PART E—PROJECT DESCRIPTION

E1 PROJECT TITLE

Sustainable futures of Australian temperate forests: An investigation of coupled carbon, water and energy exchanges from hourly to centennial time scales.

E2 BACKGROUND

Australian native forests are an important component of the Australian landscape, comprising 164 million ha or around 21 per cent of the continent landmass. Temperate open forests cover an area of ~ 5.5 million ha, which is five times greater than the area of plantation forests and therefore represent a potentially important carbon sink [*RAC*, 1992]. Temperate open forests are also economically important for the forestry industry and are significant in providing areas for recreation and maintaining the health/biodiversity of the environment. These forests also occupy many catchments used to provide water and are crucial in sustaining the amount and quality of drinking water (e.g. Maroondah catchment, Melbourne). For these reasons it important to understand how our forest assets may develop into the future. This important ecosystem is biocomplex and has physical, biological and chemical (biogeochemical) cycles that are coupled across different time scales. Cycles of energy are essential in driving photosynthesis and determining climate and water use. Biogeochemical cycles of carbon, water and nitrogen are important for provision of freshwater, carbon sequestration and forest production. In order to understand how Australian forests will develop in the future we must know how these cycles and the forest as whole will respond to changes in climate, extreme climate events, ecological succession and human disturbance which all occur on different time scales. Unfortunately we have limited understanding of these complex systems at differing spatial and temporal scales [*Nikolov & Fox*, 1994].

The fundamentals of the carbon cycle within forests are relatively well understood. Previous inventory based estimates have shown the net uptake of carbon of the ecosystem as a whole (Net Ecosystem Exchange – NEE - the net carbon gained by the ecosystem through photosynthetic production minus respiration from plants and soil) decreases with stand age and in old growth forests, carbon cycling is often assumed to be in equilibrium [*Carey et al.*, 2001; *Hollinger et al.*, 1994]. However, young trees are believed to be a net carbon sink because they rapidly sequester carbon as they grow [*Kaiser*, 2000; *RAC*, 1992]. Inverse modelling of carbon fluxes shows that Northern Hemisphere old growth forests are a stronger sink of CO_2 than calculated from previous inventory studies [*Martin et al.*, 2001] (In Australia we currently do not have a network that allows us to resolve these fluxes using this method). The reasons for high carbon uptake by old growth forests is uncertain, but it has been suggested that high rates of leaf and root turnover contribute to permanent soil carbon pools [*Dixon et al.*, 1994; *Schulze et al.*, 2000]. Therefore old growth forests, in addition to the important role in biodiversity conservation, provide a large carbon store and may act as a carbon sink, keeping carbon dioxide out of the atmosphere [*Carey et al.*, 2001]. Australia's current carbon inventory shows that growth, harvesting and regrowth in **managed** native forests and plantations has been a net carbon sink for greenhouse gases of 75.8 Mt in 1999 [*AGO*, 2001]. The role of **native** open forests in the carbon inventory is uncertain, although they have the potential to contribute a significant carbon sink given their large areal coverage. To reduce this uncertainty, investigations of the carbon cycle in native forests and how it may change with stand age and differing management are required.

The cycle of water within a forest is important and is determined by tree water use, evaporation and runoff. Understanding the ecohydrology of catchments such as the Maroondah catchment is critical given their role in the provision of potable water to large urban populations. Basic hydrological processes for these forests are well understood from comprehensive observations and modelling work (e.g. [*Vertessy et al.*, 1995] which has included research on the effect of stand age on water yields [*Cornish and Vertessy*, 2001]). However, we do not currently have a good understanding of how the water cycle is coupled with cycles of carbon and energy and how these cycles interact over annual to centennial time scales. Such knowledge is important for the future management of these forests and catchments given anticipated environmental change.

The energy cycle within the forest is critical in driving photosynthesis, evaporation, transpiration, heating of the atmosphere and soil. There is strong coupling between the energy, carbon and water cycles. The amount of energy that is used in evapotranspiration, heating and canopy energy storage, as well as the way in which this energy is partitioned between these fluxes is influenced by the biological (stand age and species composition) and physical characteristics (height, canopy structure) of the forest. For extensive forest ecosystems, this energy flow in turn feeds back to influence climate.

Although several of the individual processes within carbon, water and energy cycles (photosynthesis, respiration, leaf energy balance and turbulent exchange within plant canopies) are well characterised at the leaf level, the complex nature of the coupling between processes has not been examined extensively [*Kull*, 2002]. A greater understanding of microenvironmental forest processes are needed to be able to scale up from the leaf level to the plant canopy. This is vital if we are to be able to predict the response of whole forests to environmental change. It may be best achieved using integrated observations and ecosystem modelling of the carbon, water and energy balance of forests at a canopy scale. There have been few measurements of the carbon, water and energy processes in Australian forests, making it difficult to both quantify and predict changes with time. Some inventory-style carbon balance estimates have been made in temperate eucalypt forests [*Keith et al.,* 1997], but these do not capture the important ecosystem dynamics and variability.

Recent advances in micrometeorological techniques (namely Eddy Covariance - EC) now allow hourly measurements of carbon, water and energy fluxes from ecosystems. This technique is considered the most robust and accurate for measuring fluxes compared to inventory and inverse modelling approaches [*Moncrieff et al.,* 1997]. To date, there have been few EC studies of native vegetation. *Hutley et al.* [2000] used EC to quantify water and energy balances of tropical savanna vegetation and *Eamus et al.* [2001] estimated the carbon sink strength of tropical savanna derived from short periods of measurement. Only one study of southern temperate open eucalypt forests has been conducted, in West Australian Jarrah [*Silberstein et al*., 2001], however, carbon exchanges were not measured during their study, and measurements were short-term only. As a result of the lack of long-term integrative studies, there is a large uncertainty regarding the carbon, water and energy cycles of temperate (or any) Australian forests, particularly in relation to how they may change with time. Clearly, more rigorous long-term estimates of carbon, water and energy cycles in temperate open forests across various time scales are needed. Such studies are of considerable value in helping to determine the response of forests to environmental change and quantifying Australia's carbon and water balances.

Many of the processes driving water and carbon fluxes at ecosystem level are strongly dependent on seasonal changes and extremes in climate [*Grelle et al.*, 1999]. Seasonal changes of phenology and biomass production significantly affect rates of water and carbon exchanges. Furthermore, extreme events (extreme temperatures, high wind velocity, drought conditions) are not often captured during short-term field measurements yet these non-average conditions have a strong impact on the hydrological and carbon cycles of terrestrial ecosystems [*Baldocchi et al.*, 1997]. It is therefore critical to examine the response of Australian forests over time scales long enough to be relevant to climatic processes issues (seasonal to interannual to decadal). An improved knowledge of the complex land-atmosphere exchanges of carbon, water and energy is vital at time scales encompassing days, seasons, years, and even decades, as well as over spatial scales from a few kilometres to landscapes and will be a major outcome of this proposal. Such knowledge will provide improved parameterisations for predictive ecosystem models and ultimately aid the sustainable management of carbon and water resources within Australian forests.

E3 SIGNIFICANCE AND INNOVATION

This study aims to quantify, for the first time, the cycles carbon, water and energy of Australian temperate forests and how these cycles are coupled over various temporal scales. We will take long-term measurements using flux towers and new advances in the EC technique [*Moncrieff et al.,* 1997]. The towers will continue operating beyond the timeframe of this proposal using modest funding from Monash University and industry (Melbourne Water). Such visionary long-term measurements will be used to assess the coupling of mass and energy cycles over seasonal to interannual timescales. These measurements will define the forest carbon budgets and we will assess the sink/source strength of Australia's temperate old growth forests and hence their contributions to the national carbon inventory. The measurements will increase our understanding of how variability in climate may influence the carbon, water and energy cycles and assess the vulnerability of our forests to change. This will allow us to predict the influence of future climate change and variability including extreme events (such as particularly hot/cold or wet/dry seasons or extreme fire weather timing and frequency). It is likely that climate change (in particular warming) could have significant, long-term impacts on temperate forests carbon and water balances. *Hilbert et al.* [2001] demonstrated the sensitivity to warming of cool, wet forest types, with warming shifting forest distribution and function.

Using a second roving tower, we will conduct the same measurements over regrowth forests of different ages (ranging from 5 to 100 years old) that have been previously clear-felled. We will determine how the forest carbon and water balance changes over decadal to centennial time scales. We will assess the impact of clear-felling forest management practices and its longer term influence on forest sustainability (e.g. carbon sink strength and water balance).

The flux tower measurements will provide unique mechanistic and environmental data sets that we will use to evaluate and refine, through improved parameterisations, two current flux/ecosystem models that operate on different time scales (the Terrestrial ecosystem Model (TEM) and the CSIRO Biosphere Model (CBM)). We will work closely with CSIRO to validate and develop CBM (with Ray Leuning) and the CSIRO biogeochemical model (with Michael Raupach). We will collaberate with the CRC for Catchment Hydrology (Rob Vertessy) to provide data for catchment models and water balance research. We will work with UNSW (Ross McMurtie) to provide data for use in a range of simpler Australian ecosystem models (GDAY model).

In turn, these models will be used to provide a more accurate simulation of future carbon, water and energy budgets and hence improved management of forests and their water catchments. The models will provide a predictive response of ecosystems to change at both local and regional scales. The carbon balance across these different aged stands will also be quantified to provide an empirical basis to evaluate the carbon sink/source strength of old growth and regrowth forests and water budgets of the catchment that supplies Melbourne's water that will be vital for the future management of the catchment.

This proposal clearly addresses the National Research Priority of 'An Environmentally Sustainable Australia' through three priority goals: **1) Water – a critical resource**: We will assess the role of climate variability on water fluxes and the impact on water supplies in forested catchments. This will increase our understanding of sustainable water management. **2) Reducing and capturing emissions in transport and energy generation**: We will determine the role of native old growth forests in sequestering carbon dioxide and the impact of clear-felling. **3) Sustainable use of Australia's biodiversity**: We will provide a comprehensive understanding of the interplay between natural systems and human activities with regard to the ecosystem services the forests provide (water and carbon). The role of clear-felling forests will be examined.

We will contribute a uniquely Australian site and data set to a network of worldwide sites as part of FLUXNET [*Baldocchi et al.*, 2001]. Australia currently has only three stations in FLUXNET as part of the recently proposed OZFLUX network (Ray Leuning, CSIRO Land and Water). Given the size of the Australian land mass, this is an inadequate flux monitoring network if Australia is to provide realistic continental-scale carbon source/sink estimates. Investment in European, North American and Asian research programs in this field are 2 to 3 orders of magnitude greater than that currently occurring in Australia. This project is an attempt to address this lack of development in this field in Australia and we will contribute strongly to the development of OZFLUX and foster further flux research in Australia. This project will be central in providing the research capability to build an Australian biosphere monitoring system.

We will provide a sustained set of detailed observations of ecosystem level exchanges of carbon, water, and energy on an hourly basis, spanning diurnal, synoptic, seasonal, and interannual time scales to FLUXNET, OZFLUX and other users. This will facilitate important international networking and our data will be used by FLUXNET in inverse models that attempt to determine uptake by the terrestrial biosphere at regional, continental and global scales using an inverse modelling analysis of observed CO_2 concentrations [*Kaminski and Heimann*, 2001]. As our contribution to FLUXNET we will coordinate and quality assure measurements across our site(s), lead cross-network data analysis and synthesis of results, and communicate results to the scientific community and other users. Our flux measurements will be compared to values of net primary productivity, evaporation and energy absorption that are generated by the NASA TERRA satellite.

Our study will quantify the carbon sink/source of a temperate Mountain Ash forest and identify the contribution of such forest types to the continent's National Carbon Inventory, a task that is identified as extremely important by the National Land and Water Resources Audit [*NLWRA*, 2000]. They identified that this will require characterisation of the linked carbon, water and energy exchanges between the Australian land surface and the atmosphere. These exchanges play key roles in the terrestrial biospheric components of Australia's greenhouse gas inventory and in the landscape budgets of carbon and water that are crucial measures of land use viability.

Finally, our project will contribute to the Australian Climate Observing System that is part of the Global Climate Observing System and will supply observational data for the improved understanding of Australian and global climate, prediction of the seasonal and interannual variations in Australia's climate and the detection and quantification of longer term climate change. This project is closely linked with two of the core programs in the International Geosphere-Biosphere Programme. Firstly, our project objectives are commensurate with those of the Global Change and Terrestrial Ecosystems program, Focus Group 1 (Ecosystem physiology and global change). Their primary aim is to understand and model the effect of global change on primary ecosystem processes such as the exchange of carbon, water and trace gases with the atmosphere, element cycling and storage, and biomass accumulation or loss. Second, the project has important links with the Global Analysis, Integration and Modelling that aims to improve our understanding of how the Earth functions as a system using both data and models as tools.

E4 APPROACH

The overall objectives of this study are to understand the complex coupling of carbon, water and energy cycles within Australia's temperate forests over various temporal scales in order to assess the impact of future environmental change. We will measure hourly fluxes of carbon, water and energy above the forest using the EC technique on a tall tower over a period of more than 3 years. Concurrent measurements of meteorological variables and component processes will be made. Our approach is to combine continuous flux measurements of these cycles on a multi-year time basis with ecological process interpretation and modelling. This will allow us to understand the complexity of these systems and incorporate this into our models to improve future simulations.

The site will be located within the Maroondah Water catchment that supplies Melbourne's drinking water. The catchment is an excellent example of temperate eucalypt forest and is unique because it has intact old growth stands with individual trees as old as 300 years. The forest is primarily Mountain Ash (*Eucalyptus regnans*) and has been the site of intensive hydrological research. Our proposed research will provide ongoing information on canopy scale water budgets that will be used by the CRC for Catchment Hydrology (Dr. Rob Vertessy, pers. com.). In addition, areas of the surrounding catchment are host to commercial clear felling practices. Operations over the past century have subsequently allowed forests to regrow and there are many areas of homogeneous forest of varying age. We will investigate these sites to examine decadal to centennial changes to carbon, water and energy cycles. There are two major project objectives:

Objective 1: To quantify the carbon, water and energy exchanges in a temperate forest and the factors regulating them over hourly to inter-annual time scales.

Observational Strategy

- Establish a tall tower in the old growth Mountain Ash forest of the Maroondah catchment using the EC technique [*Moncrieff et al., 1997*] to measure the carbon, water and energy fluxes. Hourly measurements of fluxes, meteorological variables and component processes will be used to examine canopy scale processes and mechanisms controlling fluxes. Longer term flux measurements over the 3 year funding period (and beyond) will be used to investigate controls over these fluxes over a range of different temporal and climatic conditions (including seasonal, inter-annual, extreme events and stress limitations). The site will become a long-term research site and EC measurements will continue beyond this funding using small funding.

- We will measure the input fluxes of net radiation (R_n – Wm^{-2}) and output fluxes of water vapour (LE – Wm^{-2}), atmospheric heating (H – Wm^{-2}) and heating of the soil (G - Wm^{-2}) every 30 minutes. These components define the energy balance (R_n=H+LE+G). The net radiation is comprised of incoming and outgoing shortwave and longwave radiation fluxes and these will be measured independently in order to quantify changes in radiative exchanges and the efficiency of radiation trapping of the forest (i.e. albedo). To measure the soil heat flux (***G***) we will use the combination method and utilise a spatial array of soil heat flux plates and soil temperature sensors. Net Ecosystem Exchange (***NEE*** – g C m^{-2} s^{-1}) of carbon will be measured.
- EC instrumentation will include a 3D-sonic anemometer and a fast response CO_2/H_2O open path infrared gas analyser (IRGA). An open path analyser is preferred because of the remoteness of the site and use of solar power. Care will be taken during site selection to ensure adequate fetch, uniform vegetation, proper instrument placement, sampling duration and frequency. We will use a walk-up scaffolding tower (70m height and secured within a fenced compound) to mount instrumentation above the canopy (55m height). To ensure intercomparability of results amongst the proposed OZFLUX network we will collaborate with FLUXNET, who sponsor a set of reference of instruments to sites in Europe, Asia and Australia.
- Post processing of EC data is a significant issue with nocturnal (u*) corrections, energy balance closure and gap filling being important. Nocturnal measurements in low turbulence conditions remains contentious and is being considered by the Fluxnet community of which we are already involved. We will use profile based CO_2 storage measurements, below canopy EC measurements and chamber-based techniques to assess the ‘true’ nocturnal flux and the applicability of a nocturnal correction for our site. We prefer to leave flux numbers uncorrected and quantify the magnitude of the energy balance closure error. Gap filling will be performed using a variety of methods but will likely be based on a neural network or site-specific modelled output.
- The nature and cost of EC based measurements prohibits site replication and necessitates measurements at the patch scale. However, the EC method provides an area-averaged flux estimate, representative of hundreds of hectares of vegetation. We will ensure all our sites are representative of the surrounding region by taking advantage of existing and extensive knowledge of vegetation characteristics and by utilising remote sensing.
- A full suite of environmental and climate measurements will be made concurrently with the flux measurements and will include photosynthetically active radiation, air temperature, vapour pressure, atmospheric pressure, soil moisture content, wind speed (at various height to define roughness lengths), wind direction (to determine fetch) and phenology. We will also measure energy stored within the biomass using thermocouples to measure leaf, stem and trunk temperatures. We will also measure CO_2 and water vapour storage within the canopy air volume (an important term during stable conditions) by establishing a closed path CO_2/H_2O analyser that will sequentially sample a vertical profile through the canopy.
- We will measure components of the carbon balance and its change over time, along with additional key model variables for integrative measurement/modelling studies. Soil respiration will be determined in short, regular campaigns using ‘top-hat’ chamber measurements along with soil temperature and moisture in order to provide functional relationships between climatic factors and fluxes. We will use the second EC system for short periods to measure understorey CO_2 fluxes that will be compared with simultaneous chamber-based measurements. Soil carbon storage and turnover will be investigated by Tony Patti (Monash, Green chemistry). Stem and branch respiration will be estimated using cuvette measurements on trees selected to be representative of the stand according to diameter distribution, age and species. Leaf level respiration will be measured by portable gas exchange system (provided by NTU) and these measurements will be correlated with leaf position within the canopy and other variables (vapour pressure deficit, PPFD, foliar N status and

photosynthetic capacity). Leaf Area Index (LAI) will be estimated both by light interception and direct sampling. Leaf litter will be measured using leaf fall traps.

- Additional component processes that define the water balance will be made. Tree transpiration will be measured using the heat pulse technique (provided by NTU). The balance of the tower based evapotranspiration measurements minus the tree transpiration gives evaporation from canopy/ground and evapotranspiration from the understorey ecosystem. This will allow us to partition the water balance of the forest, which is of fundamental importance for the hydrology of the catchment and is of primary interest to catchment hydrology research. The remainder of the hydrological balance is well characterised for the 'Maroondah' catchment, however we will measure water inputs using raingauges and existing measurements of throughfall and stemflow. Soil moisture changes will be followed during the season using TDR type probes.

Modelling strategy

- ***Hourly to daily time scales:*** We will work closely with the CSIRO Land and Water group (or their potential equivalent) (Ray Leuning) and use our observations to validate the CSIRO Biosphere Model (CBM) for temperate forests and test our current understanding of the complex cycling in this system. CBM is a one-dimensional land surface model of energy, momentum, water, and CO_2 exchange between the atmosphere and land, and is described by *Wang et al.*, [2001]. The model is forced by incident solar and longwave radiation, precipitation, temperature, wind, specific humidity, and pressure provided specified from our observations. CBM accounts for structural and ecological differences among vegetation types and thermal differences among soil types. Vegetation parameters included plant type (broad canopy structure) leaf and stem areas, root profile, canopy height, leaf dimension, optical properties, stomatal physiology, roughness length, displacement height, and biomass. The model runs on an **hourly** timescale and is ideal for studying processes at this time scale. CBM calculates surface water, energy and carbon fluxes. We will use our observational knowledge, gained above, to improve and incorporate these complex processes that will assist in refining CBM. The model will be parameterised for our sites and we will simulate the forests net carbon uptake, water and energy cycles at the canopy level.
- ***Monthly to centennial time scales:*** The Terrestrial Ecosystem Model (TEM) is a process-based ecosystem model that considers interactions among carbon, nitrogen, and water dynamics on **monthly to centennial time** scales. We will verify/validate TEM using longer term EC data from our site. We will then be able to examine the impact of environmental changes, including climate change scenarios, on the water and carbon balances of the catchment. TEM has been applied at a number of spatial scales including stand-level studies, [*Amthor et al.*, 2001], regional [*Schimel et al.*, 2000], and global scales [*Melillo et al.*, 1993]. In these studies, the model has been used to investigate questions about the response of carbon dynamics to changes in atmospheric carbon dioxide, climate, and disturbance (forest harvest and fire). The simulations of monthly carbon and water dynamics by TEM have been verified and validated at sites that have measured carbon and water fluxes with EC methods [*Amthor et al.*, 2001]. TEM has successfully simulated decadal to century scale responses to fire at stand scales and forest harvest at continental to global scales [*McGuire et al.*, 2001]. TEM is also currently being used to investigate the role of forest harvest in carbon dynamics of the United States, a study that has been funded by the USDA Forest Service. In a number of studies, the model has been applied to evaluate responses of the forest sector to climate change at the national and global scales [*Perez-Garcia et al.*, 1997]. Model output variables of monthly, seasonal, and annual fluxes of carbon will be compared with measurements. We will refine and develop TEM using information gained on the complex coupling of these cycles. Model validation at the old growth site will provide confidence in using the model to simulate stand level changes in carbon and water balances. The model will then be used to simulate annual carbon, water and nitrogen exchanges and the sensitivity to seasonal and interannual variability in climate.

Outcomes

- Enhanced understanding of the controls over carbon, water and energy fluxes in Australian temperate forests on **hourly** timescales that will quantify the complex cycles and interrelationships.

- Validate and improve CBM in relation to growth, primary production, water and energy cycling. CBM will be used to simulate **hourly** fluxes that we will then use to investigate the effect of changes in driving variables and hence how the ecosystem may respond to short-term changes. Improvements in CBM will then be incorporated into CSIRO's atmospheric models.
- Using longer term measurements to assess the variability of the water balance and carbon sink/source strength to environmental factors over **monthly, seasonal and interannual** time scales. An understanding of how the carbon and water balance may change under varying climatic conditions (including future climate change) will be gained.
- Obtain **annual** carbon sink/source strength from direct measurements of CO_2 fluxes. Contribute critical new information on the annual carbon balance of old growth forests that will help validate the current Australian and global CO_2 inventories. This will provide a scientific foundation for a range of CO_2 policy and mitigation actions.
- Observations will validate and refine the current TEM model and improve **seasonal to interannual** simulations of the carbon and water budgets. The model will then be used to assess the impact of future changes (including climate change scenarios) on the carbon and water budgets.
- The tower will remain operational following this proposed funding as a long-term observational site. This site will become a valuable asset for assessing how forests may respond to long-term change or variability particularly in terms of climate.
- Measurements obtained in this study and modelling of the canopy scale water balance is of importance to managing Melbourne's water supply. Catchment scale hydrological modelling such as Topog-IRM [*Vertessy et al.*, 1996] will be conducted by the CRC for Catchment Hydrology using our data for validation and comparison.

Objective 2: Establish the carbon, water and energy cycles of different aged forest stands and investigate how they change over successional time scales (decadal to centennial).

Strategy

- Because we cannot measure continuously over the course of succession from clear felled to old growth (**centuries**) we will employ a space for time substitution. To do this we will establish the carbon, water and energy balances for the different age stands (space) and investigate how the carbon balance may change over successional timescales (**decadal to centennial**). This aspect of the project is particularly innovative and has not been applied elsewhere.
- We will develop a mobile EC tower system using a second tower to be deployed sequentially in short campaigns at a recently clear-felled site and then along a chronosequence of sites of differing stand ages (1, 5, 10, 20, 50 and 100 yrs). These sites are available in the catchment and are within 10km of each other, such that measurements across paired towers experience similar weather.
- Short term (10 week) campaigns will be undertaken in each aged forest stand to measure the carbon, water and energy fluxes. The will be compared directly with the long-term old growth EC tower which will act as a reference. A full suite of environmental conditions, meteorological parameters and component process will be made, as described for the long term tower. Measurements will be taken over summer to minimise confounding influences of climate. The influence of stand age (architecture) on the carbon, water and energy cycles will be investigated. During non-campaign times the portable system will be installed over a stand that is phenologically dynamic to investigate the important shoulder season periods.
- In this study, TEM will be verified/validated in the context of EC measurements for a chronosequence of Mountain Ash. Temporal patterns of vegetation, carbon storage, and water budgets will be compared between simulations and the stands in the chronosequence. To conduct these simulations, spatially and temporally explicit data sets on the timing and extent of forest harvest must be developed for Australia. The method has already been developed in an ongoing study of the role of forest harvest in carbon dynamics of the USA.

Outcomes

- Determination of the carbon, water and energy budgets and the role of clearfelling and succession over decadal to centennial time scales. An understanding of the influence of various forest management strategies on net carbon sink/source and water balance. This will provide critical new information to help define and validate the current Australian and global CO_2 inventories with particular reference to land clearing activities and subsequent recovery. We will address whether clear felling management practices can be sustained as a carbon sink

- Validate and improve TEM to provide confidence in using the model to simulate regional changes in carbon and water budgets. This will enable improved predictions and management of future carbon sink/sources from old growth and regrowth forest beyond our own study site.

Timetable

2004: Jan – PhD students and research assistant selected; Feb - Site selection for old growth tower; Mar – lay base, erect access tower, instal power supply; Apr – Install instrumentation, test and calibrate and begin long term measurements; May – Quality check measurements and develop real time data system and www pages. May-Dec Provide ongoing data retrieval and calibration. July-Dec – Initiate measurements of component carbon fluxes (soil, leaf, stem respiration and photosynthesis). Explore use of TEM and CBM using preliminary data.

2005: Summer - Establish regrowth tower and rotate for 10 week periods through clear-felled and stands aged 1 and 5 years. Jan-Dec Provide ongoing data retrieval and calibration for old growth tower. Initial manuscript on controls on carbon, water and energy exchange. Validate TEM and CBM and develop/refine parameterisations as required. Jan – Dec - Continue measurements of component carbon fluxes (soil, leaf, stem respiration and photosynthesis). Hold flux science meeting and separate shortcourse for theory, measurement and analysis using flux towers.

2006: Jan – Dec - Rotate second tower for 10 week periods through stands aged 10, 25 and 50 yrs. Develop comparative manuscripts on data from old growth/regrowth sites. Use model output to further develop models and generate future simulations for different climate and management strategies. Jan – Dec - Continue measurements of component carbon fluxes (soil, leaf, stem respiration and photosynthesis). Past the final year of the proposal, obtain additional funding for further operation of tower. Finalise remaining manuscripts and continue communicating results.

E5 NATIONAL BENEFIT

Australias forests are a critical natural resource and provide ecosystem services through the provision of potable water and the cycling (and possible sequestration) of carbon. In order to use these resources in a sustainable manner we must understand the current cycles of carbon, water and energy and how these may change over time (seasons to centuries). We will provide a major contribution to the National Research Priority of '**An environmentally sustainable Australia'** through three priority goals in which we will provide: 1) an understanding the **critical water resources** within forests and the impact of forest practices (clear-felling), 2) a rational basis to account for the possible **capture and sequestration of carbon dioxide** in native forests and the impact of clear-felling and succession, 3) A comprehensive understanding of the **sustainable use of Australian native forests**, gained from examing interrelationships between native forests and human activity (clearfelling and the role of anthropogenic climate change and climate extremes). We will address the national prioroties through advanced research on quantifying carbon, water and energy budgets in Austraian temperate forests and the controls and complex coupling between them. Using an integrated observational and modelling approach we will drive, test, and improve models that will ultimately reduce the uncertainty of our predictions.

Our observations will provide reliable forest landscape estimates of carbon and water budgets. Such landscape budgets are crucial measures of land use viability on both short and long time scales. We will assist in validating Australia's biospheric carbon budget and the potential sequestration of old growth and regrowth forests. Such information can assist in the management of forests for maximum carbon uptake. This could be of national economic importance given Australia's stated commitment to meeting greenhouse gas emissions targets.

We expect to provide quantitative information to adequately predict large-scale long-term responses of our forest resources to changing environmental conditions (such as anthropogenic climate change or extended drought) and management strategies (such as clearfelling), both of which have long term consequences for our forests. We will then use our models to provide robust future estimates of carbon and water that will aid our management of forests to ensure viable water resources and carbon sequestration. As this project deals with the environmental sustainablity of Australian native forests, it will be of considerable social benefit for Australia.

One of the strengths of this project lies in the collaberation between disciplines (atmospheric science, biological sciences, remote sensing and modelling) and amongst institutions (Australia and overseas) to obtain the best possible outcomes. Importantly we will contribute to the establishment of the OZFLUX network and build essential research capability. We will operate our site beyond the requested funding period to provide an essential mechanism for longterm climate/flux observations that will address the role of the terrestrial biosphere in global change. Our international linkages are important in ensuring top-class research and worldwide exposure.

Throughout this project we are focussed on providing high quality, collaberative research projects and research training for honours and postgraduate students. In doing so we aim to strengthen Australian research capacity and expertise in this growing area of Global Change science. We request funds for two scholarships (one to examine each objective-above) focused on micrometeorology, instrumentation, land surface change. If funded the three participating institutions will fund the third scholarship to work on the modelling aspects of the project. Support for priority scholarship topups from CSIRO have been indicated (Michael Raupach, Pers. Comm.).

E6 COMMUNICATION OF RESULTS

Real-time data will be made available through a cell-phone link to a Monash web server and will help foster inter-site collaborations. The project will be linked and promoted via the Ozflux and FLUXNET web sites and we will initiate/contribute to any collective OZFLUX meetings. Final data will be archived within two years of collection through FLUXNET who have a well developed data and IP policy. A educational web site will be developed for high school students and teachers that will include basic scientific principles and a project kit that utilises real time data.

We will strengthen research interactions through inter-disciplinary studies and involvement in FLUX networks. The value of this ARC proposed project is that it allows for innovation, but it will also contribute to a network that will allow us to address larger questions and develop general principals of vegetation interaction with the atmosphere. We will attend international AmeriFlux and/or FLUXNET meetings to share results, innovative measurements and analysis methods, and develop inter-site coordination to work toward common network objectives.

We will produce key findings in at least 4-6 key DEST publications in prominent national and international journals that will cover aspects of controls over fluxes, annual carbon balance, model simulations and development and long-term observations and variability. We will communicate results in a timely manner through national and international conferences.

We will hold a flux science workshop in year 2 and invite colleagues involved in other flux-based research and other interested parties from university, government and industry to participate. The workshop will be held over three days in Melbourne and include one day at the site. The workshop will be aimed at fostering collaboration and synthesis across flux sites that may incorporate different ecosystems, climatic or disturbance characteristics. A one-week short course on micrometeorological techniques and flux integration will be held in conjunction with the Australian Meteorological and Oceanographic Society conference in year 2.

E7 DESCRIPTION OF PERSONNEL

Dr. Jason Beringer (CI) – Will coordinate the overall project; assume main supervision for PhD student (objective 1) and co-supervision of the modelling PhD student. Responsible for research assistant at Monash; select the site; shared responsibility for EC measurements. Beringer will liase with McGuire for model simulations and development. Publish on modelling and controls over carbon, water and energy exchanges.

Dr. Lindsay Hutley (CI) – Will be responsible for the ecophysiological and component carbon balance measurements; supervision of the PhD student (objective 2); shared responsibility for EC measurements. Publish on long term carbon, water and energy balances

Dr. A. D. McGuire (PI) – Will coordinate the ecosystem carbon modelling (TEM) and associate supervision for PhD student. Will publish on effect of stand age on carbon uptake.

PhD student (modelling) - Will work on model validation, improvement and simulations; carbon ecosystem model (TEM) with Dave McGuire; land surface modelling (CBM) with Beringer and advice from Ray Leuning (CSIRO). Publish on modelling forest ecosystem at various timescales.
PhD student (objective 1) –Focus on processes and mechanisms of hourly to annual carbon and water cycles. Resposible for longer term tower; publish on annual balances and seasonal variations.
PhD student (objective 2) – Focus on the successional regrowth stands; undertake fieldwork and be responsible for the majority of measurements in the regrowth forest stands; publish on carbon, water and energy balances of different aged forest stands.
Research assistant – Prime responsibility for the maintenance, calibration and data collection for the old growth tower; preliminary data processing/validation; maintain the web site and equipment.

E8 REFERENCES

AGO, *National Greenhouse Gas Inventory Land Use Change and Forestry Sector 1990 – 1999*, 214 p, Australian Greenhouse Office, Canberra, Australia, 2001.

Amthor, J.S., J.M. Chen, J.S. Clein, S.E., et al., Boreal forest CO2 exchange and evapotranspiration predicted by nine ecosystem process models: Intermodel comparisons and relationships to field measurements, *Journal Geophysical Research*, *106*, 33623-22648, 2001.

Baldocchi, D., E. Falge, L.H. Gu, et al., FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, *Bul.Am. Met. Soc.*, *82* (11), 2415-2434, 2001.

Baldocchi, D.D., C.A. Vogel, and B. Hall, Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest, *Agricultural and Forest Meteorology*, *83*, 147-170, 1997.

Carey,E., A. Sala,R. Keane, et al., Are old forests underestimated as global carbon sinks?,*Glb. Chg. Biol.*,*7*(4),339-344, 2001

Cornish, P.M., and R.A. Vertessy, Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest, *Journal of Hydrology*, *242* (1-2), 43-63, 2001.

Dixon, R., S. Brown, R. Houghton, et al., Carbon Pools and Flux of Global Forest Ecosystems, *Science*, *263*, 185-190, 1994.

Eamus, D., L.B. Hutley, and A.P. O'Grady, Daily and seasonal patterns of carbon and water fluxes above a north Australian savanna, *Tree Physiology*, *21* (12-13), 977-988, 2001.

Grelle, A., A. Lindroth, and M. Molder, Seasonal variation of boreal forest surface conductance and evaporation, *Agricultural and Forest Meteorology*, *98-99*, 563-578, 1999.

Hollinger, D.Y., F.M. Kelliher, J.E. Hunt, et al., Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere, *Ecology*, *75* (1), 134-150, 1994.

Hutley, L. B., A. P. O'Grady, and D. Eamus. Monsoonal influences on evapotranspiration of savanna vegetation of northern Australia. *Oecologia* 126: 434-443, 2001.

Kaiser, J., SAVING KYOTO: Soaking Up Carbon in Forests and Fields, *Science*, *290* (5493), 922, 2000.

Kaminski, T., and M. Heimann, Inverse modeling of atmospheric carbon dioxide fluxes, *Science*, *294* (5541), 259a, 2001.

Keith H., R.J. Raison, K.L. Jacobsen. Allocation of carbon in a mature eucalypt forest and some effects of soil phosphorus availability. Plant Soil 196: 81-99, 1997.

Kull, O. Acclimation of photosynthesis in canopies: models and limitations. Oecol 133: 267-279, 2002.

Martin, P., G.J. Nabuurs, M. Aubinet, et al., Carbon sinks in temperate forests, *Ann. Rev. Energy Env.*, *26*, 435-465, 2001.

McGuire, A., S. Sitch, J. Clein, et al., Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO2, climate and land use effects with four process-based ecosystem models, *Gb.l Biogeochemical Cyc.*, *15*, 183-206, 2001.

Melillo, J.M., A.D. McGuire, D.W. Kicklighter, B. et al., Global climate change and terrestrial net primary production, *Nature*, *63*, 234-240, 1993.

Moncrieff, J.B., J.M. Massheder, H. de Bruin, H., et al., A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. J. Hydrol. 188-189:89-611, 1997.

Nikolov, N.T., and D.G. Fox, A Coupled Carbon-Water-Energy-Vegetation Model to Assess Responses of Temperate Forest Ecosystems to Changes in Climate and Atmospheric Co2 .1. Model Concept, *Env. Poll.*, *83* (1-2), 251-262, 1994.

NLWRA, National Land and Water Resources Audit: Annual report 1999-2000, pp. 34 pp, Canberra, Australia, 2000.

Perez-Garcia, J., L.A. Joyce, C.S. Binkley, and A.D. McGuire, Economic impacts of climatic change on the global forest sector: An integrated ecological/economic assessment, *Critical Rev.Env. Sci. and Tech.*, *27*, S123-S138, 1997.

RAC, Forest and Timber Inquiry, pp. 570 pp, AGPS, Canberra, Australia, 1992.

Schimel, D., J.M. Melillo, H. Tian, et al., Carbon storage by the natural and agricultural ecosystems of the US (1980-1993), *Science*, *287*, 2004-2006, 2000.

Schulze, E., C.Wirth, and M.Heimann, CLIMATE CHANGE: Managing Forests After Kyoto, *Science*,*28*, 2058-2059, 2000.

Silberstein, R., A. Held, T. Hatton, et al., Energy balance of a natural jarrah (Eucalyptus marginata) forest in Western Australia: measurements during the spring and summer, *Ag. & For. Met.*, *109* (2), 79-104, 2001.

Vertessy, R.A., R.G. Benyon, S.K. Osullivan, et al., Relationships between Stem Diameter, Sapwood Area, Leaf Area and Transpiration in a Young Mountain Ash Forest, *Tree Phys.*, *15* (9), 559-567, 1995.

Vertessy, R.A., T.J. Hatton, R.G. Benyon, et al., Long-Term Growth and Water Balance Predictions for a Mountain Ash (Eucalyptus Regnans) Forest Catchment Subject to Clear-Felling and Regeneration, *Tree Phys.*, *16* (1-2), 221-232, 1996.

Wang, Y.P., R. Leuning, H.A. Cleugh, et al., Parameter estimation in surface exchange models using nonlinear inversion: how many parameters can we estimate and which measurements are most useful?, *Glb. Chng. Bio.*, *7* (5), 495-510, 2001.