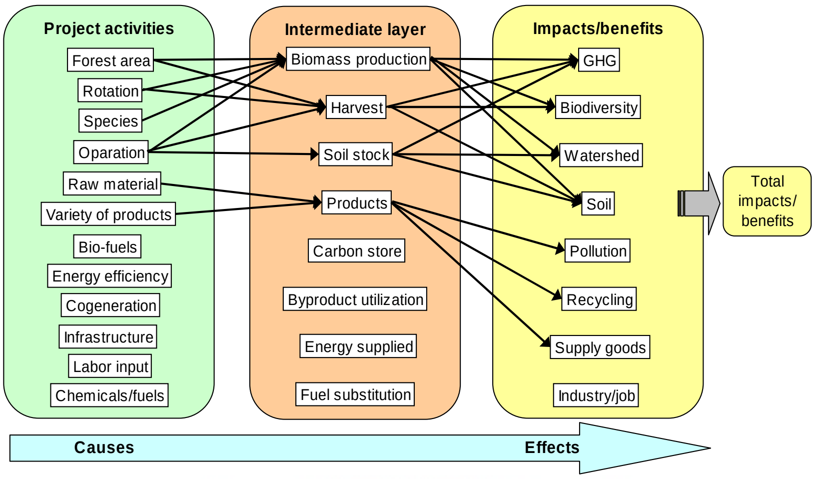

Fig. 1: Schematic of the graphical model

While dealing with practical case studies (see below), it has been convenient to frequently refer to the graphical model in order to clarify the relationships between project activities and SE impacts/benefits. The graphical layout is also adopted for the visualisation of the quantitative results following the data collection and analysis.

Another important function of graphs such as in Fig. 1 is that it eases the task of delineating each project system with a finite boundary. For example, for the purpose of the case studies documented in this paper, we defined a system boundary of combined carbon management projects which contains as project and intermediate activities (“cause” side): land use (afforestion, reforestation and forest management), biomass use by manufacturing industries, and bio-fuel use in energy supply and steel-making. On the “effect” side, we appraise four types of environmental impacts/co-benefits (greenhouse gas emissions, biodiversity, watershed, soil, and pollutant emissions), and three types of socio-economic impacts/co-benefits (recycling, commodity output, and job creation). Tab.1 below provides an overviews of cause-effect compartment.

Probably the most fundamental step of ECA is complementing the arrows in a graphical model of the type shown in Fig. 1 with numerical coefficients. This is a classical problem in ecological-economic analysis which was already encountered by Daly 1968) and Isard *et al.* 1972). Experiences from these and subsequent attempts have abundantly demonstrated the dearth of understanding about ecological-socio-economic interactions, and the utter lack of adequate data. As a consequence, instead of further pursuing an information-based approach, we focus on a value- or utility-based, anthropocentric approach to enumerate our transactions matrix, and hence apply “expert judgment”.

Accordingly, the data we collect are not observations, but responses from interviews, which reflect human judgment about the strength of correlations between the compartments in the graphical model. Each respondent is given a questionnaire showing an interaction matrix with cause and effect compartments labeled, but cells empty. The respondents’ task is to decide on the magnitude of correlation, based on their scientific and professional background and experience, but following a rating rule (Tab. 2).

Tab. 1: Project activities, intermediate output, and SE impacts/co-benefits

Cause-effect compartment	Explanation	Unit
Project activities		
Forest area	Plantation and cultivation area	ha
Rotation	Rotation length between plantation and clear-cut (final-cut); forestry operation methods	year
Species	Species selection for plantation and cultivation	-
Oparation	Intensity of thinnning and clear-cut, density of forest; forestry operation methods	%
Raw material	Raw material for manufacturing	m^3, t
Variety of products	Variety of wood products	-
Bio-fuels	Bio-fuel production as input for power plants	m^3, t
Energy efficiency	Energy conversion efficiency	%
Cogeneration	Sequential use of energy for the production of electrical and useful thermal energy	-
Infrastructure	Infrastructure input into process within the system boundary	$ or other
Labor input	Labor input into process within the system boundary	$ and emp-y
Chemicals and fuels	Chemicals input and fuel consumption into process within the system boundary, causing pollution within the system and elsewhere	L or t or J
Intermediate layer		
Biomass production	Standing biomass or standing crop, net primary production, amount of vegetable matter produced	t, m^3
Harvest	Harvest (natural resources)	t, m^3
Soil stock	Biomass or carbon content of soil	t or m^3
Products	Production of wood manufacturing	t, m^3
Carbon store	Carbon store until decay, related to product life cycle	t CO_2e
Byproduct utilization	Byproduct utilization within system boundary	%
Energy supplied	Supply of energy, such as sold electicity, used by manufacturing process	kWh, J
Fuel substitution	Substitute of fossil fuel by bio-energy	kWh, J
Impacts/benefits		
1)Environmental		
GHG	GHG balance: removals + storage - emissions	tCO_2e
Biodiversity	Biodiversity, value aspect of ecosystem	not yet quantified single unit
Watershed	Regulation of watershed and retention and storage of water resource	not yet quantified single unit
Soil	Soil conservation, such as erosion control	not yet quantified single unit
Pollution	Chemical safety, low emissions/pollution	t or ppm or other
2)Socio-economic		
Recycling	Cyclical use of resources, reducing waste	% or other
Goods/Services	Commodity output (goods and services), market value	$ or other
Industry/Job	Industrial income and job creation	$ and emp-y

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Tab. 2: Rating rule for respondents of questionnaire.

Rating by respondent	Value inserted in cell	Correlation coefficient*
Very strong	3	0.7
Intermediate	2	0.4
Weak	1	0.2
Absent	0	0.05

* We interpreted respondents as correlation coefficient by Iwanaga et al.(2003)

The correlation coefficients in Tab. 2 note that the respondents make their decision about the interaction strengths without prior knowledge about the correlation coefficients. The translation into the latter is made by the analyst, and yields a final transactions matrix (Fig. 2). A criticism of the interview approach is provided in Section 4.

Code	Cause-effect compartment	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	11	12	13	14	15	16	17	18
101	Forest area	-																											
102	Rotation	3	-																										
103	Species	3	1	-																									
104	Oparation	3	2	3	-																								
105	Raw material	3	2	2	1	-																							
106	Variety of products	2	2	3	1	2	-																						
107	Bio-fuels	0	0	0	0	0	0	-																					
108	Energy efficiency	0	0	0	0	0	0	3	-																				
109	Cogeneration	0	0	0	0	0	0	3	3	-																			
110	Infrastructure	1	1	0	1	1	2	3	2	2	-																		
111	Labor input	1	1	0	1	1	2	3	2	2	3	-																	
112	Chemicals/fuels	1	1	0	1	0	1	1	2	2	2	2	-																
113	Biomass production	3	3	3	2	1	1	0	0	0	0	0	1	-															
114	Harvest	3	3	3	3	3	2	0	0	0	2	2	1	3	-														
115	Soil stock	3	3	3	3	2	2	0	0	0	1	1	1	3	3	-													
116	Products	3	3	2	2	3	2	0	0	0	2	2	1	3	3	3	-												
117	Carbon store	0	0	1	1	1	2	0	0	0	1	1	1	1	3	2	2	-											
118	Byproduct utilization	1	1	1	1	2	2	1	1	1	1	1	1	3	3	2	3	3	-										
119	Energy supplied	1	1	1	1	1	1	3	3	3	2	1	1	2	2	2	3	2	2	-									
120	Fuel substitution	0	0	1	1	1	2	1	2	3	1	1	1	2	2	2	3	3	3	3	-								
11	GHG	3	3	2	2	3	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	-							
12	Biodiversity	3	3	2	3	1	1	0	0	0	1	1	1	2	3	2	3	2	2	1	2	2	-						
13	Watershed	3	3	2	3	2	2	0	0	0	1	1	1	3	2	3	2	1	1	1	1	2	3	-					
14	Soil	3	3	3	3	2	2	0	0	0	1	1	1	2	3	3	3	1	1	1	1	3	2	3	-				
15	Pollution	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	2	2	2	1	-			
16	Recycling	2	2	1	2	1	3	3	2	2	2	2	1	1	2	2	2	1	2	1	1	3	2	3	2	1	-		
17	Supply goods	2	2	2	2	3	3	2	2	2	2	2	1	0	2	2	3	1	1	1	1	2	2	3	2	1	3	-	
18	Industry/job	0	0	0	0	2	2	2	2	2	2	2	1	0	2	2	2	1	1	1	1	3	2	3	1	1	3	3	-

Fig. 2: An example interaction matrix.

After having arranged the interview data, the transactions matrix is subjected to quantitative causal analysis and path analysis (Kojima, 2002). These methods involve multivariate and covariance structure techniques.

The output of the quantitative causal analysis is visualised using a path representation, once again employing the compartmental graphic in Fig. 1. As a result, interactions are represented by cause-and-effect links between project activities, intermediate layers and impacts/benefits (Fig. 3).

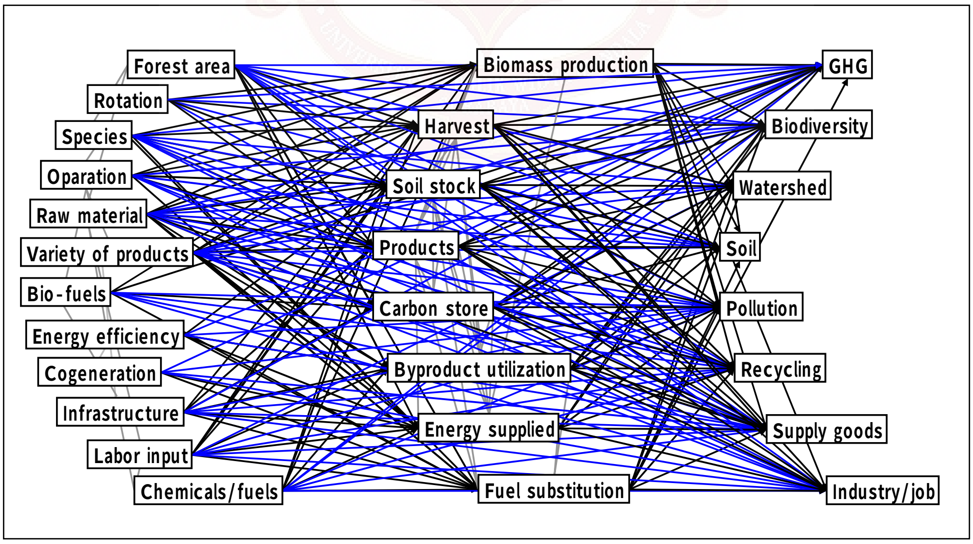

Fig. 3: Visualisation of outputs from quantitative analyses of interview data.

Ideally, Fig.3 would now be used for quantifying total impacts/benefits. However, the interactions matrix in Fig.2 could so for only be expressed as correlation coefficients in one compartment from causes in another. Therefore, in this preliminary study, total impacts/benefits were calculated separately (See 2.2).

2.2. Evaluation of total SE impacts/co-benefits and costs

SE impacts/benefits are evaluated as individual benefits as total benefit with a rating, and as multidimensional benefits.

First, we evaluated individual benefits, which are impact/benefits in terms of the compartments, for example GHG, biodiversity etc. From these, we can calculate total benefits as follows:

$$Benefit_{total} = F(Benefit_1; Benefit_2; ....; Benefit_i) \tag{1}$$

for the eight impacts/benefits compartments shown in Tab.1.

Of course, in order to be able to determine a total benefit measure, it is necessary to weight individual benefits.

In this study, we evaluated some quantifiable individual benefits as follows.

Individual benefits in terms of GHG are estimated as a net balance of GHG removals by forestry sink and emission reductions in manufacturing or bio-fuel power generation in units of tCO_2:

$$Benefit_{GHG} = \sum \left(GHGremovals_i + GHGstorage_i - GHGemissions_i \right) \tag{2}$$

Individual benefits of goods/services out put are estimated the sum of commodity values, at market prices in units US$.

$$Benefit_{goods/services} = \sum goods/services_i \tag{3}$$

Impacts of pollution from fuel consumption and chemicals use could be assessed, by using an environmental impact assessment method (for example LIME, Life-cycle Impact assessment Method based on Endpoint modeling; developed in the Research Center for Life Cycle Assessment at the National Institute of Advanced Industrial Science and Technology, 2003).

In order to further ease decision-making, some of these individual benefits – GHG, goods/services, and job creation – could be combined into a total benefit measure, expressed in terms of a unit of common understanding. One candidate for such a unit is the net present value (NPV), defined as,

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{4}$$

where B_t denotes benefits at time t, C_t costs at time t (both aggregated by summation), and r is the selected discount rate. If $NPV > 0$, the project is deemed beneficial.

Note that especially when applied to environmental issues, (monetary) cost-benefit analysis has significant drawbacks. First, and probably most importantly, some impacts such as biodiversity, soil and watershed are at present not quantifiable at all, and may not be for some time.

3. Case studies

3.1. Description of the project activities

So far, two case studies are able to provide an insight into how ECA might be applied to real-world applications, and what experiences could be gleaned from the outcomes. These case studies are 1) a feasibility study on an international afforestation project in the scope of the Clean Development Mechanism (CDM) carried out by a Japanese paper company, and 2) a feasibility study for a domestic Japanese strategic project involving forest cooperatives and wood manufacturing industries in the Maniwa region of Okayama prefecture (details in Tab. 3).

Tab. 3: Summary of the two projects assessed using ECA.

Case study	CDM project in Madagascar 1)		Regional carbon management project in Japan 2)	
Location	Toamasina		Maniwa, Okayama	
Project life time (year)	30		30	
Combined-project components	Base line	Project	Base line	Project
1) Afforestation/Forest management	abandoned land	afforestation	forest management	forest management
Area (ha)	-	10,000	25,000	25,000
Species	-	eucalypts	cedar and cypress	cedar and cypress
Rotation (year)	-	10	45	90
Intensity of thinning and clear-cut	-	favorable(100%)	weak(40%)	favorable(100%)
2) Wood material manufacturing	-	chipping and charcoal factory	wood mill	wood mill and charcoal factory
Variety of products	-	chips, charcoals	timber, chips, biomass materials	timber, chips, charcoals, biomass materials
3) Renewable energy	-	installed in factories	-	installed in factories
Bio-fuels	-	wood waste	-	harvest and wood waste
Energy power (MW)	-	2.4	-	8.0
Electricity	-	factory utilize and supply to power grid	-	supply to power grid
4) Carbon storage	-	-	-	charcoals for agriculture

1) The project scenario and related data was obtained from Oji Paper Co. LTD (2004) . A part of bio-energy project scenario was assumed in this study.

2) The project scenario and related data was obtained from the latest study of Nomura (2004)

3) Implementation rate of thinning and clear-cut based on an operation plan(%)

3.2. Results of the two ECA case studies

As already outlined in Fig. 1, we estimated four types of SE impacts/co-benefits resulting from the combined carbon management project. These are two environmental impacts (emission of greenhouse gases and pollution), one economic benefit (commodity output, that is goods and services), and one social benefit (job creation). We estimated a base line scenario and project scenario for each impacts/co-benefits, and compared them (Tab. 4).

Tab. 4: Four types of SE impacts/co-benefits resulting from the combined carbon management project

Impacts/ benefits[1]	Environmental						Socio-economical				
Project	GHG[2]			Pollution			Goods/services			Job creation	
CDM Madagascar	Removals	$ktCO_2$	36	SO_x	t	27	Chip	10^3m^3	4,000	Employment (Person)	254
	Reductions		43	NO_x		73	Charcoal	10^3t	9		
	Storage		0	Total[4]	10^6_{LIME}	0.07	Electricity	GWh	224		
	Total		80								
	10^6US$[3]		7.3	10^3US$		-	10^6US$		171	10^6US$	5.8
	% of total cost		4.1	% of total cost		-	% of total cost		95.7	% of total cost	0.03
National project Maniwa, Japan	Removals	$ktCO_2$	8,369	SO_x	t	409	Timber	10^3m^3	1,836	Employment (Person)	615
	Reductions		1,634	NO_x		278	Chip	10^3m^3	1,832		
	Storage		237	Total[4]	10^6_{LIME}	574	Biomass materials	10^3m^3	900		
	Total		10,240				Charcoal	10^3t	72		
							Electricity	GWh	2,635		
	10^6US$[3]		51	10^3US$		-	10^6US$		3,772	10^6US$	1,007
	% of total cost		1.1	% of total cost		-	% of total cost		85	% of total cost	23

1) SE impacts/benefits shows sum during project periods（30 years).
2) Accounting method of carbon is the base line and credit approach.
3) A carbon credits of removals by sink is adopted a temporary credit.
4) Integrated values by LIME (Research Center for Life Cycle Assessment,2003).

Before total impacts and benefits were calculated, the systems had to be delineated by a boundary. Fig. 4 provides a self-explanatory schematic of the result of this process, and for the sake of brevity, no further details shall be provided here.

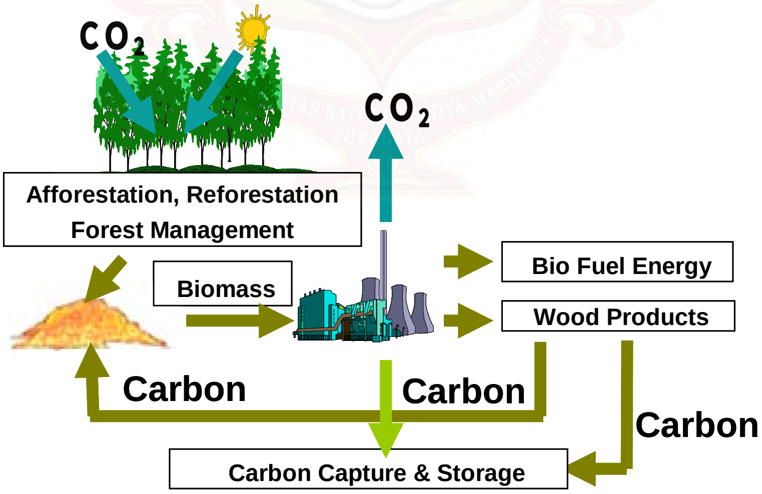

Fig. 4: Boundary chosen for Eco-Carbon Accounting (ECA) of the two case studies.

In order to evaluate the total SE impacts/co-benefits and costs in economic terms, a number of estimations were carried out. Economic benefits arising out of the revenue from selling carbon credits and renewable energy were established as follows: The revenue from selling carbon credits was used as an estimate of the economic benefit of reduced greenhouse gas emissions, while the revenue from selling renewable electricity to the power grid was used as an estimate of the economic benefits of the renewable energy supplied.

In these calculations, the electricity price in Madagascar was taken as 0.04 US$/kWh, while that in the Maniwa region is 0.1US$/kWh. As for the revenue from carbon credits, ideally a shadow price should be assumed. However, reliable shadow price estimates are hard to come by. Even though some approximations are available, for example from the DNE21 model by Fuji and Yamaji (Akimoto et al., 1998), it was decided to follow a conservative approach (compare Nomura 2003: Latest study) by using the present market price of carbon (data obtained from the feasibility report; Oji Paper Co. LTD, 2004).

Based on these data we arrive at the following results:

	Madagascar	Maniwa
Carbon credit revenue	4.3 %	1.4 %
Renewable energy revenue	5.2 %	7.1 %

Finally, we estimated the net present value (NPV) of the project using ECA, including both revenues from carbon credit and renewable energy sales. The discount rate for economic benefit was set to be 5%.

3.2.1 The Madagascar case study

This CDM project scenario stretches over 30 years. Clear-cutting occurs first after 10 years and then after 20 years, with a subsequent 10-year harvest period each clear-cut. Post-harvest removals are excluded from our analysis. So this is the main reason for the relatively small removals in Tab.4.In a comparative analysis, this CDM projects would provide many socio-economic benefits, goods/services output and would create job creation.Using wood waste would provide charcoal (equivalent for 200 households per year) and renewable energy to local communities and cities in Madagascar.

On the other hand, project would bring about additional negative environmental impacts, for example pollution in terms of SO_x and NO_x, and watershed impacts. However, table.4 shows that these impacts are only minor, and in Madagascur there are no environmental regulations anyway.

In this study, because of lack of data, we could not assess impacts of soil and watershed, however there assessment is necessary.

Carbon credits and renewable energy revenue both increase the NPV of the project, estimated at about 3 million US$.

3.2.2 The Maniwa case study

With the help of the graphical model and the interaction matrix analysis, a few interesting findings could be distilled from the data collected in the interviews. First, a longer rotation period applied during forest management would yield an increased biomass production, which in turn would positively affect greenhouse gas sequestration. Longer rotation might also increase soil stock and provide benefits for the watershed, however these effects could not be enumerated in this preliminary study because of a lack of data. The downside of this management change would of course be that less timber could be harvested, resulting in a diminished value of commodity output (goods and services), and hence negatively affecting society.

Second, increased utilisation of biomass wastes positively influences greenhouse gas sequestration, either through replacement of fossil energy by biofuels, or through storage of carbon in charcoal and other wood products. In addition, some of the wood waste products require labour and acquire added commodity value, and thus increase output. On the other hand, employment, income and output are lost in the traditional energy supply industries due to the replacement of fossil fuels.

Third, an increase in the intensity of forest thinning and clear-cut would increase the harvest and in turn wood/biomass product output, jobs and social benefits, but would decrease greenhouse gas reductions because of low carbon removal rates.

Carbon credits and renewable energy revenue would increase the NPV slightly. Nevertheless for Maniwa, the NPV was estimated to be negative at about 172 million US$. This result is caused by factors, such as industrial structural problems associated with high cost of forest management and low prices of logs and wood products.

4. Preliminary conclusions and research outlook

In this study we have introduced the Eco-Carbon Accounting (ECA) method, and investigated how this method can be applied to carbon management projects that focus on forestry activities. For these projects we have defined and causally connected 28 compartments that contain indicators for socio-economic-environmental impacts and benefits, using a graphical model. This graphical model provides the underlying framework for ECA, by providing a clear picture of a project system’s interdependencies, both assisting the analyst during the investigation, and the decision-maker in interpreting results, and deciding on priorities for initiating changes towards improved management.

During the Maniwa case study we found a strong influence of the rotation period, the intensity of forest thinning and clear-cut, and the utilisation of biomass wastes, on greenhouse gas avoidance and removals, through replacement of fossil fuels and storage of carbon in wood products, which in turn contribute to economic output and employment creation.

We would like that this is an ongoing study and that the findings presented here are preliminary. We are aware that our method needs improvements, in terms of concepts and methodology, as well as regarding the information and data used. One aspect that we plan to address is the substitution of the expert interview stage with statistical approaches, as much as possible. We recognise the problem of involving human judgment into the analytical process, and the subjectivity and qualitativeness it entails. Experimental psychology and social research will be consulted in order to shed more light on the validity of this approach. We envisage that more numerical approaches such as the Delphi method (Linstone, H. and Turoff, M editors,) will subsequently replace interviews and questionnaires.

Other changes will have to address the problems of uncertainty of relationships and the quantifiability of indicators. During both the intermediate cause-effect modeling and the final impact/benefit/NPV calculation only quantifiable indicators were considered. A wealth of not (yet) quantifiable indicators is necessarily left out. Even those indicator that lend themselves to quantitative analysis, are of varying nature and expressed in incommensurable units, requiring multi-criteria decision tools, weighting, and sustainability criteria. An analytical hierarchy process (AHP) method could assist in gaining ground on this front.

In addition to requiring modification, the method needs to be extended as well. The present study operates with a limited number of compartments only for the sake of simplicity during method development. Exogenous factors such as climatic, geographical and ecosystem features as well as market demand and prices should be incorporated if adequate data can be found. Probably even more important for the immediate business environment of the decision-maker are community issues, for example of cultural/religious and recreational nature, which can at times be strongly linked to industry activities affected by carbon management projects. In particular, stakeholders will be concerned about issues of land use, and stakeholder relationships therefore need to be a future compartment of the ECA framework.

In spite of this host of shortcomings and challenges, we believe that the ECA method that we have developed – once matured – has many applications such as

- certification of sustainable carbon credits at both project and regional level,
- informing decision-makers, policymakers and investors,
- project design and assessment,
- ongoing monitoring and management of projects, and
- accounting of global carbon sequestration activities including carbon capture and storage.

This study – although preliminary – is a first attempt to sketch a consistent, comprehensive and holistic approach to carbon accounting which, after being exposed to critical review and improved in an iterative process, will hopefully progress to a stage where it will be able to be applied widespread.

Acknowledgment

We wish to thank to the helpful advice and cooperation from participants of Oji Paper co. Ltd, The Oakayama Cooperation Conference, Mr. Tasuo Hoshihara, an executive director of Maniwa forest owner’s cooperatives, Juta Taniguchi, Tadashi Ohara and forestry administrators of Kuse and Regional Development Bureau of Maniwa. Special thanks to Manfred Lenzen, The University of Sydney for giving scientific advice.

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Carbon-accounting methods and reforestation incentives[1]

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Contributed Paper to the 46th Annual Conference of the Australian Agricultural and Resource Economics Society
Canberra, Australian Capital Territory, 13-15th February 2002

ABSTRACT

The emission of greenhouse gases, particularly carbon dioxide, and the consequent potential for climate change are the focus of increasing international concern. Eventually, an international agreement will likely be enacted to reduce greenhouse gas emission levels and assign rules for emission trading within and between countries. Temporary land-use change and forestry projects (LUCF) can be implemented to offset permanent emissions of carbon dioxide from the energy sector. Several approaches to accounting for carbon sequestration in LUCF projects have been proposed. In this paper, the economic implications of adopting some of these approaches are evaluated in a normative context, based on simulation of Australian farm-forestry systems.

Keywords: climate change, carbon accounting, reforestation, bioeconomics

INTRODUCTION

Concerns over global warming have led to proposals for the establishment of markets for greenhouse gas emissions. Although formal markets have not emerged, a number of international exchanges have occurred, whereby power companies and other energy-intensive industries have invested on "green" projects, to partially offset their emissions of carbon dioxide (CO_2) and other greenhouse gasses (GHG).

Until recently, the Kyoto Protocol (KP) has provided the context within which much of the policy debate on global warming has occurred. The KP established a commitment period (2008 to 2012) over which Annex I countries[2] would undertake to reduce their greenhouse gas emissions by an aggregate 5 percent relative to their 1990 emissions. The recent collapse of the KP, caused by the withdrawal of the USA, means that the first commitment period and other rules set by KP may not stand. However, global warming processes will continue to operate and, eventually, some sort of international agreement will have to be ratified. Such an agreement is likely to contain provisions for exchange of greenhouse-gas emission permits. Over the last decade or so, a large amount of high-quality scientific contributions have been made to the United Nations Framework Convention on Climate Change (UNFCCC), particularly through the Intergovernmental Panel on Climate Change (IPCC), which has produced a number of technical reports. Many of these contributions will influence the shape of the agreement that may eventually be reached to replace the KP.

The KP contains two articles of special relevance to this paper:

Article 6 states that "any Party included in Annex I may transfer to, or acquire from, any other such party emission reduction units resulting from projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of greenhouse gasses in any sector of the economy", subject to certain provisos. This mechanism covers the so-called activities implemented jointly (AIJ). The proposed medium of exchange under this Article is the ERU (Emission Reduction Unit).

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[1] Working paper CC04. ACIAR project ASEM 1999/093, http://www.une.edu.au/febl/Econ/carbon/.

[2] Annex I countries include the OECD countries (except Mexico and Turkey) and transition economies in eastern Europe.

Article 12, The Clean Development Mechanism (CDM), has the purpose of assisting " Parties not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention, and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments...". The proposed medium of exchange under this Article is the CER (Certified Emission Reduction).

We use the term "carbon credits" to refer to both exchange mechanisms throughout this paper. There has been much debate regarding the kinds of activities that may receive credit under these Articles and the meaning of various definitions (e.g. see Watson *et al.* 2000). Much of the controversy has been in regard to land-use change and forestry (LUCF) activities. Forestry and other land-use activities act as sinks of greenhouse gasses, particularly CO_2. Growing forests contribute to the reduction of net CO_2 emissions by fixing carbon in wood, leaves and soil. Some Parties (particularly the European Union) are opposed to the eligibility of LUCF projects for carbon credits, while other Parties (particularly the USA) argue in their favour. The problem of *permanence*, which is the focus of this paper, arises because LUCF projects tend to be temporary in nature, since CO_2 captured during forest growth is released upon harvest. In contrast, projects in the energy sector that reduce emissions are permanent, in the sense that an avoided emission will never reach the atmosphere.

So, in comparing sources and sinks, the duration of a carbon sequestration project is important because, whereas technological advances in the energy sector have a permanent mitigation effect, forestry projects will release carbon upon harvest. Smith *et al.* (2000) point out that "non-permanent forestry projects slow down the build up of atmospheric concentrations, unlike energy projects, which actually reduce emissions. Non-permanent forestry projects should therefore be regarded as an intermediate policy option".

The problem of permanence must be addressed before LUCF projects are acceptable in a carbon-credit market. Proponents of LUCF projects point to several advantages of temporary sequestration; such as (i) some proportion of temporary sequestration may prove permanent, (ii) deferring climate change has benefits, (iii) temporary sequestration 'buys time' while affordable energy technologies are developed, and (iv) temporary sequestration projects have value in saving time to gain information on the process of global warming (Lecocq and Chomitz 2001).

In this paper, we review four accounting methods that have been proposed to allow sources and sinks of greenhouse gasses to be compared and measured by a common unit of exchange. We use a numerical example to show the economic implications of these different accounting methods from the standpoint of an individual firm. We then discuss the implications of our results from a policy perspective and identify possible obstacles to implementation.

THE ROLE OF LAND-USE CHANGE AND FORESTRY

Although the main focus in the battle against global warming is on emissions (sources), sinks, such as carbon sequestration, have also received considerable attention. Through the process of photosynthesis trees absorb large quantities of CO_2 from the atmosphere. CO_2 remains fixed in wood and other organic matter in forests for long time periods, and hence trees are a convenient way of sequestering carbon from the atmosphere to reduce net emissions.

A forest will fix carbon while it grows, but it will release CO_2 after harvest. The fate of harvested forest products may influence the choice of systems considered efficient for greenhouse gas control. Depending on harvest techniques, a substantial amount of CO_2 may be released back to the atmosphere within a decade after harvest occurs. Also, the merchantable portion of trees releases some CO_2 during processing, but a considerable portion of carbon remains fixed in timber products for a long time.

Lecocq and Chomitz (2001) use an optimal control model of global mitigation strategies to show that temporary sequestration projects can be cost effective in the short to medium run provided the marginal damages of climate change are high enough. They also point out that temporary sequestration contracts make sense when it is desirable to keep CO_2 concentrations below a threshold, then "the sequestration project serves to bridge the "hump" of high energy abatement costs" (Lecocq and Chomitz 2001, p. 21). In this case sequestration follows a bang-bang optimal dynamics.

If the incentives are right, the physical environment may be radically affected by changed patterns of land use associated with the emergence of carbon markets. Surface flora and fauna, both in and adjacent to new forests, is likely to change as land uses evolve to incorporate incentives arising from the carbon markets. Trees provide environmental benefits such as soil erosion control and fertility maintenance in addition to carbon-sequestration services. In Australia, for example, there is a sizeable dryland salinity problem, which can be partially controlled through tree planting. However, there is generally no private incentive to address the problem because (downstream) landholders who benefit from tree planting are often not the same as those (upstream) who incur the cost of planting the trees. Hence, incentives for increased tree production to control global warming may have secondary benefits in the form of reduced land degradation.

RADIATIVE FORCING AND GLOBAL WARMING

The impact of a greenhouse gas (GHG) on global warming depends on the amount of heat that is blocked from escaping into space (Fearnside *et al.* 2000). This is explained by the concept of *radiative forcing*.

On average over a year, about a third of solar radiation entering Earth is reflected back to space; the remainder is absorbed by land, ocean and ice surfaces, as well as by the atmosphere. The solar radiation absorbed by the Earth surface and atmosphere is balanced by outgoing (infrared) radiation at the top of the atmosphere. Some of the outgoing radiation is absorbed by naturally occurring greenhouse gasses and by clouds. A change in average net radiation at the top of the troposphere is known as *radiative forcing*. An increase in atmospheric GHG concentration leads to a reduction in outgoing infrared radiation and hence to positive radiative forcing, which tends to increase global temperatures (IPCC 1995).

Although there are several greenhouse gases, CO_2 has received the most attention, because of its concentration in the atmosphere and because it is the main gas emitted by burning fossil fuels. Gasses differ in their capacity to cause global warming, and their resident times in the atmosphere also vary. Greenhouse gas emissions are measured in CO_2 equivalents, a measure that takes the warming potential of individual gasses into account[3]. The measurement of CO_2 equivalents is based on an arbitrary time period of 100 years. This arbitrary time horizon was used by Moura-Costa and Wilson (2000) and Fearnside at al. (2000) to derive equivalence factors between temporary sequestration and emission reductions, and we apply their techniques in this paper.

The approach proposed by Moura-Costa and Wilson (2000) is based on the concept of absolute global warming potential (*AGWP*), which is defined as the integrated radiative forcing of the gas in question (Houghton *et al.* 1995):

$$AGWP(x) = \int_{0}^{T} a_x \cdot F\left[x(t)\right] dt \tag{1}$$

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where T is the time horizon (years), a_x is the climate-related radiative forcing caused by a unit increase in atmospheric concentration of gas x and $F(\bullet)$ is the time decay of an emitted pulse of x.

CO_2 added to the atmosphere follows a complex decay path. There is an initial fast decay caused by uptake by the biosphere over the first 10 years or so; followed by a gradual decay over the next 100 years or so reflecting transfer to the ocean and, finally a very slow decline occurs over thousands of years as carbon is transferred to deep ocean sediments (Houghton *et al.* 1995, p. 217). To evaluate this decay process, the IPCC Special Report on Climate Change used a carbon-cycle model that incorporates interactions between the atmosphere, oceans and land systems (the "Bern model"). A simplified fractional CO_2 decay function was then derived to crudely characterize the CO_2 removal processes by biosphere and oceans (Houghton et al, 1995, p. 218). This function was used by Moura-Costa and Wilson (2000) to derive their equivalence factor between sequestration and emission reduction.

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[3] Other important greenhouse gasses in the context of land use are methane and nitrous oxide, which have 21 and 310 times the warming potential of CO_2, respectively.

The ‘revised Bern model’, which incorporates greater uptake by the biosphere and hence increases the value of temporary sequestration of CO_2, was later used by Fearnside *et al.* (2000). The function is:

$$\begin{aligned} F[CO_2] = {} & 0.175602 + 0.137467\exp\left(-t/421.093\right) + \\ & 0.185762\exp\left(-t/70.5965\right) + 0.242302\exp\left(-t/21.42165\right) \\ & + 0.258868\exp\left(-t/3.41537\right) \end{aligned} \tag{2}$$

This function is plotted in Figure 1 and compared with the original function used by Moura–Costa and Wilson (2000) to derive their “tonne-year approach”. Substituting equation (2) for $F[x(t)]$ into equation (1), and setting $a_x = 1.0$ and $T = 100$, results in a value of $AGWP$ of 46.4. This means that a LUCF project would have to keep the agreed amount of CO_2 off the atmosphere for 46 years in order to receive the same credit as an energy project that decreases emissions by the same amount. This value is the *Equivalence Time* (T_e), assuming a linear relationship between the residence of CO_2 in the atmosphere and its radiative forcing effect over the time horizon T. The *Equivalence Factor* (E_f) is $1/T_e$ (Moura-Costa and Wilson 2000) and estimates the effect of keeping 1 t CO_2 out of the atmosphere for 1 year. Given equations (1) and (2), $E_f = 1/46.4 = 0.0215$. This factor is used below to derive a profit function under tonne-year accounting.

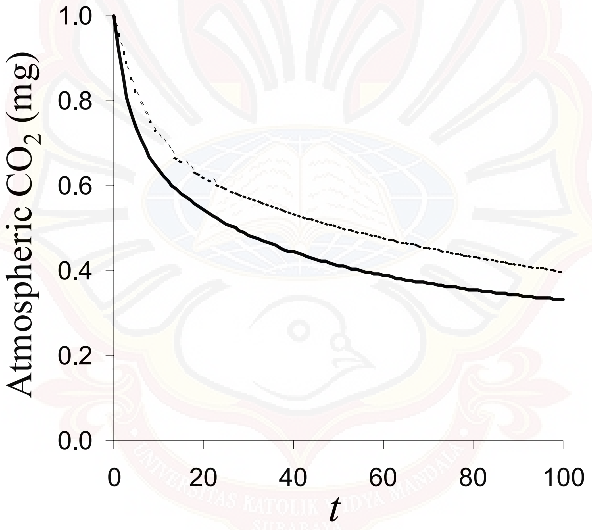

Figure 1. Alternative decay functions for one unit of CO_2 emitted to the atmosphere. Dashed line is the function used by Moura-Costa and Wilson (2000), solid line is the revised Bern model reported by Fearnside *et al.* (2000).

ALTERNATIVE CARBON-ACCOUNTING SYSTEMS

The theoretically ideal accounting system

From an economic standpoint, the theoretically correct way of accounting for carbon-sequestration payments is to estimate the stream of sequestration services provided in perpetuity. Payment for carbon sequestration must occur as the service is provided and, when the forest is harvested, the value of the carbon released back into the atmosphere must be paid back by the forest owner (eg. some credits would be redeemed). The need for using an infinite time horizon arises when we wish to compare energy projects (or forest conservation projects) against forestry projects, because the former have a permanent effect on atmospheric carbon stocks, while the latter exhibit periods of slow carbon accumulation followed by periods of quick release of carbon to the atmosphere. Although such a detailed accounting system is not possible in practice, the scheme discussed below represents the ideal situation against which alternative policies for actual implementation of the system should be compared.

Consider the case of a landholder evaluating the prospect of planting trees. The value of a stand of forest in the presence of carbon-sequestration payments and with redemption upon harvest can be represented as:

$$\pi(T) = v(T)\cdot p_v \cdot e^{-rT} + \int_0^T \dot{b}(t)\cdot \upsilon \cdot p_b \cdot e^{-rt}\,dt - c_E - b(T)\cdot \upsilon \cdot p_b \cdot e^{-rT} \tag{3}$$

where $\pi(T)$ is the net present value (NPV) of a forest harvested in year T after planting. The first term on the right-hand side represents the value of the timber harvest, the second term represents the value of the total flow of carbon sequestered in the interval $(0, ..., T)$, c_E is the establishment cost, p_v and p_b are the prices of timber and biomass carbon respectively, υ converts biomass carbon into CO_2 units, and r is the discount rate. The state variables $v(t)$ and $b(t)$ are, respectively, the timber volume in cubic meters per hectare (m^3/ha) and the carbon contained in forest biomass in tonnes per hectare (t/ha), at time t. The last term in (3) represents the assumption that credits obtained during forest growth have to be fully redeemed upon harvest (at time T). Timber yield at harvest is estimated by solving the differential equation:

$$\dot{v}(t) = \frac{dv}{dt} = f\big(v(t)\big) \tag{4}$$

This function is then used to estimate carbon sequestration, $\dot{b}(t)$, as explained below. The profit function defined in (3) accounts only for one forest cycle, and ignores the profits from future harvests. To account for multiple cycles the profit function becomes:

$$NPV = \pi(T) + \frac{\pi(T)}{e^{rT} - 1} \tag{5}$$

where the last term on the right-hand side represents the opportunity cost of delaying the harvest. By maximising (5) with respect to T we find the optimal forestry cycle-length for an infinite planning horizon.

The objective function (5) allows comparison between emission reductions in the energy sector and sequestration in the forestry sector, as it accounts for an infinite planning horizon. This approach may not work in practice because (i) the cost of accurately measuring annual carbon flows may be too high, especially in remote locations; and (ii) the risk of a forestry project defaulting on its “permanent capture” commitment may be unacceptable. How can we guarantee that the forestry cycle will continue in perpetuity? The problem is compounded by the possibility that future rotations may not be as productive as the first, because of soil exhaustion, and so the carbon stock may be eroded over time unless measures are taken to maintain soil productivity.

It must also be noted that this mechanism may be too harsh because, whereas the total amount of credits are redeemed upon harvest, not all carbon is being released back to the atmosphere. The amount of biomass carbon released depends on the final use of the harvest (consider firewood as compared to construction timber). However, it may not be economically feasible, or desirable, to track the fate of forest products after harvest.

Tonne-Year Accounting

An alternative to the method described above is to use the equivalence factor derived from the *AGWP* for CO_2. This method does not require redemption of carbon credits upon harvest. Under this accounting method the objective function becomes:

$$\pi_E(T) = v(T) \cdot p_v \cdot (1+r)^{-T} + \sum_{t=0}^{T} \left[b(t) \cdot \upsilon \cdot E_f \cdot p_b \cdot (1+r)^{-t} \right] - c_E \tag{6}$$

This method has the advantage that no guarantee is required to ensure that the project will last T_e years, as the annual payments are adjusted by the equivalence factor. If the project is abandoned and the carbon is released there is no need to recover payments.

Ex-Ante Full Crediting

Another accounting method discussed by Moura-Costa and Wilson (2000) consists of awarding carbon credits in full when the project starts. This requires a commitment that the project will last for T_e years after the agreed-upon forest carbon stock has been reached. The objective function becomes:

$$\pi_A(T+T_e) = v(T+T_e) \cdot p_v \cdot (1+r)^{-(T+T_e)} + b(T) \cdot \upsilon \cdot p_b - c_E \tag{7}$$

Under this method the fate of the carbon sequestered in year t is irrelevant after $t+T_e$ years from an accounting standpoint. This method will provide strong incentives for forest establishment, because of the large initial carbon-credit payment, provided that the cost of providing a guarantee of permanence is not too high.

Ex-Post Full Crediting

The final accounting method analysed here, also proposed by Moura-Costa and Wilson (2000), consists of a full carbon-credit payment when the project reaches T_e years. The objective function becomes:

$$\pi_P(T+T_e) = v(T+T_e) \cdot p_v \cdot (1+r)^{-(T+T_e)} + \sum_{t=0}^{T} \dot{b}(t) \cdot \upsilon \cdot p_b \cdot (1+r)^{-(t+1+T_e)} - c_E \tag{8}$$

Although this method does not require a guarantee, the delayed payment eliminates the incentive provided by a cash flow in the early years of the project; discounting also reduces the attractiveness of the final payment.

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A NUMERICAL EXAMPLE

The growth of a forest stand can be represented by Chapman-Richards functions (Harrison and Herbohn 2000, p. 75), for timber volume (*v(t)*) and basal area (*a(t)*), respectively:

$$\frac{dv}{dt} = \alpha_v \cdot v(t)^{\beta_v} - \gamma_v \cdot v(t) \tag{9a}$$

$$\frac{da}{dt} = \alpha_a \cdot a(t)^{\beta_a} - \gamma_a \cdot a(t) \tag{9b}$$

The α, β and γ parameters in (9a) and (9b) are specific to a given tree species and may be affected by climatic and soil characteristics. Equation (9a) was substituted into equation (4) to implement the ideal accounting method.

The solutions for the differential equations (9a) and (9b) are, respectively:

$$v(t) = \theta_v \left[1 - \exp\left(-\gamma_v (1-\beta_v) \cdot t\right)\right]^{1/1-\beta_v} \tag{10a}$$

$$a(t) = \theta_a\left[1 - \exp\left(-\gamma_a\left(1 - \beta_a\right)\cdot t\right)\right]^{1/1-\beta a} \tag{10b}$$

where the maximum values at steady state are given by the θ parameters, as follows:

$$\theta_v = \left(\frac{\alpha_v}{\gamma_v}\right)^{1/_{1-\beta_v}} \tag{11a}$$

$$\theta_a = \left(\frac{\alpha_a}{\gamma_a}\right)^{1/_{1-\beta_a}} \tag{11b}$$

Equations (10a) and (10b) are useful to estimate parameter values from data. Equation (9a) is useful to estimate the annual carbon sequestration rate, and equation (10b) is useful to estimate the average diameter (cm) of individual trees in the forest stand, as explained below.

If wood density and the carbon content of biomass are known, the stock of carbon in stemwood at any time is:

$$w(t) = \delta \cdot v(t) \tag{12}$$

where *w(t)* is the biomass content of the stemwood in tonnes of carbon per hectare (tC/ha) and δ is the carbon content per cubic meter of wood (tC/m^3). Equation (12) considers only stemwood and underestimates the carbon content of the forest, as *w(t)* may represent up to about 70 percent of the biomass contained in a forest, which also includes branches, foliage and soil carbon. The ratio of forest biomass to stemwood biomass depends on the type of trees and on the age of the trees. Young trees generally have more foliage and branches relative to stem than old trees. Based on the paper by Kischbaum (2000) we derived the function:

$$b(t) = \phi \cdot \left[\left(\delta \cdot \theta_v\right)^{\mu} \cdot w(t)\right]^{1/_{1+\mu}} \tag{13}$$

where *b(t)* is standing biomass in terms of carbon (t C/ha), ϕ and μ are parameters determined by tree shape, and the remaining variables have been previously defined. Note that *b(t)* includes timber and branches but not carbon contained in soil and roots.

The average diameter (*dbh*, cm) of individual trees in the forest stand at any time is given by:

$$dbh(t) = 200 \cdot \sqrt{\frac{a(t)}{pi \cdot tph}} \tag{14}$$

where *pi* is 3.1416 and *tph* is the number of trees per hectare.

Land-use Scenarios and Model Calibration

Any carbon-accounting method must consider the baseline. That is, the stocks and flows of carbon under the present land use, or under “business as usual”, must be evaluated. Only the carbon sequestered in the project above that which would have been sequestered without the project would receive credits. For simplicity we assume a baseline of zero.

Table 1. Tree parameter values used in the model, estimated from data reported by Wong *et al.* (2000).

Parameter	Site 1	Site 2
α_v	4.279	3.880
β_v	0.734	0.785
γ_v	0.713	1.171
α_a	2.810	3.784
β_a	0.420	0.800
γ_a	0.240	1.915

Tree-growth parameters for equations (9a) and (9b) are presented in Table 1 for two sites in south-eastern Australia. These parameters were estimated statistically based on values reported by Wong *et al.* (2000) for *Eucalyptus nitens* (commonly known as Shining Gum). The two sites are described in Table 2. Site 1 is a high-rainfall site and Site 2 is a moderate-rainfall site.

Table 2. Site Characteristics.

	Site 1	Site 2
Site code	VRV140	EP205
Location	Gippsland, VIC	Mount Gambier, SA
Date Planted	August 1986	July 1988
Previous Land Use	Improved Pasture	Pasture
Annual Rainfall (mm)	1212	766
Average Temperature (^{o}C)	January: 10.5 – 22.2 July: 3.6 – 10.0	January: 11.4 – 23.7 July: 5.1 – 12.9
Annual Pan Evaporation (mm)	1018	1262
Slope	Gentle (24 – 28 percent)	Gentle
Altitude (m)	380	60
Soil Type	Sand over medium clay	Structured, clay loam

Source: Wong *et al*. (2000).

Observed and predicted values for timber volume for *E. nitens* for the two sites are presented in Figure 2. Both sites were selected to perform the analysis of carbon-accounting methods to gain insight into the consequences of differences in the temporal path of sequestration to reach a given steady state.

Base values for other parameters used in the numerical model are presented in Table 3. Note that the price of timber is a function of tree diameter. The price of carbon and discount rate are subject to sensitivity analysis later on. Results of running the models represented by equations (3), (6), (7) and (8) with the parameters in Table 3 for trees at both sites (Table 1) are presented in the next section.

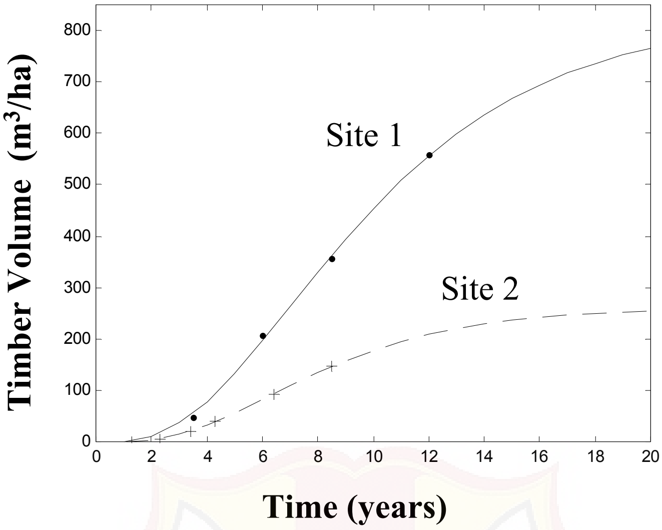

Figure 2. *Eucalyptus nitens* growth at the two sites. Predicted and observed values for Site 1 (solid line and dots respectively) and Site 2 (dashed line and plus-mark respectively). Data from Wong *et al.* (2000).

Table 3. Base parameter values.

Parameter	Value	Units	Description	Source
p_v	0.936*dbh*-4.342	\$/m^3	timber price net of harvest costs, $0 \leq p_v \geq 70$	g
p_b	20	\$/t	price of CO_2	a
r	6	%	discount rate	f
υ	3.67	t CO_2/t C	CO_2 absorbed per unit of carbon fixed in the forest	b
tph	250	trees/ha	tree density	h
c_E	2,300	\$/ha	establishment cost	a
T_e	46.4	yr	equivalence time	c
E_f	0.0215	1/yr	equivalence factor	c
δ	0.378	t C /m^3	carbon content of wood	d
ϕ	1.429	*	biomass in mature forest relative to stemwood biomass	e
μ	0.2	*	forest biomass parameter	e

* unitless coefficient.

Sources: a: Hassall and Associates (1999); b: based on molecular weights of CO_2 and C; c: Fearnside *et al.* (2000); d: estimated as wood density × C content of biomass = 0.7 (t/m^3) × 0.54; e: calculated from parameters presented by Kirchbaum (2000); f: arbitrary value subject to sensitivity analysis; g: linear approximation to assumed data following discussions with Signor (2001, pers. comm.); h: assumed value following discussions with Signor (2001, pers. comm.).

RESULTS

Carbon sequestration in the standing biomass (t CO_2/ha/year) of the forest is presented in Figure 3. For both sites the sequestration rate increases after planting as the forest grows and a higher portion of carbon is fixed in the stemwood of the trees relative to their foliage and branches. The sequestration rate reaches a maximum and then declines as the trees mature. For Site 1, sequestration peaks in year 10 when it reaches 102 t CO_2/ha/year. For Site 2, sequestration peaks a year earlier, in year 9 when it reaches 41 t CO_2/ha/year.

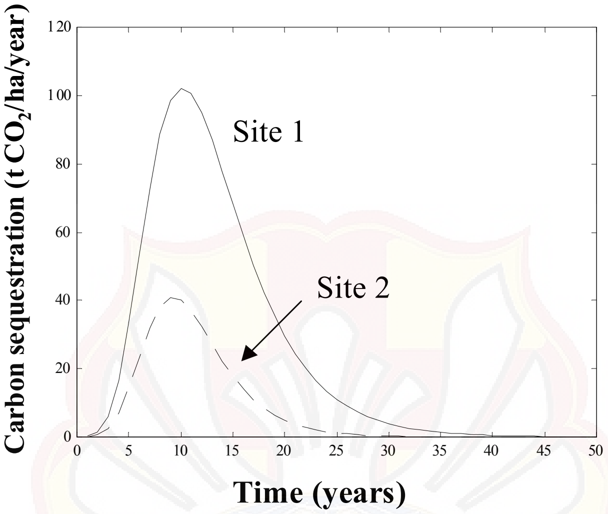

Figure 3. Carbon sequestration for Site 1 (solid line) and Site 2 (dashed line).

Total carbon stocks (t CO_2/ha) corresponding to the sequestration rates discussed above are presented in Figure 4 (A) for both sites. Carbon stocks follow the expected sigmoid pattern, being initially low and then increasing towards a maximum as the trees grow. They are highest for Site 1, tending towards a maximum of 1252 CO_2/ha after 58 years. For Site 2, carbon stocks tend towards a maximum of 395 t CO_2/ha after 62 years.

Optimal model results are presented in Table 4 for cycle-length (T^*), present value of profits (NPV^*), stemwood volume (v^*), standing biomass (b^*), carbon-emissions offset by the farm-forestry project per hectare (EO^*) and per year (EOA^*), and the net carbon payment for emissions offset (CEO^*) for both sites. EO^* takes into account both the carbon sequestration rate, and the number of years for which each annual increment in the carbon stock is stored, adjusted by the equivalence time between LUCF and energy projects. EO^* is therefore a measure of the amount of carbon emitted from an energy project that is permanently offset by the farm-forestry project.

With no carbon sequestration credits, it is optimal to harvest the forest after 16 years for Site 1 and 15 years for Site 2. These values correspond to the maximum points on the graphs in Figure 4 (B). Even though T^* is very similar for both sites, v^* and b^* are larger for Site 1 due to more growth, and the corresponding carbon-emissions offset over the optimal life of the project ($E0^*$) are threefold those for Site 2. On an annual basis, carbon-emissions offset ($E0A^*$) for Site 1 are over twofold those for Site 2.

With the inclusion of carbon sequestration credits, T^* is unchanged for both sites when carbon-sequestration payments are accounted using the tonne-year and ex-post full crediting methods. This is illustrated in Figures 4 (D) and (F). Hence, v^*, b^*, $E0^*$ and $E0A^*$ are also unchanged. For the ex-post full-crediting method, profits are the same as for the no-carbon credits case. This result clearly demonstrates that delayed payment provides no incentive to landholders to undertake farm forestry for carbon-sequestration objectives. Profits increase slightly with the tonne-year method but not enough to encourage landholders to farm trees for carbon. With this method it actually costs \$2/t CO_2 offset ($CE0^*$) at both sites, yet the same carbon emissions would have been offset with no carbon payment.

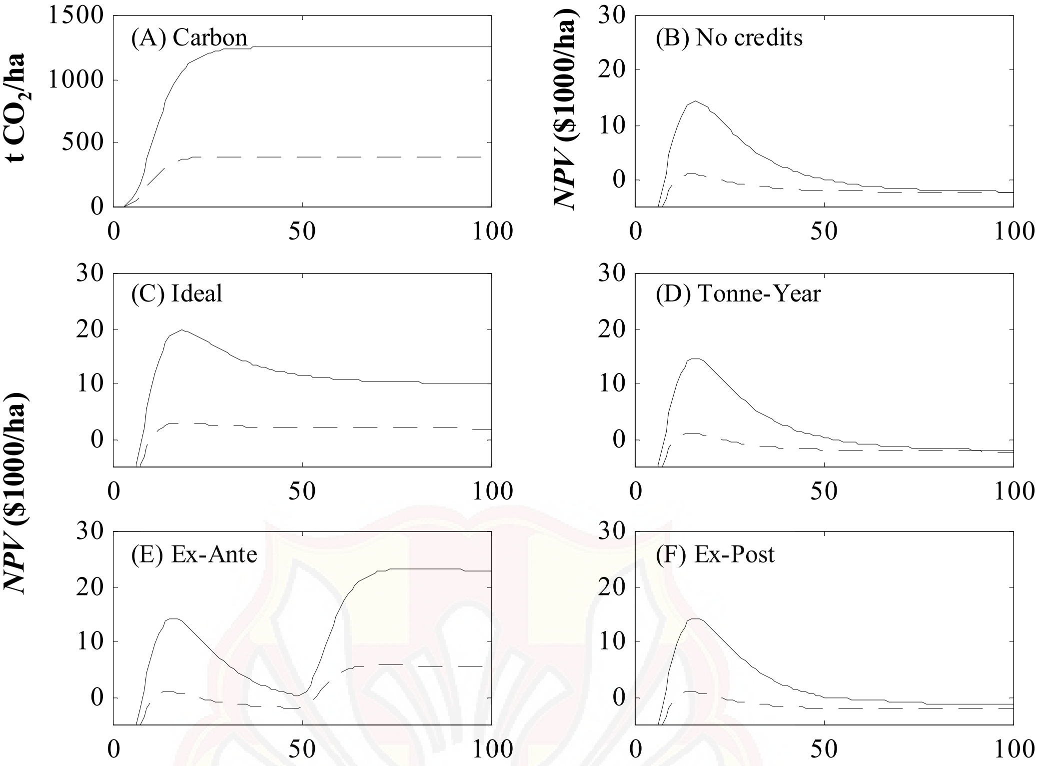

Figure 4. Carbon stocks and present value of profits for Site 1 (solid line) and Site 2 (dashed line).

Table 4. Optimal results for Site 1 and Site 2

	Site	T^* (years)	NPV^* (\$/ha)	v^* (m^3/ha)	b^* (t C/ha)	$E0^*$ (t CO_2/ha)	$E0A^*$ (t CO_2/ha.yr)	$CE0^*$ (\$/t CO_2 offset)
No credits	1	16	14290	607	262	134	8	0
Ideal	1	18	19707	678	287	178	10	22
Tonne-Year	1	16	14666	607	262	134	8	2
Ex-Ante	1	79	23221	834	341	1804	23	14
Ex-Post	1	16	14290	607	262	134	8	0
No credits	2	15	1026	216	91	45	3	0
Ideal	2	18	3014	242	100	68	4	22
Tonne-Year	2	15	1168	216	91	45	3	2
Ex-Ante	2	73	5754	263	108	534	7	15
Ex-Post	2	15	1026	216	91	45	3	0

When carbon-sequestration payments are accounted using the theoretically-ideal system and the ex-ante full crediting method, T^* and NPV^* increase for both sites, compared to their no-carbon-credit case values. This is also illustrated in Figures 4 (C) and (E) for the respective accounting systems. v^* , b^* $E0^*$ and $E0A^*$ also increase due to the longer cycle-lengths involved.

With the ex-ante method, payment for carbon sequestration when the project starts provides the greatest incentive to landholders to farm trees for carbon. Optimal cycle-length is longest and profits are highest by a significant margin with this method. T^* increases by five times for both sites, while NPV^* increases by 1.6 times for Site 1, and 5.6 times for Site 2, compared to their no-carbon-credit case values. $E0^*$ and $E0A^*$ are also considerably higher with this accounting method; they are highest for Site 1 because growth is better than at Site 2. With this method, *CE0** is \$14/t CO_2 offset and \$15/t CO_2 offset for the respective sites.

Sensitivity Analysis

To evaluate the effect of changes in the price of carbon and the discount rate on the optimal cycle-length (T^*), carbon-emissions offset per year (EOA^*, t CO_2/ha.yr) and net carbon payment (CEO^*), the model was solved for six carbon prices (from 5 to 30 \$/t CO_2 at \$5 intervals) and ten discount rates (from 1 to 10 percent at 1 percent intervals), for both sites. As expected from the base results, only the ideal system and the ex-ante system exhibited any sensitivity within the range tested. Hence the following discussion is limited to these two systems (see Figures 5 and 6).

With the ideal accounting system the price of carbon has only a small effect on optimal rotation length (Figure 5A). With the ex-ante method, there is a significant incentive for landholders to farm trees for carbon at Site 1 when P_b increases above \$10/ t CO_2, and at Site 2 when P_b increases above \$5/ t CO_2, at these prices the optimal cycle-length increases well above the equivalence time (Figure 5B). The switch from timber to carbon farming depends on the value of carbon relative to the value of timber. Carbon farming becomes desirable at Site 2 at a lower carbon price than at Site 1, because the value of timber is lower in the former, due to lower growth rates.

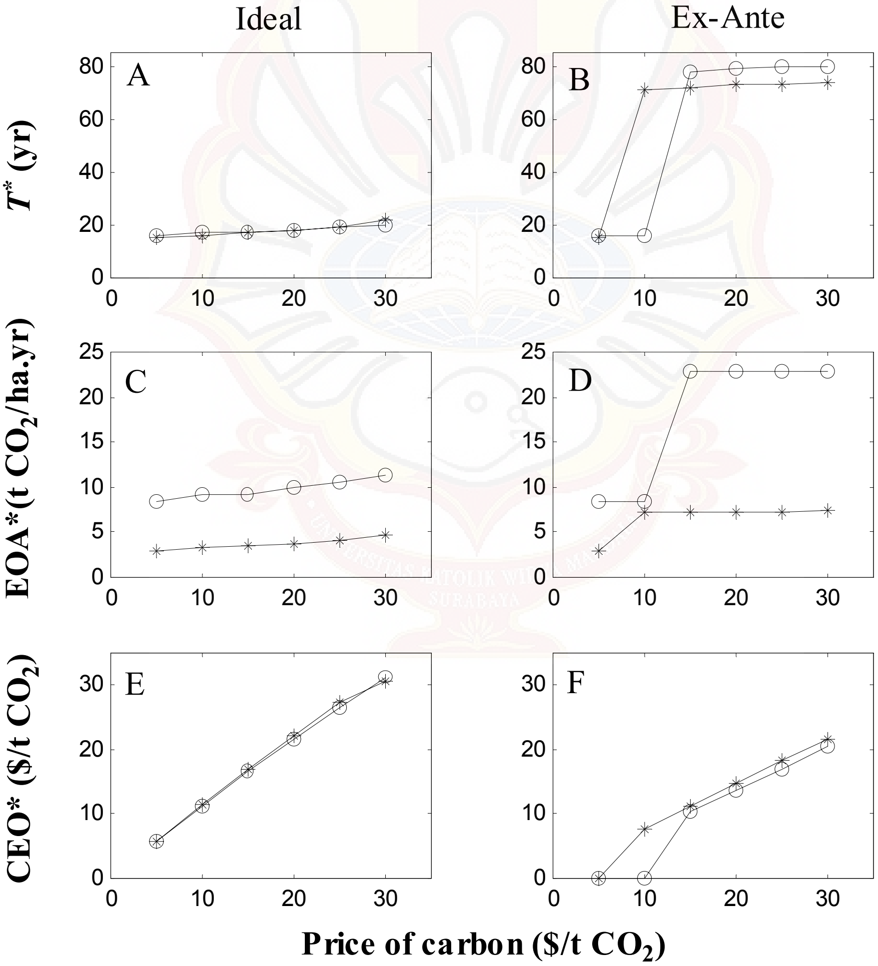

Figure 5. Sensitivity of optimal cycle-length (*T), carbon-emissions offset (EO*) and carbon payments (CEO*) to changes in the price of carbon for Site 1 (circles) and Site 2 (stars).**

For both accounting methods, annual emissions offset (EOA^*) increase with P_b, as the optimal cycle-length increases (Figure 5C and 5D). The greatest impact occurs with the ex-ante method at Site 1 when P_b increases from 10 to 15 \$/ t CO_2, because there is a significant jump in T^*. There is a similar but lower impact at Site 2 when P_b increases from 5 to 10 \$/ t CO_2, because even though there is a significant jump in T^*, carbon-sequestration rates are lower in this site. The net carbon payment (CEO*) increases with the carbon price for both accounting systems (Figure 5E and 5F).

The discount rate has a considerable impact on cycle length under the ex-ante method (Figure 6B). With this method, the incentive for carbon farming at Site 1 is eliminated at discount rates below 5 percent, as T^* falls significantly below the equivalence time. For Site 2, the incentive is eliminated below 3 percent.

The effect of the discount rate on EOA^* (Figure 6C and 6D) is related to the optimal cycle-length. The greatest impact is felt with the ex-ante method for which the discount rate has the most impact on T^*. EOA^* is highest for Site 1 due to the higher carbon-sequestration rates.

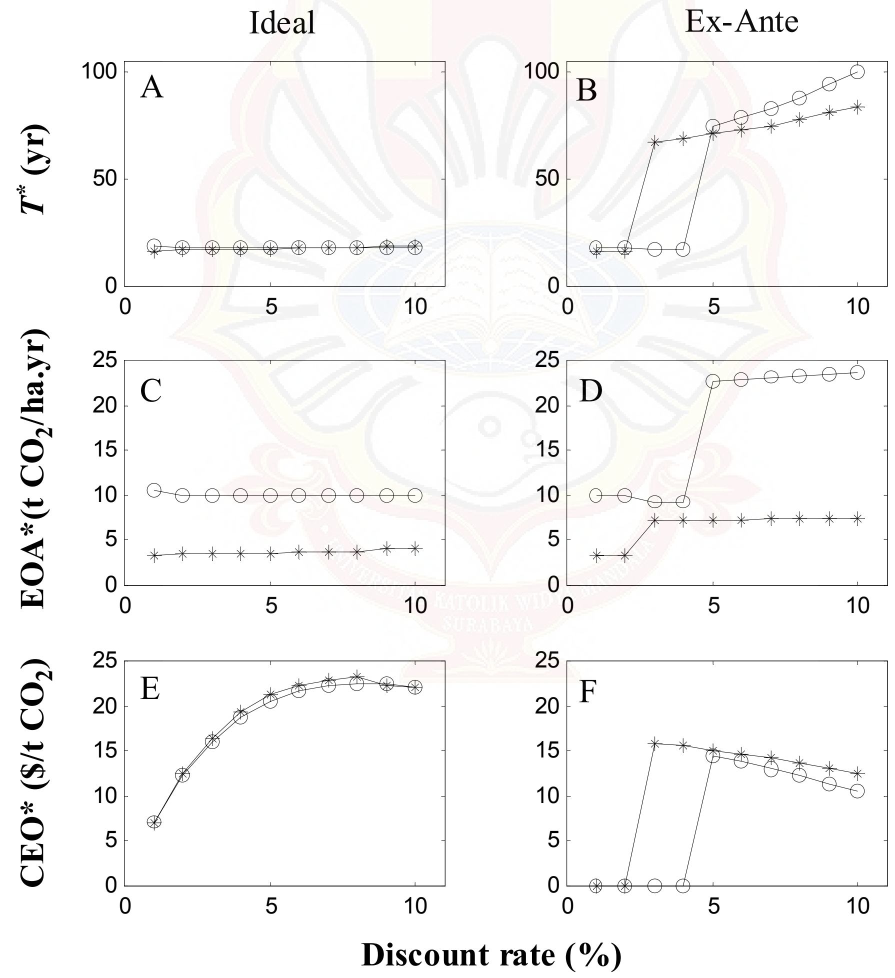

Figure 6. Sensitivity of optimal cycle-length (T^*), carbon-emissions offset (EO*) and carbon payments (CEO*) to changes in the price of carbon discount rate for Site 1 (circles) and Site 2 (stars).

Obviously, the discount rate affects the cost to the investor of making carbon payments. For the theoretically-ideal system, CEO^* increases at a decreasing rate with increases in *r* (Figure 6E). Although the gross carbon payment decreases with increases in *r*, the value of the redeemed credits decreases to a greater extent. Hence, the net carbon payment (ie. gross carbon payment less the value of the redeemed credits) increases. For the ex-ante system, CEO^* is zero for low rates of discount, because there is no incentive for carbon farming (Figure 6F). CEO^* becomes sensitive to the discount rate once *r* reaches 3 percent for Site 2 and 5 percent for Site 1when it becomes desirable to farm trees for carbon.

DISCUSSION

Tonne-year accounting has the advantage that it removes the uncertainty related to the long-term permanence of forests and the need for long-term guarantees (Moura-Costa and Wilson 2000), as well as eliminating concerns about loss of sovereignty caused by CDM projects that require permanent or very long-term sequestration strategies (Chomitz 1998). However, this method provides no incentive to plant forests or keep trees standing longer than is optimal with no carbon credits (16 years for Site 1 and 15 years for Site 2). The optimal emission reductions per year are also the same (8 t CO_2/ha for Site 1 and 3 t CO_2/ha for Site 2), hence it is not rational for a policy maker to pay for sequestration using a tonne-year approach, when the same service would be provided for free by the timber market.

Other than the theoretically-ideal accounting method, only the ex-ante method provides an incentive to plant trees and keep them longer (79 years for Site 1 and 73 years for Site 2). The optimal amount of emission reductions under this method is 23 t CO_2/ha/yr for Site 1 and 7 t CO_2/ha/yr for Site 2. This is a threefold increase over the no-incentive case for Site 1 and more than a twofold increase for Site 2. The disadvantages of this approach are that it requires large up-front payments by the party purchasing the service, and that a guarantee is required regarding the length of time the carbon will remain out of the atmosphere. This guarantee may be expensive and raises the issue of liability should the project fail before meeting its commitment.

A different approach was proposed by Fearnside *et al.* (2000), whereby the benefit of delayed emissions was represented as the difference in the integrals of the revised Bern model (see Figure 1), one starting in year zero and the other starting when the forest is harvested, and both ending in year 100. This method was not evaluated here, but given it is more stringent than the tonne-year approach, it will provide no incentive for farm forestry.

An issue that was not explored in this paper, but which is relevant to the debate on permanence, is that of discounting carbon emissions, so that delaying emissions becomes more attractive. Arguments in favour and against discounting carbon are discussed by Fearnside *et al.* (2000). In short, postponing emissions will postpone some radiative forcing, which has a cumulative effect on climate, so temporary sequestration that shifts downward the future time path of temperature increases has value provided society has a positive discount rate, ie. postponement of damages has value (Chomitz 2000).

Fearnside *et al.* (2000) support discounting future carbon emissions, not just because it delays damage, but because it saves lives. They argue that each million tonne of avoided emission results in the saving of 16.4 human lives (p. 255).

A plantation that eventually reaches a steady-state equilibrium (harvest and planting of stands is even) will obtain no more carbon credits, but the role of carbon credits in helping establish the plantation can be very important. In the long run the problem is complicated by population increases coupled with reduced land available (tied up in forestry) which may drive land prices up to a level that encourages deforestation over sequestration.

Finally, it must be mentioned that not all carbon is released back into the atmosphere upon harvest, since carbon may remain in timber for centuries, but also CO_2 is emitted during harvest and timber processing. A complete accounting system should account for both these factors, but the practical obstacles may be insurmountable.

SUMMARY AND CONCLUSIONS

This paper presents an analysis of some of the accounting methods that have been proposed to deal with the problem of permanence, so as to allow temporary carbon sequestration by forests to be compared to permanent emission reductions in the energy sector. The analysis is based on the growth of a *Eucalyptus* species planted in high- and moderate-rainfall areas in south-eastern Australia.

It is shown that the tonne-year approach, which has attracted much interest in the policy debate surrounding the Kyoto Protocol, does not offer incentives to plant commercial forests under plausible assumptions regarding tree growth rates, prices, costs and discount rates in Australia. Of the accounting systems studied, only two provide forest establishment incentives: a theoretically-ideal system based on infinite forest cycles with redemption of credits after each harvest, and an ex-ante payment scheme that requires a guarantee that the forest will stand for 46 years (the equivalence time) after it reaches its private-optimal level of carbon sequestration. This applies to both sites considered here, but the incentives are much greater in the lower-rainfall area.

As pointed out by Chomitz (2000), there is no unique way to determine the conversion rate between tonne-years and perpetual tonnes; the choice from a set of scientifically sound approaches is a policy decision. It is possible that the decision will take environmental and social objectives into account in addition to net greenhouse-gas emission reductions. Hence there is still much room for policy debate.

ACKNOWLEDGEMENTS

The authors would like to thank Anthony Signor for useful discussions which have contributed to the content of this paper.

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CSIRO PUBLISHING

www.publish.csiro.au/journals/ajb *Australian Journal of Botany*, 2005, **53**, 663–675

The utility of the eddy covariance techniques as a tool in carbon accounting: tropical savanna as a case study

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Abstract. Global concern over rising atmospheric CO_2 concentrations has led to a proliferation of studies of carbon cycling in terrestrial ecosystems. Associated with this has been widespread adoption of the eddy covariance method to provide direct estimates of mass and energy exchange between vegetation surfaces and the atmosphere. With the eddy covariance method, fast-response instruments (10–20 Hz) are typically mounted above plant canopies and the fluxes are calculated by correlating turbulent fluctuations in vertical velocity with fluctuations in various scalars such as CO_2, water vapour and temperature. These techniques allow the direct and non-destructive measurement of the net exchange of CO_2 owing to uptake via photosynthesis and loss owing to respiration, evapotranspiration and sensible heat. Eddy covariance measurements have a high temporal resolution, with fluxes typically calculated at 30-min intervals and can provide daily, monthly or annual estimates of carbon uptake or loss from ecosystems. Such measurements provide a bridge between 'bottom-up' (e.g. leaf, soil and whole plant measures of carbon fluxes) and 'top-down' approaches (e.g. satellite remote sensing, air sampling networks, inverse numerical methods) to understanding carbon cycling. Eddy covariance data also provide key measurements to calibrate and validate canopy- and regional-scale carbon balance models. Limitations of the method include high establishment costs, site requirements of flat and relatively uniform vegetation and problems estimating fluxes accurately at low wind speeds. Advantages include spatial averaging over 10–100 ha and near-continuous measurements. The utility of the method is illustrated in current flux studies at ideal sites in northern Australia. Flux measurements spanning 3 years have been made at a mesic savanna site (Howard Springs, Northern Territory) and semi-arid savanna (Virginia Park, northern Queensland). Patterns of CO_2 and water vapour exchange at diurnal, seasonal and annual scales are detailed. Carbon dynamics at these sites are significantly different and reflect differences in climate and land management (impacts of frequent fire and grazing). Such studies illustrate the utility of the eddy covariance method and its potential to provide accurate data for carbon accounting purposes. If full carbon accounting is implemented, for ideal sites, the eddy covariance method provides annual estimates of carbon sink strength accurate to within 10%. The impact of land-use change on carbon sink strength could be monitored on a long-term basis and provide a valuable validation tool if carbon trading schemes were implemented.

Introduction

The carbon cycle is pivotal to the earth system, being linked to the biosphere, atmosphere, geosphere and hydrosphere, and is strongly coupled to other cycles of nutrients, water and energy. Carbon accounting involves the quantification of sources and sinks of carbon (particularly CO_2) from various carbon pools, including terrestrial ecosystems. Precise measurement and monitoring of the carbon cycle in time and space is difficult, but the development of the eddy covariance method over the last three decades is providing a direct measure of the exchange of carbon between land surfaces and the atmosphere (Baldocchi *et al*. 1988; Baldocchi 2003). Eddy covariance (EC) is a micrometeorological method that directly measures the integrated mass and energy exchange between a uniform surface (e.g. plant canopy, soil, water body) and the atmosphere. For vegetated surfaces, the method involves the deployment of fast-response instruments (samples taken at 10 or 20 Hz) above plant canopies, which measure the covariance of vertical wind velocities and scalars such as CO_2, water vapour

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and temperature. The turbulent upward and downward movements of air (eddies) that develop within and above plant canopies are responsible for the *net* exchange of mass (CO_2, water vapour) and energy (heat) between the canopy and the lower atmosphere. During the daytime, CO_2 fluxes represent the net exchange of carbon owing to canopy photosynthesis (uptake) and ecosystem respiration (loss). Ecosystem respiration (R_e) comprises both autotrophic (root, stems, leaves) and heterotrophic (soil microorganisms) respiration and occurs continuously, but is the dominant CO_2 flux at night.

Fluxes measured with EC systems are representative of canopy exchanges integrated over areas ranging from hundreds of hectares to many square kilometres. The EC system considers the canopy as a single functional unit and it integrates the complex interactions between organisms in an ecosystem. Fluxes are calculated continuously, at 30- or 60-min intervals. This enables high-resolution temporal sampling not possible by using inventory approaches, and integration of these fluxes over time enables net daily, weekly, monthly, seasonal or annual exchanges of carbon to be calculated. Such data can be used to assess whether sites are sources or sinks of carbon, to validate existing methods and to estimate parameters required by models (Wang *et al.* 2001). Eddy covariance studies thus provide data at temporal and spatial scales that yield process-level understanding that is readily applicable to ecological studies. In a recent review, Baldocchi (2003) found more than 800 peer-review papers associated with the EC method, with a rapid increase in activity in the past decade.

The operation of EC systems has traditionally relied on micrometeorologists and atmospheric scientists, but technological advances now enable plant ecologists and ecophysiologists to use this method as a tool in landscape ecology and physiology. This paper provides information for a general plant science audience on the nature of EC methods and their utility in carbon accounting and as an ecological tool in general. The paper briefly discusses the theoretical basis of the method, recent advances in instrumentation and the constraints of the method. These themes will be illustrated by documenting the application of the method at two contrasting tropical savanna ecosystems of northern Australia, where it has been deployed to examine carbon budgets.

Theoretical considerations

Turbulent motions are responsible for the net exchange of mass (CO_2, water vapour), momentum and energy between the canopy and the lower atmosphere. Modern application of the EC method (Baldocchi *et al.* 1988) is grounded in the theory of fluid dynamics and micrometeorology (for an introductory text, see Arya 2001), which provides a rigorous physical description of mass and energy exchange. Initial attempts at using EC theory to measure mass exchange have been made over short crops under ideal conditions of flat terrain and uniform crop structure (e.g. Swinbank 1951). Early work focused on heat and momentum transfer between crops and the lower atmosphere and were fundamental to developing theory and instrumentation for the later addition of CO_2 flux measurements during the late 1960s and early 1970s (Baldocchi 2003). The precision of these early estimates of CO_2 fluxes were constrained by limits in instrumentation stability and responsiveness, problems that have largely been overcome with the recent development of low-power, fast-response water vapour and CO_2 analysers and sonic anemometers for the measurement of the turbulent three-dimensional wind components.

The physical principles involved with the EC technique can be seen by examining an imaginary control volume of air with sides $2L$ and height h placed over a vegetated surface (Fig. 1). Conservation of mass of quantity c, with concentration c_c, requires that the change in mass stored in the volume is equal to the net (vector) sum of the mass flowing through the walls of the volume. Under steady conditions, there is no change of mass in the volume and so the fluxes through the walls are in balance. With the further restriction of horizontally homogeneous flow, the horizontal fluxes $<uc_c>$ and $<vc_c>$ into and out of the end and side walls of the volume are in balance, where u and v are the horizontal velocities in the direction of the mean wind and normal to it. The angle brackets indicate spatial averages across the faces of the walls. Under steady, horizontally homogenous conditions, net fluxes occur only in the vertical direction and hence the flux into the base of the volume, plus the net exchange of mass across all plant surfaces within the volume, is equal to the spatially averaged vertical flux across the upper surface, $<wc_c>$, assuming this is above the tallest vegetation and w is the vertical velocity. Measurements across the 'lid' of the control volume thus provide the desired net exchange between the underlying surface and the atmosphere.

Measurements on a single tower cannot provide the required spatial average across the upper surface of the volume, so it is necessary to assume that air flowing past the measurement point provides an adequate sample of the motions responsible for the vertical exchange across the lid. Under these circumstances, a time-average vertical flux across the lid replaces the spatial average $<wc_c> = \overline{wc_c}$, where the overbar indicates a time-average. Micrometeorologists conventionally partition the velocities and concentrations into mean and fluctuating components so that $w = \overline{w} + w'$ and $c_c = \overline{c_c} + c'_c$ and hence the time-average flux is given by

$$\overline{F_c} = \overline{wc_c} = \overline{(\overline{w} + w')(\overline{c_c} + c'_c)} = \overline{w}\,\overline{c_c} + \overline{w'c'_c}. \qquad (1)$$

The two terms containing averages of fluctuating quantities are zero by definition and hence do not appear in Equation 1. The vertical flux is thus the sum of two

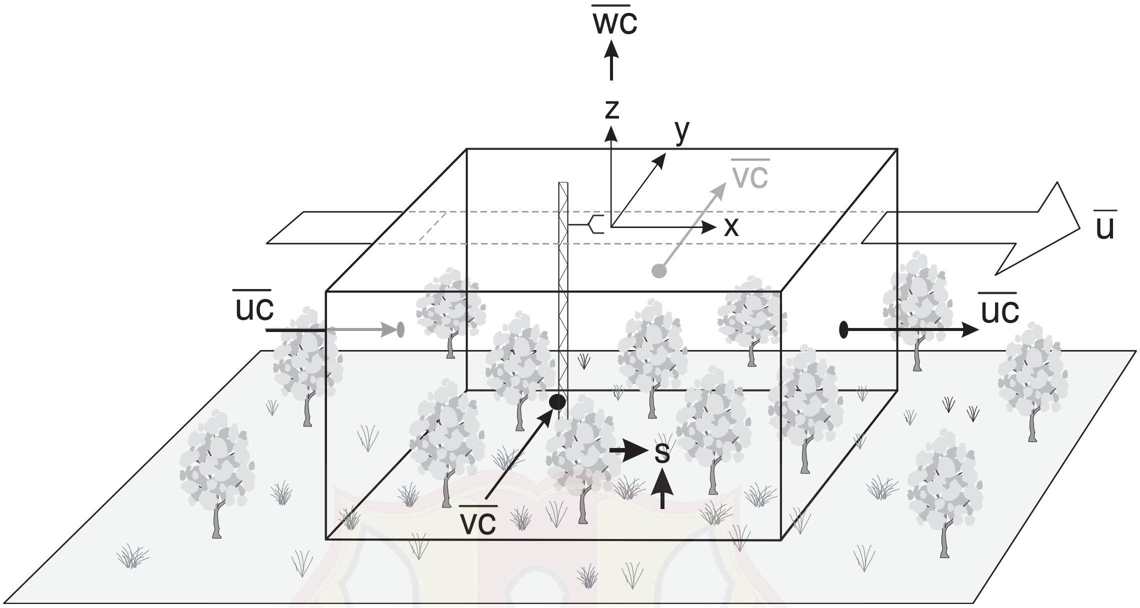

Fig. 1. A Cartesian control volume placed over a vegetated surface.

terms, one the product of the mean vertical velocity and the mean concentration at height *h*, and the second, the covariance between fluctuations in the vertical velocity w' and the concentration c'_c.

Prior to publication of the seminal paper by Webb *et al.* (1980) (WPL hereafter), it was assumed that $\overline{w} = 0$ and that the vertical turbulent flux density is simply $\overline{F_c} = \overline{w'c'_c}$. WPL showed that the assumption that $\overline{w} = 0$ is not quite correct and neglect of this term in Equation 1 can give significantly incorrect estimates of $\overline{F_c}$, particularly for CO_2 and other trace gases. The vertical velocity term can only be neglected when constituent *c* is measured as the mixing ratio relative to dry air, χ_c, and then the flux is calculated correctly as

$$\overline{F_c} = \overline{c_d}\,\overline{w'\chi'_c}, \tag{2}$$

where $\overline{c_d}$ is the molar density of dry air. Unfortunately, instruments used to measure CO_2 and water vapour typically measure c_c rather than χ_c so it is necessary to determine $\overline{w}$ for use in Equation 1. WPL developed the necessary theory, along with the steps needed to calculate the eddy fluxes of heat (*H*), water vapour (*E*) and CO_2 (F_c). Further information on the theoretical and practical aspects of micrometeorological measurements may also be found in Leuning and Judd (1996) and Leuning (2004).

When combined with standard meteorological measurements (photosynthetically active radiation (*PAR*), wind speed, vapour pressure deficit (*VPD*), temperature, atmospheric pressure) and structural descriptors of vegetation (e.g. *LAI*, basal area, canopy height), the EC method provides comprehensive datasets describing biotic fluxes and their abiotic determinants. However, the method does have limitations. Flux tower installations represent a significant investment in infrastructure, including core sensors (3D anemometer, gas analysers), associated meteorological instrumentation and maintenance requirements, although real costs have reduced considerably in the last 10 years. Despite technological advances, instrument failure can be frequent, especially during periods of extreme meteorological conditions. As a result, site-specific gap-filling strategies need to be employed to estimate missing flux data from empirical models developed using periods with reliable data that are correlated with meteorological variables (Papale and Valentini 2003).

Eddy covariance measures can systematically underestimate nocturnal respiration fluxes if cold-air drainage flows occur under low wind speed, stable atmospheric conditions (Aubinet *et al.* 2002), or when averaging periods are too short to sample all the intermittent motions contributing to the flux through the lid of the control volume (Fig. 1). These errors can lead to large long-term, systematic errors in ecosystem carbon budgets (Moncrieff *et al.* 1996), because annual net ecosystem production (*NEP*) is the small difference between the two large quantities of photosynthesis and respiration. For example, Kruijt *et al.* (2004) calculated a two-fold range in ecosystem respiration rate in an Amazonian rainforest, depending on the method used to evaluate these fluxes. To eliminate such errors, nocturnal fluxes are typically replaced by empirical relationships between ecosystem respiration and soil moisture and temperature. These relationships are derived from flux measurements on windy nights, when there is good coupling between turbulence within and above the canopy (Goulden *et al*. 1996).

As implied by Fig. 1 and Equation 1, eddy flux measurements need to be made above relatively flat terrain with uniform vegetation structure extending upwind of the measurement location. For ecologists, this can impose considerable limits on ecosystem types that can be investigated (e.g. ecosystems in mountainous terrain). Measurements at non-ideal sites can systematically bias flux estimates, with errors compounding when fluxes are integrated over daily or annual time periods, temporal scales of most interest to ecologists. However, recent theoretical advances (Massman and Lee 2002) are improving our ability to make satisfactory flux measurements under non-ideal conditions (Baldocchi *et al*. 2000; Finnigan 2002). There is also uncertainty relating to basic calculation of fluxes from raw data and also post-processing algorithms, with debate centring on the need to filter raw data and optimal averaging times (e.g. 15, 30 or 60 min). Work on these problems is continuing (Finnigan *et al*. 2003).

While spatial heterogeneity places limitations on micrometeorological methods, heterogeneity also poses severe sampling challenges to traditional ecological methods, and complete studies should include multiple approaches to estimating carbon and water budgets as mutual constraints.

Utility of eddy covariance as an ecological tool

Global systematic observations are essential to underpin research to improve our understanding of ecosystems and climate–earth systems (IPCC 2001). Modelling of these systems is limited by our process-based understanding and observational data. The EC method measures the ecosystem response to environmental variations at time scales from hours to years, providing valuable insight into the processes controlling CO_2 and water vapour exchange, as well as ecosystem sensitivity to climate variability.

With the increasing focus on relationships between global climate and the carbon cycle, ecological production indices such as gross primary production (*GPP*) and net primary production (*NPP*), as used by ecologists, do not provide a complete description of the terrestrial carbon cycle, as they do not specifically include soil-derived fluxes or fluxes associated with disturbance events. Soil carbon fluxes are a key component of global carbon balance and climate change may have a large impact on shifts in soil carbon storage (Valentini *et al*. 2000). As EC flux measurements represent net exchange of CO_2 from all sources and sinks within an ecosystem, integration of daily flux measurements over annual periods provides an estimate of the *NEP*, also called net ecosystem exchange (*NEE*), which represents the net annual ecosystem-scale exchange of carbon. *NEP*/*NEE* is a measure of the carbon sequestration rate for an ecosystem relative to the atmosphere, quantifying carbon accumulation or loss. These quantities are related to the more commonly used *GPP* and *NPP* as follows:

$$\begin{aligned} NPP &= GPP - R_a \\ NEP &= NPP - R_h \\ NBP &= NEP - D \end{aligned} \tag{3}$$

where R_a and R_h are autotrophic and heterotrophic respiration, respectively. *NBP* is the net biome production (Steffen *et al*. 1998), which uses *D*, a measure of the loss of carbon from an ecosystem because of disturbance agents, such as fire and insect plagues. *NBP* represents carbon fluxes over periods of decades to centuries that include the relevant cycles of disturbance as opposed to annual estimates, and reflects the mean return time or frequency of disturbance events and their impact on the ecosystem carbon balance.

Relationships between total ecosystem respiration, R_e ($= R_a + R_h$), and soil temperature and moisture can be derived from nocturnal eddy fluxes (Falge *et al*. 2002), but R_e can also be partitioned into R_a and R_h by using chambers which measure soil, stem and leaf scale respiration. When combined with site measures of stem increment, litter fall and component respiration, EC data provide a complete description of carbon fluxes between ecosystem carbon pools and provide powerful datasets to calibrate and validate canopy and ecosystem scale biogeochemistry models.

Much of the power of the EC technique as an ecological tool comes from the ability to compare fluxes and cycling across contrasting sites or across bioclimatic gradients. For instance, Law *et al*. (2002) compared carbon and water exchange over forest, grassland, crops and tundra, and found global relationships between gross ecosystem production and evapotranspiration. Similarly, Wilson *et al*. (2002) examined the diurnal patterns of surface energy and carbon fluxes across stations in Europe and North America. They confirmed the dependence of the surface energy balance on factors such as available radiant energy, leaf area index, surface resistance to evapotranspiration, atmospheric transport resistance, stomatal response to *VPD* and advection. They also found that the timing of peak carbon uptake varied across climatic zones and that it was useful to group ecosystems into plant functional types for evaluating carbon exchanges (Falge *et al*. 2002).

The utility of the EC technique is fully realised when it is coupled with other ecological, remote-sensing and modelling methods. This suite of measurements provides a direct means of testing carbon cycle, ecological and hydrological models. Furthermore, EC fluxes can be used to improve algorithms used to scale up from canopy to regional estimates of *NEP* and evaporation (e.g. Eamus *et al*. 2001; Baldocchi *et al*. 2001; Wang and Barrett 2003; Isaac *et al*. 2004). Baldocchi *et al*. (1996) recommended that this method be employed for terrestrial ecosystems of the world to help close regional and global carbon and water budgets.

Traditional studies of ecosystem-scale carbon exchange can offer complementary information and has involved the collection of data related to component processes (e.g. leaf photosynthesis, heterotrophic and autotrophic respiration, stem or biomass increment, litter fall, root turnover). Rates of CO_2 exchange have been measured by using chambers or cuvettes enclosing leaves, stems and soil. Such measures can be scaled up in a 'bottom-up' approach, often via a canopy model, to construct canopy- or stand-scale carbon balance (McGuire *et al*. 2001). Scaling from point measures of leaf, stem or soil gas exchange to canopy/stand scale is problematic because characterisation of canopy-scale gas exchange via chamber measurement limits spatial and temporal sampling, and may not reflect the variation of gas exchange within plant canopies (Roderick *et al*. 2001). Leaf, soil and whole-tree chambers have been used to derive environmental response functions that describe responses to radiation, temperature, vapour pressure and soil moisture. Moreover, chamber measurements tend to modify leaf, canopy (Denmead *et al*. 1993) or soil (Hooper *et al*. 2002) microclimate and introduce biases (Davidson *et al*. 2002). Denmead *et al*. (1993) found significant overestimation of tree-scale CO_2 assimilation rates, with water-use efficiency overestimated by as much as 50% as measured by chambers compared to micrometeorological methods. Canopy-scale gas exchange models driven by leaf level data require complex methods of scaling from leaf to canopy-scale fluxes of heat and mass (Leuning *et al*. 1995). These include spatial descriptions of canopy *LAI*, submodels describing radiative and turbulent transfer through the canopy coupled to submodels of photosynthesis and stomatal conductance that are parameterised for both sunlit and shaded leaves (DePury and Farquhar 1997; Wang and Leuning 1998; Roderick *et al*. 2001).

Eddy covariance data can be used to derive ecophysiological responses to radiation, temperature, vapour pressure and soil moisture deficit. These functions can be readily incorporated into ecosystem-scale physiology models for calibration and verification. The need to capture small-scale ecosystem complexity (leaf and microbial level) can be reduced through the use of EC data. EC measurements of canopy fluxes are of most value to models when they are matched to the same scale (canopy-scale models). Such canopy-scale models form the backbone of land-surface models (Bonan *et al*. 2002) used in larger-scale climate and earth-systems models (Blackmon *et al*. 2001).

Eddy covariance measurements provide a bridge between these 'bottom-up' and 'top-down' approaches such as satellite remote sensing (Anderson *et al*. 2004), air sampling networks and inverse numerical methods (Kaminski and Heimann 2001), which assess regional or global carbon budgets. All these tools need to be utilised to provide an integrated understanding of carbon cycling in ecosystems. Data assimilation methods allow carbon fluxes to be constrained through multiple data sources including short-term canopy fluxes, longer-term carbon-pool measurements, remote sensing and modelling. The utility of this technique is detailed by Barrett *et al*. (2005, this issue) and will ultimately allow more robust estimates of carbon balances across a range of scales.

Application of EC in savannas of northern Australia

Two EC sites have been established in the tropical savannas of northern Australia to examine patterns of carbon, water and energy exchange as a function of climate and land management. Tropical savannas of northern Australia represent about 10% of the world's savanna biome (Woinarski *et al*. 2001). Given the size of this biome, the nature of the dominant land-management practices that includes frequent burning and pastoralism, which produce significant greenhouse gas emission, there is a need for better understanding of carbon stocks and fluxes in this region. A frequent fire regime (Williams *et al*. 2002) and strongly seasonal climate results in complex carbon dynamics (Chen *et al*. 2003; Beringer *et al*. 2004) and generic productivity models may not be appropriate for estimating carbon flux in this ecosystem (see Barrett *et al*. 2005).

Savanna flux sites

Our sites have been established to represent the broad climatic range of tropical savanna in northern Australia. Howard Springs, near Darwin, Northern Territory, is a wet coastal tropical savanna receiving an annual rainfall of 1750 mm and is subjected to near-annual fire frequency (Hutley *et al*. 2000). By contrast, Virginia Park, Queensland, is a semi-arid (670 mm annual rainfall) savanna site subjected to heavy grazing pressure (Leuning *et al*. 2005). Continuous flux measurements have been made at these two sites since mid-2001 and provide key data describing seasonal and interannual variation of savanna carbon exchange. Comparative site data for the two savanna flux stations are given in Table 1.

The Howard Springs site has been subjected to a range of ecological studies over a 10-year period. It is located within the Howard River catchment near Darwin, with vegetation at this site representative of mesic open-forest savanna, consisting of an overstorey dominated by *Eucalyptus tetrodonta* (F.Muell.) and *E. miniata* (Cunn. ex Schauer). The understorey is dominated by C_4 grasses such as annual *Sorghum* and *Heteropogon* (Hutley *et al*. 2000). Flux measurements commenced at this site during 1997, with 10-day measurement campaigns conducted at key periods during the strongly seasonal wet–dry climate cycle (Hutley *et al*. 2000; Eamus *et al*. 2001). The EC method was used to estimate annual evapotranspiration, which was then combined with measurements of soil and groundwater dynamics and streamflow data to construct a catchment water balance for the Howard River catchment

Table 1. Site features for the Howard Springs and Virginia Park flux sites

Characteristic	Howard Springs, NT	Virginia Park, Qld
Location	12°17′24″S, 131°5′24″E	19°53′00″S, 146°33′14″E
Mean annual rainfall (mm)	1750	667
Mean annual temperatures (max./min., °C)	31.9/23.2	30.1/17.1
Soil texture	Sands, sandy loams, red Kandosol	Sandy loam, Alfisol
Vegetation type	Open-forest savanna	Low open-woodland savanna
Canopy species	*Eucalyptus tetrodonta*, *E. miniata*, *Erythrophleum chlorostachys*, *Terminalia ferdinandiana*	*E. crebra*, *E. drepanophylla*
Understorey species	*Sorghum* spp., *Heteropogon contortus*	*Aristida* spp., *Eriachne* spp.
Stand height (m)	14–16	5–8
Stem density (ha^{-1})	500–700	20–30
LAI, wet season (overstorey/understorey)	0.9/1.4	0.3/1.0
LAI, dry season (overstorey/understorey)	0.6/0.02	0.3/0
Land use	Vacant crown land	Pastoral lease

(Cook *et al*. 1998; Hutley *et al*. 2000). Daily carbon fluxes from these campaigns were extrapolated to estimate an annual *NEP* for the site with a sink of 2.8 t C ha^{-1} $year^{-1}$ calculated for the period 1997–1998 (Eamus *et al*. 2001). Improvements in flux instrumentation in the late 1990s meant that near-continuous flux measurements have been possible from 2001 to the present at the Howard Springs site. More recent work has focused on the impacts of fire on carbon sink strength, energy balance and feedback to meso-scale climate patterns (Beringer *et al*. 2003; Williams *et al*. 2004). Chen *et al*. (2003) used inventory methods at this and similar sites of the Darwin region and constructed a carbon balance for tropical savanna; such studies provide valuable comparative data for the eddy flux measurements.

In contrast to the mesic Howard Springs site, the Virginia Park flux site is located in a heavily grazed semi-arid savanna, 40 km north-east of Charters Towers, in tropical northern Queensland (Table 1). Vegetation at the Virginia Park site consists of scattered *E. crebra* and *E. drepanophylla* trees 5–8 m tall, 30–40 m apart, with a visual estimate of *LAI* of 0.3 (Leuning *et al*. 2005). A C_4 grassy understorey is also present during the November–April summer wet season ($LAI < 1$) but extensive grazing results in little grass cover (dead or alive) during the dry season. Soils surrounding the tower are alfisols characterised by a marked contrast in texture, ranging from sandy loams to clay loams in the A horizon, to heavy clays in the B horizon. These deeply weathered soils are generally low in nutrients (Mott *et al*. 1985).

Flux instrumentation

Eddy flux instruments were mounted above each savanna site by using guyed towers, 23 and 27 m in height at the Howard Springs and Virginia Park sites, respectively. Terrain at both sites is flat (~1° or less) with extensive fetch of savanna vegetation in all directions from the towers and, as such, both sites can be considered to be near ideal for EC measures. Core instrumentation at each site consists of open-path infrared gas analysers that measure CO_2 and water vapour concentrations and sonic anemometers that measure turbulent wind vectors and virtual air temperature. At the Howard Springs site, a 3D ultrasonic anemometer (Campbell Scientific Inc., CSAT3, Campbell Scientific Inc.) is being used with a LI 7500 open-path CO_2/H_2O analyser (Licor Inc., Lincoln, USA). At Virginia Park, an LI 7500 gas analyser is matched with a type HS sonic anemometer (Gill Instruments Ltd, Lymington, UK). At both sites, all flux variables are sampled at 20 Hz, with 30- and 60-min mean fluxes calculated at the Howard Springs and Virginia Park sites, respectively. All CO_2 fluxes are corrected for the effects of air density fluctuations arising from sensible and latent heat fluxes (Webb *et al*. 1980). Artificial neural network analyses (Papale and Valentini 2003) were used at both sites to develop gap-filling algorithms and corrections to nocturnal CO_2 fluxes (Baldocchi *et al*. 2000). Daily rainfall, air temperature, relative humidity and soil moisture and soil heat flux are also measured at both sites. Further details of instrumentation may be found in Beringer *et al*. (2003) and Leuning *et al*. (2005). Daily estimates of net carbon exchange from the contrasting mesic, tall-grass savanna at Howard Springs and the semi-arid savanna site at Virginia Park are available from March 2001 to March 2004, and represent the most comprehensive mass and energy flux database for any Australian ecosystem.

Seasonal patterns of energy and CO_2 fluxes

Long-term flux data collection enables examination of the responses of plant canopies to environmental drivers over diurnal and seasonal time scales. Examples of such data are given for both savanna sites in Figs 2 and 3, which describe typical diurnal patterns of energy fluxes (H, λE, R_n) and F_c (Fig. 4) during wet- and dry-season conditions. Also shown is mean *VPD* for the reporting period in the wet and dry seasons. Figure 5 describes seasonal changes in canopy fluxes as a function of radiation. Nocturnal CO_2 fluxes can be used to construct empirical models of ecosystem respiration and *NEP* can be partitioned into its components R_e and *GPP* (Fig. 6). Long-term flux measures also enable the calculation of annual carbon balance (*NEP*) and evapotranspiration, and an examination of their interannual variation. Such data are given in Table 2.

Large seasonal variations in energy and CO_2 fluxes are clearly evident at both savanna sites (Figs 2–4). In the dry season (August 2001), most of the sun's energy reaching the savanna is partitioned into heating the air, with average values of sensible heat H in excess of λE, the energy consumed to evaporate water (Figs 2*b*, 3*b*). For the Howard Springs and Virginia Park sites, average daily dry season λE was 38 W m^{-2} and 16 W m^{-2}, equivalent to an evapotranspiration rate of 1.4 and 0.6 mm day^{-1}, respectively. February is

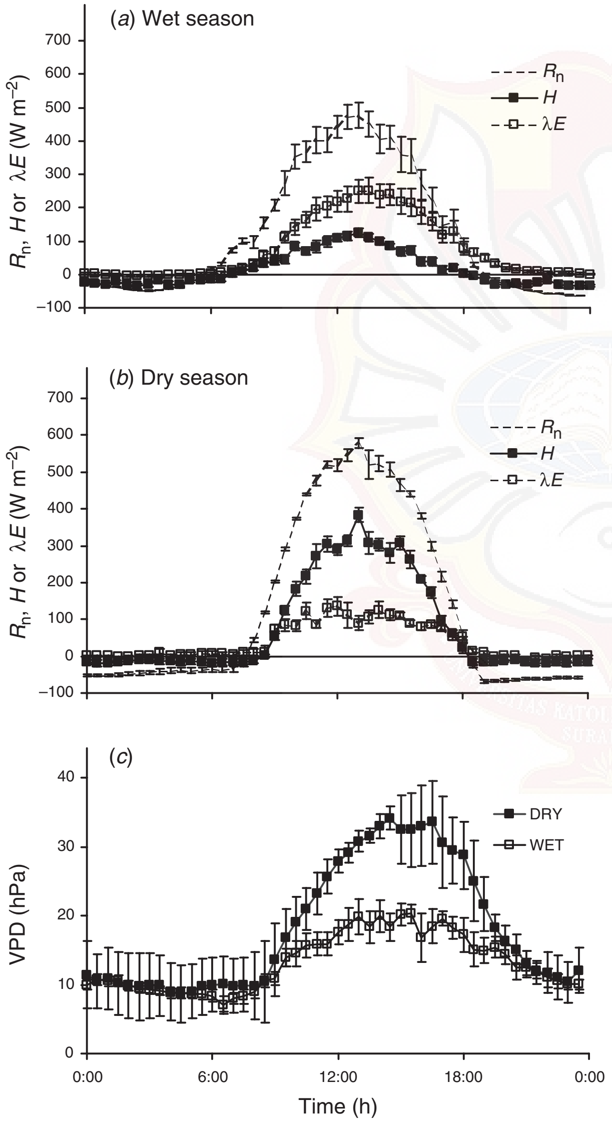

Fig. 2. Typical diurnal variation in 30-min fluxes of (*a*, *b*) sensible (H) and latent heat (λE) and net radiation (R_n), and (*c*) vapour pressure deficit (*VPD*) at the Howard Springs eddy covariance site. Data are shown for (*a*) the dry season, August 2001, and (*b*) the following wet season, February 2002. Data are 7-day ensemble averages, with error bars the standard error of the mean.

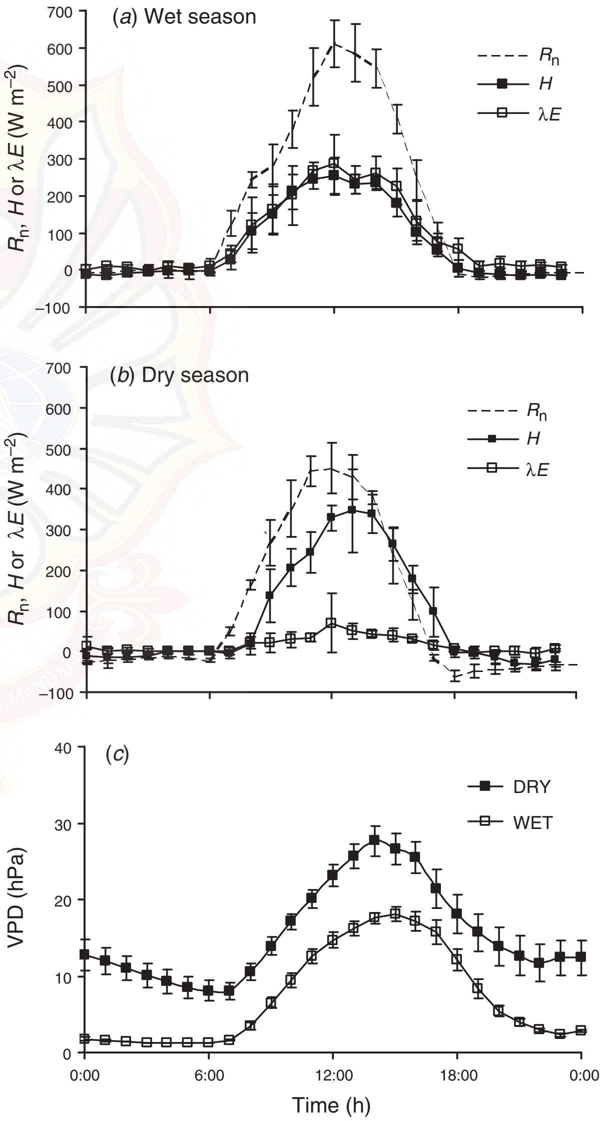

Fig. 3. Typical diurnal variation in 60-min fluxes of (*a*, *b*) sensible (H) and latent heat (λE) and net radiation (R_n), and (*c*) vapour pressure deficit (*VPD*) at the Virginia Park eddy covariance site. Data are shown for the dry season, August 2001 (*a*) and the following wet season, February 2002 (*b*). Data are 7-day ensemble averages, with error bars the standard error of the mean.

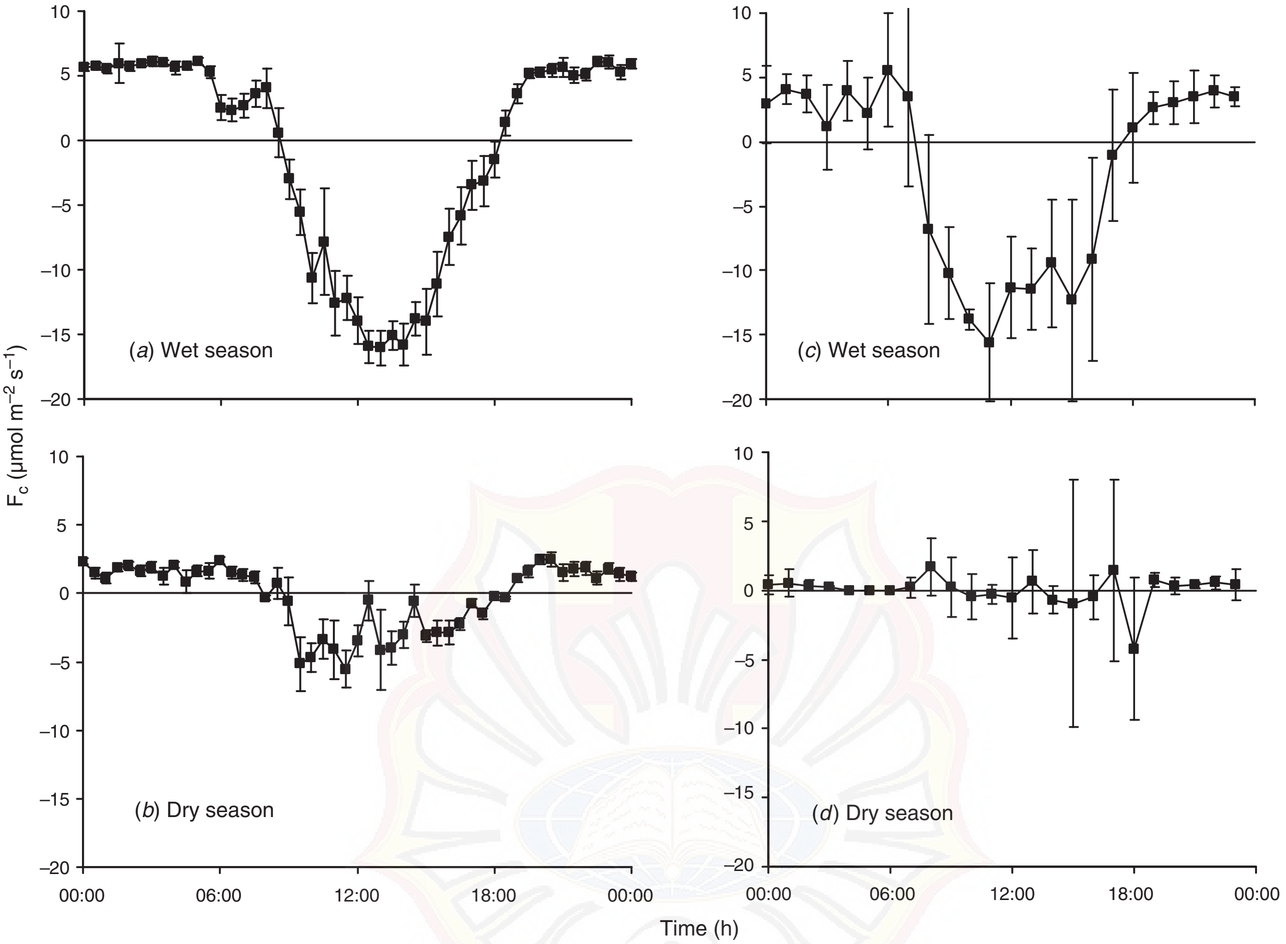

Fig. 4. Typical diurnal variation in CO_2 fluxes at (*a*, *b*) Howard Springs and (*c*, *d*) Virginia Park. Data are for (*a*, *c*) the wet season, February 2002, and (*b*, *d*) the dry season, August 2001. Data are 7-day ensemble averages, with error bars the standard error of the mean. Negative values imply net carbon uptake by the ecosystem, positive values imply a carbon source.

typically one of the wettest months in the wet–dry tropics of northern Australia and this is reflected in wet-season rates of λ*E*, which were more than double the dry-season rates. At Howard Springs, peak λ*E* was 250 W m^{-2} and about two-thirds of the available energy was used in evapotranspiration, whereas at Virginia Park, peak λ*E* was 300 W m^{-2} and available energy was partitioned almost equally between *H* and λ*E* (Figs 2*a*, 3*a*). Despite a lower wet-season *LAI* at Virginia Park (Table 1), the mean evapotranspiration rate was 3.5 mm day^{-1}, compared with the 2.8 mm day^{-1} observed at Howard Springs for this same period. Higher wet-season evapotranspiration rates at Virginia Park were due to more net radiation for the reporting period (cf. Figs 2*a*, 3*a*). The daily integral of R_n at Virginia Park was 14.2 MJ day^{-1}, compared with 10.7 MJ day^{-1} at Howard Springs, caused by greater cloud cover associated with the northern Australian monsoon. While R_n was 33% greater at Virginia Park than at Howard Springs, evapotranspiration was only 25% higher. The discrepancy resulted from lower *VPD*s in early morning and late afternoon at Virginia Park (cf. Figs 2*c*, 3*c*) which contributed to lower evapotranspiration rates than at Howard Springs at those times. Peak daytime values of *VPD* were similar at both sites.

Large seasonal differences in CO_2 fluxes were also evident at both sites (Fig. 4). By the micrometeorological convention, negative values of F_c represent a net downward flux of CO_2 from the atmosphere to the ecosystem, via uptake from photosynthesis. Daily maximal values of F_c exceeded −15 μmol m^{-2} s^{-1} during the wet season at both sites (Fig. 4*a*, *c*), close to wet-season rates observed in savannas in Africa (Hanan *et al.* 1998; Verhoef *et al.* 1996; Monteny *et al.* 1997) and South America (Miranda *et al.* 1997). At Virginia Park, daily averaged F_c for the wet season was −2.35 μmol CO_2 m^{-2} s^{-1}, corresponding to a net uptake of −2.4 g C m^{-2} day^{-1}. Fluxes were close to zero during the dry season, when soil moisture availability was low (Fig. 4*d*) and the ecosystem was essential carbon ‘neutral’, with a net flux of +0.02 g C m^{-2} day^{-1}, a small net loss

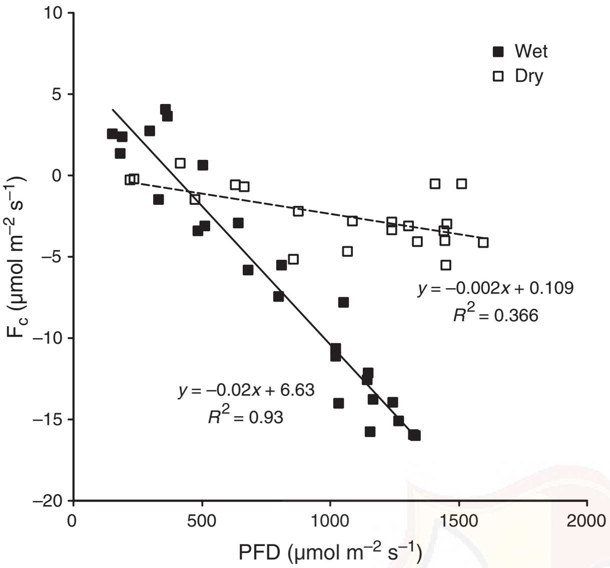

Fig. 5. Relationship between 30-min average CO_2 flux (F_c) and *PFD* for the Howard Springs site for the wet- (February 2001) and dry-season (August 2001) measurement periods.

of CO_2 to the atmosphere. Seasonal variations in F_c were also evident at the Howard Springs site (Fig. 4*a*, *b*) where the daily integral of F_c was $-1.07\,\mathrm{g\,C\,m^{-2}\,day^{-1}}$ during the wet season. This C sink was maintained into the dry season with F_c at $-0.23\,\mathrm{g\,C\,m^{-2}\,day^{-1}}$ for the August 2001 reporting period.

Like λE, wet-season magnitudes of F_c at Virginia Park were higher than those observed at Howard Springs, despite a lower *LAI*. This could be explained by lower radiation at Howard Springs than at Virginia Park, although mid-day maximal rates of F_c were similar at both sites (Fig. 4*a*, *c*). However, the average nocturnal respiration rate was approximately 35% higher at Howard Springs than at Virginia Park (Fig. 4*a*, *c*) and the larger tree size and density at Howard Springs (Table 1) resulted in an increased respiration for this site compared with Virginia Park. This reduced the daily *net* CO_2 uptake, despite similar rates of canopy uptake during the daytime.

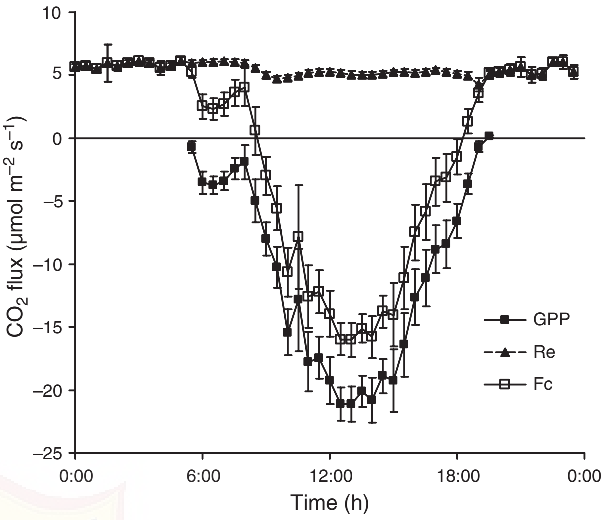

Fig. 6. Component fluxes (F_c, R_e, *GPP*) derived from eddy covariance data from the Howard Springs site during the early wet season 16–29 December 2001. Data are 13-day ensemble averages, with error bars the standard error of the mean.

Flux data can also be used to develop ecophysiological response functions to radiation, temperature, vapour pressure and soil moisture deficit. An example is given in Fig. 5, which shows a strong relationship between F_c and above-canopy radiation for the Howard Springs site. Available soil moisture decreases as the dry season progresses (Hutley *et al.* 2000) and both the slope and intercept of this relationship are significantly different, suggesting that the radiation-use efficiency and *LAI* of the ecosystem changes with season (Fig. 5). Such functions are fundamental drivers of canopy physiology models and provide powerful data for model calibration and validation.

Annual productivity estimates

Continuous EC measurements of λE and F_c enable the calculation of annual water and carbon balances. An example is given in Table 2 for the savanna sites for two hydrological years, July 2001–June 2003. At Virginia Park,

Table 2. Annual water and carbon budgets for Virginia Park (VP) and Howard Springs (HS) sites for the two hydrological years between July 2001 and June 2003

GPP, gross primary production. *NEP*, net ecosystem production. Here *GPP* is given as a negative value representing carbon uptake by the ecosystem. $GPP = F_c - R_e$, where R_e is ecosystem respiration. $NEP = F_c$, so a negative sign indicates net uptake of carbon by the ecosystem, positive a net source of carbon. *NEP* is calculated with 24-h fluxes. The data for these years at Howard Springs include the impact of fire. See Table 3 for details

Period	Site	Rainfall (mm year^{-1})	Evapotranspiration (mm year^{-1})	*GPP* (t C ha^{-1} year^{-1})	*NEP* (t C ha^{-1} year^{-1})
Jul 2001–Jun 2002	VP	571	540	−5.76	+0.21
	HS	1699	978	−16.8	−0.7
Jul 2002–Jun 2003	VP	360	388	−1.82	+0.49
	HS	1487	892	−18	−1.64

rainfall in the 2001–2002 wet season was just below the long-term average but rainfall in the subsequent wet season was in the lowest 15th percentile (Leuning *et al.* 2005). Rainfall and evapotranspiration were in close balance for the 2 years shown, but low rainfall and evapotranspiration in the second wet season caused a strong reduction in daytime *GPP* compared with the first year. Despite these large differences in *GPP*, there was a small net loss of carbon by the ecosystem in both years, largely because carbon uptake in the wet season is dominated by the C_4 grass understorey (Eamus *et al.* 2001) and this is subsequently lost through heavy grazing by cattle and by plant respiration. These results also suggest little or no net carbon gain by the trees during the reporting period. It is likely that the duration of high F_c during the wet season at Virginia Park site would be short-lived, constrained by the short duration of available moisture given the low annual rainfall. The wetter Howard Springs site was a net carbon sink on an annual basis (Table 2), despite having lower wet-season peak F_c than Virginia Park during the reporting period and the occurrence of frequent fire (Table 3). Ability to compare such differences at various sites underlines the utility of long-term flux measurements in gaining greater understanding of carbon cycling within ecosystems. This is especially important in seasonal ecosystems such as savannas, which are subject to large inter-annual variation in the timing, duration and size of wet seasons (Cook and Heerdegen 2001). Short-term measurements may not adequately capture variation in fluxes associated with the dynamics of climate.

The EC method is being used at the Howard Springs site to investigate the effects of fire on energy balance, surface albedo and carbon dynamics. Up to 75% of all fires in Australia occur in the savanna and fire is one of the most significant ecological determinants of savanna form and function (Williams *et al.* 2002). Key questions concern the effects of frequent dry-season fires on savanna productivity, resultant greenhouse gas emissions and impacts on the atmosphere from smoke, changes in albedo and energy partitioning (Beringer *et al.* 2003). Fluxes prior, during and after individual fire events have been monitored at the Howard Springs site since 2001 and have provided data on carbon sink strength following fire (Table 3). Annual production indices *GPP*, *NEP* and *NBP* have been calculated for 2001–2003 and data can be compared with findings of Eamus *et al.* (2001) who provided an *NEP* estimate at the Howard Springs site without the effects of fire. Data given in Table 3 suggest that fire reduces net biome productivity by at least 50%. Howard Springs remains a weak carbon sink despite frequent burning, in contrast to Virginia Park, which is essentially carbon neutral or a small source of carbon to the atmosphere, with annual productivity more determined by annual rainfall and grazing pressure. Fire is absent at Virginia Park owing to reduced fuel loads caused by grazing. The flux data provide insights into factors contributing to carbon sink strength (*NEP/NBP*) as a function of climate (rainfall) and land management (fire frequency and grazing), with assessment of seasonal and interannual variability of these factors also possible.

Table 3. Estimates of *NEP* (excluding fire) and *NBP* ($t\,C\,ha^{-1}\,year^{-1}$) for the Howard Springs site, based on 2 years of flux measurements that include fire events and previous measurements without fire events included

NBP is calculated assuming fire occurrence of two in every 3 years. The calculated mean includes the value of *NEP* for the 2 years with fire and the *NEP* value of Eamus *et al.* (2001), which was estimated by using fluxes made during fire-free periods

Parameter	2001–2002	2002–2003	Eamus *et al.* (2001)
R_e	+16.1	+15.6	
GPP	−16.8	−18.0	
NEP	−0.7	−2.6	−2.81
Fire losses	+0.52	+0.96	
NEP—fire	−0.18	−1.64	
NBP	Average of 2 values = −1.54		

Utility of eddy covariance in carbon accounting

Carbon accounting can be broadly defined as the quantification of changes to carbon stocks, via emissions or sinks, using consistent and transparent methods (IPCC 2001). The Kyoto Protocol, as it is currently defined, provides for the calculation of sinks in restricted 'Kyoto' forests during non-contiguous commitment periods. As such, the Kyoto Protocol is essentially a 'partial' carbon accounting system. A more rigorous or full carbon accounting system would quantify all atmospheric exchanges of CO_2 from both autotrophic and heterotrophic components of an ecosystem (*NEP*) and would be applied continuously (Steffen *et al.* 1998). Monitoring of biomass increment alone (*NPP*) is insufficient as it does not account for carbon loss from soils and longer-term net biome production (*NBP*) which include losses via disturbance which also require quantification (Schulze *et al.* 2000). Implementing full carbon accounting represents a major challenge but would provide a more effective means of understanding and managing terrestrial carbon cycling and greenhouse emissions. Although Australia has not ratified the Kyoto Protocol, the Australian Government has developed the National Carbon Accounting System (NCAS) to provide data on terrestrial carbon cycling for Australian ecosystems, in particular, focusing on greenhouse gas sources and sinks as a result of land-use change. The NCAS system uses the FullCAM model (Richards 2001), which is a full carbon-accounting model with a range of empirical submodels that calculates exchanges of carbon, loss and uptake between the terrestrial ecosystems and the atmosphere. Impacts of land-management practices (e.g. fire, harvest and thinning, tillage) on carbon pools and fluxes in forest, agricultural and transitional (afforestation, reforestation, deforestation) sites can also be modelled (Richards 2001). FullCAM has been used to predict changes to soil organic carbon pools under a range of afforestation scenarios (Paul *et al.* 2003) and rates of litter decomposition under Australian conditions (Paul and Polglase 2004), but requires further verification, especially in tropical environments. Under a full carbon accounting and trading environment, there is potential for changes in land management in Australian savannas that result in carbon sinks to be claimed as carbon credits. For instance, a measurable and documented decrease in human-induced CO_2 emissions via changed fire or grazing management could be counted in future trading schemes.

Given the requirements of partial and possibly full carbon accounting in the future, the EC method would appear to provide a useful tool for quantification and verification of ecosystem sink strength, given its ability to monitor *NEP*/*NBP* directly and non-destructively and provide estimates of *NPP* and *GPP*. Advances of the last two decades have enabled modern EC systems, at ideal sites, to estimate CO_2 fluxes, evapotranspiration and carbon balance with errors of less than 10% (Baldocchi 2003). Improvements in flux technology will foster collaborative research between flux scientists and ecologists, plant physiologists, modellers, remote sensors and, it is hoped, land managers and policy makers. Such synergies between some of these research disciplines are evident with the development of international research networks, such as Fluxnet (Baldocchi *et al.* 2001, http://daac.ornl.gov/FLUXNET). This is a global network of flux towers of over 250 registered sites that are monitoring long-term carbon fluxes, providing key data examining climatic controls and interannual variability of mass and energy exchange from terrestrial ecosystems.

Given the scale and number of measurements being made as part of this international network, estimates of *NEP* and *NBP* are possible for a suite of natural and agricultural ecosystems, with integration providing quantification of the global terrestrial carbon sink. Large uncertainties associated with the size of this sink remain and such networks provide a powerful approach to reduce such uncertainty. Major regional networks include Ameriflux (America—71 towers), Europe (CarboEurope—39), Canada (Fluxnet-Canada—21), Asia (AsiaFlux—41) Australia (Ozflux—5) and Africa (Afriflux—6). At the time of writing, there are five flux sites within the Australia network (Ozflux) and clearly more investment in this network is required. For tropical savanna of northern Australia, advances have been made in quantifying carbon flux (Eamus *et al.* 2001; Leuning *et al.* 2005), impacts of disturbance (Beringer *et al.* 2004; Williams *et al.* 2004) and carbon stocks (Chen *et al.* 2003; Williams *et al.* 2005, this issue), with measurements on-going. Full carbon accounting within this ecosystem could be made with more confidence than for most Australian ecosystems.

Ideally, multiscale methods and models are required to quantify the carbon budget. Studies are needed that combine measurements of process at plant and stand scales (e.g. soil, stem and leaf respiration), fluxes at canopy scale through to regional- and even continental-scale estimates employing measurements of CO_2 in the planetary boundary layer and inversion modelling methods (House *et al.* 2003; Xiao *et al.* 2004). No single method provides data on the numerous terms of the carbon balance in terrestrial ecosystems at all scales from the local to global. Networks such as Fluxnet and EUROFLUX (Valentini 2003) provide a collaborative mechanism, with participants working on problems at all required scales and such groups may provide integrated, verifiable and transparent methods for improved understanding of carbon cycling in terrestrial ecosystems and the implementation of more meaningful full carbon accounting systems.

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Manuscript received 22 September 2004, accepted 24 February 2005