TCP Progress Report and Renewal Proposal: Measuring the Effects of Stand Age and Soil Drainage on Boreal Forest Net Ecosystem Production

Michael L. Goulden, University of California, Irvine, Principal Investigator
Gregory Winston, University of California, Irvine, Co-Investigator
Scott D. Miller, University of California, Irvine, Co-Investigator

I. Summary

We request support to continue investigating the exchange of CO_2 between the atmosphere and the boreal forest in Manitoba, Canada. During the last two years we have used year-round eddy covariance and associated ecological measurements to study the effects of forest age on forest-atmosphere CO_2 exchange. During the next three years we plan to: (1) complete our study of the effect of stand age on CO_2 exchange by collecting 18 more months of data at six sites that differ in time since burn from 4 years to 150 years, and (2) begin investigating the effect of soil drainage on carbon balance.

Our work to date has yielded several major payoffs for DOE's TCP Program. We have (1) designed, tested, and demonstrated a lightweight, fully portable eddy flux system that will allow relatively inexpensive year-round measurements of CO_2 exchange at almost any micrometeorologically-suitable site, (2) added six year-round sites to AmeriFlux, at a relatively low per site cost, and (3a) developed a partial understanding of how and why ecosystem carbon balance changes as forests age. Our work during the next three years will add to this list of payoffs. We will (3b) develop a much more complete understanding of how and why ecosystem carbon balance changes as forests age, and (4) develop an understanding of how soil drainage affects NEP, and how the carbon balance of poorly-drained sites compares with that of nearby well drained sites. All of these issues have been identified by the US Global Carbon Cycle Plan and the North American Carbon Cycle Plan as problems or approaches that merit priority attention.

II. Progress to date: Past and Present Research Questions

A. Overview

We request support to continue studying the exchange of CO_2 between the atmosphere and the boreal forest in Manitoba, Canada. During the last two years we have used year-round eddy covariance and complementary ecological measurements to investigate the effects of stand age on forest-atmosphere CO_2 exchange. This research was supported jointly by DOE's Terrestrial Carbon Processes Program (TCP), which provided 37% of the funds, and NSF's Integrated Research Challenges in Environmental Biology Program (IRCEB), which provided 63% of the funds. In the current proposal we request support from DOE to continue our work on the effects of forest age on carbon balance, and to expand our work to consider the effect of soil drainage on carbon balance.

B. The boreal landscape

We have been studying the boreal forest in Manitoba for the last 10 years, first through NASA's BOREAS program, and most recently with support from DOE and NSF. The boreal forest in Manitoba is heterogeneous, with patches that differ in soil drainage and/or stand age (time since fire, see Fig 1). The overall topography is flat, with slight differences in topography creating important differences in depth to water table (Rapalee et al 1998). Mature, well-drained areas support tall trees, moderately-thick layers of feather moss, and the development of moderately-large soil carbon stocks (Gower et al 1997, Trumbore and Harden 1997, Harden and Trumbore 1997). Nearby areas that are 1 or 2 m lower in elevation, and therefore poorly drained, support small, chlorotic trees, thick layers of sphagnum moss, the development of thick peat layers, and very large soil carbon stocks. The poorly drained areas are often referred to as muskeg, and may include wetland or peatland areas that are flooded for most or all of the summer. The effect of past fire, and the patchwork of well- and poorly-drained areas, are visible on the attached Landsat image (Fig 1b, c). Poorly drained areas with moderate LAIs appear as yellow or lime drainage courses imbedded in both recent and old fire scars. Upland areas that have fully recovered from past fires and now have high LAIs are dark. Upland areas that burned recently and have low LAIs are red or orange. Upland areas that are partially recovered and have moderate LAIs are lime or yellow.

C. Research questions during initial period of TCP support (9/15/2000-9/14/2003)

During our initial period of support from TCP we focused on the relationship between stand age and carbon balance in well-drained areas. Mature, well-drained stands are very flammable, resulting in a fire return interval of approximately 100 years (Bonan and Shugart 1989, Van Cleve et al 1986, Kasischke and Stocks 2000, Johnson 1992, Fig 1b, c). These crown fires kill the vegetation while consuming only a fraction of aboveground organic material. This results in a large increase in detritus, which gradually decomposes. The vegetation regenerates following fire (Van Cleve et al 1986), with a characteristic succession of weeds (grasses, horsetails, and fireweed for the first ~5 years), followed by shrubs (willow and alder from ~5 to ~15 years), followed by competitive trees (aspen and Jack pine from ~15 to ~60 years), and terminated by black spruce (from ~60 years on). The fire return interval in poorly drained areas is longer than

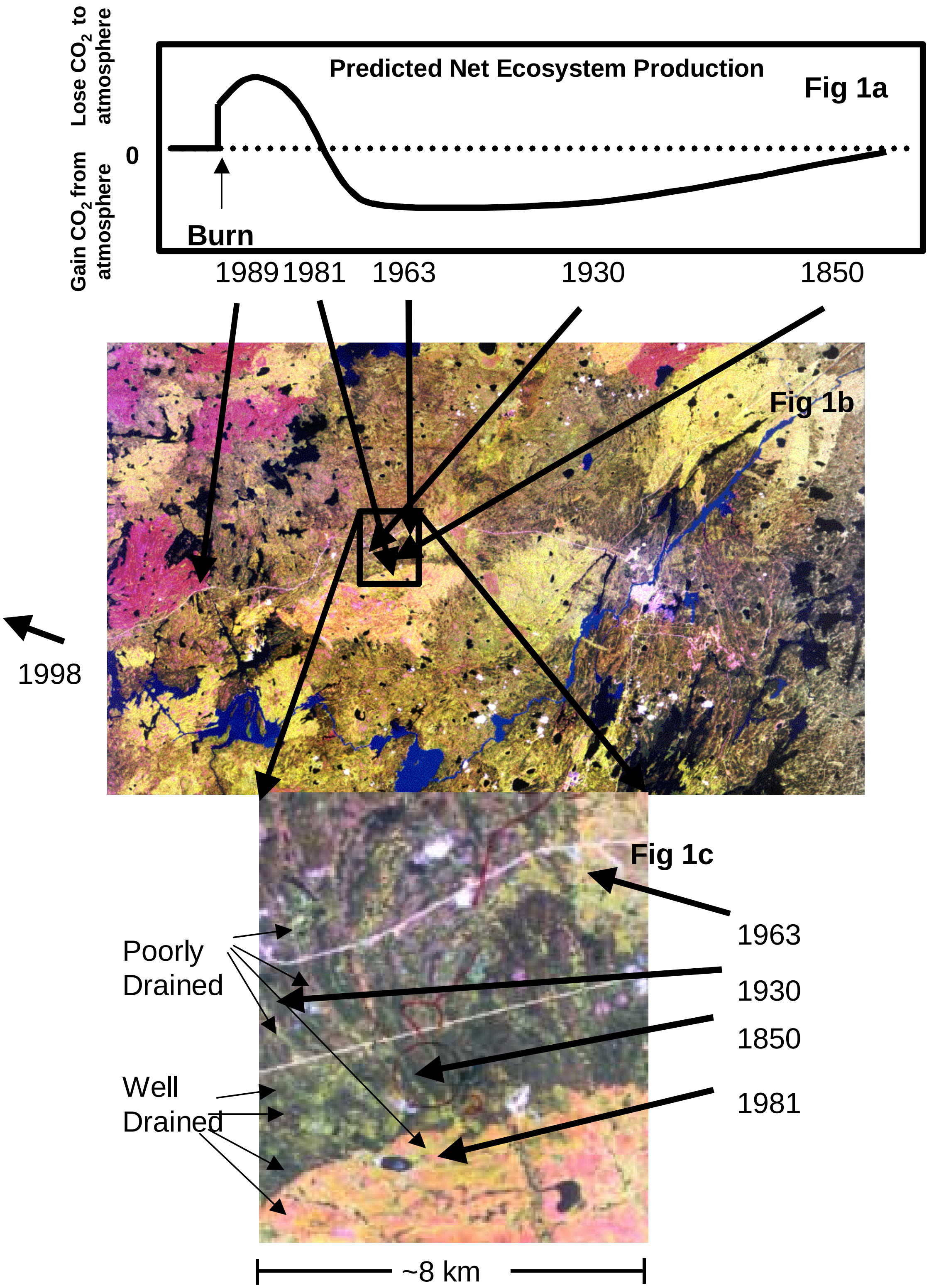

Lose CO_2 to atmosphere
0
Gain CO_2 from atmosphere
Predicted Net Ecosystem Production
Fig 1a
Burn
1989
1981
1963
1930
1850
Fig 1b
1998
Fig 1c
1963
1930
1850
1981
Poorly Drained
Well Drained
~8 km

Table 1: Research Questions.

Questions addressed during both initial and renewal periods of TCP support

Effect of stand age in well-drained stands

A At what rate do sites lose CO_2 following the burn?
How much residue remains after the burn? What controls how rapidly residue decays? How does soil T and H_2O change following burn? Does decay proceed slowly until the dead trees fall, at which point it accelerates?

B At what time do sites cross back to being a sink for CO_2?
How does species composition change following fire? How do LAI and leaf- and ground-area based rates of photosynthesis differ between these communities? What is the main determinant of increased NPP? Is it a change in species composition or a steady increase in LAI?

C How long and at what rate do sites accumulate carbon?
Is the ecosystem steady during the accumulation phase, or is it gradually changing?

D At what time, and for what reason, do sites stop accumulating carbon?
What is responsible for any observed decline in NEP with age? Is a decline in NEP related to decreased NPP or increased litter production and heterotrophic respiration? What is responsible for any observed decline in NPP with age? Is a decline in NPP related to decreased GPP? What is responsible for any observed decline in GPP? Is a decline in GPP related to leaf-level gas exchange or LAI?

Questions to be addressed during renewal period of TCP support

The carbon balance of poorly-drained stands

E Are poorly drained stands a large C sink?
How does the carbon balance of poorly-drained stands compare with that of nearby well drained stands? Do tower measurements in poorly-drained areas confirm the uptake reported by Bond-Lamberty et al (~1.4 tC $ha^{-1}yr^{-1}$)?

F Is the soil carbon in poorly drained stands climatically vulnerable?
Do poorly drained stands show a late summer increase in respiration and C loss that coincides with the thaw of deep soil or a decline in water table depth? Is the interannual variability of poorly drained areas most strongly controlled by the temperature and amount of precipitation in summer? How does this compare with the interannual variation in well-drained stands?

that in well-drained areas. Fires may bypass the wet areas, either because they have less fuel or because they are too wet.

Biogeochemical theory predicts that stands of different ages differ markedly in carbon balance (Fig 1a, Table 1; Odum 1969, Gorham et al 1979, Sprugel 1985, Waring and Schlesinger 1985, Chapin et al 2002). Observations from a single site therefore tell little about the current or future carbon balance of a region since the site's carbon balance may be positive or negative depending on its history and time since disturbance. Reliable determination of regional or global carbon balance requires consideration of the effect of stand age on CO_2 exchange (Apps and Price 1996, Rapalee et al 1998, Schulze et al 2000, Schulze and Heimann 1998, Kasischke and Stocks 2000).

Several research groups are now making important contributions to understanding the relationship between stand age and CO_2 exchange (for example, E.D. Schulze, C. Wirth, R. Valentini and colleagues in Siberian Taiga; F.S. Chapin, J. Randerson, E. Kasischke and colleagues in Alaskan boreal forest; B.D. Amiro in Canadian boreal forest; B. Law and colleagues in Oregon coniferous forest; and H. Gholz and colleagues in Florida pine forest). The prevailing theory predicts that recently-disturbed sites are sources of CO_2, since the decomposition of fire residue is expected to far exceed the uptake of carbon by regrowing biomass (Fig 1a; Odum 1969, Gorham et al 1979, Sprugel

1985, Waring and Schlesinger 1985, Chapin et al, 2002). Furthermore, prevailing theory holds that middle-aged stands are significant carbon sinks, since much of the fire residue should be gone by this point and substantial carbon is sequestered in growing trees. In the first phase of our TCP funded research, we investigated the pattern of carbon balance with forest maturation by deploying and operating six eddy-covariance towers along a chronosequence (Table 1, 2, Figure 1, 2).

D. Research questions during renewal period (9/15/2003-9/14/2006)

Our original TCP grant expires in September 2003, at which point we will have made significant progress toward understanding the effect of stand age on carbon balance. Nonetheless, the questions we are addressing (Table 1) are difficult and beyond the scope of what can be fully answered in a single 3-year funding cycle, a point we discussed in our original proposal. As a result, we request funding from TCP to finish studying the effect of stand age on carbon balance. Specifically, we plan to continue measuring the exchange of CO_2 at six well-drained tower sites until October 2004. This will give us two or three years of data for each of our sites, and will allow us to fully address our original questions (Table 1). In the absence of continued TCP funding, we will cease operation in August 2003, giving us only one year of data for the oldest and youngest sites. While the resulting data sets will begin to answer the questions in Table 1, there is little doubt that an additional year of observation will greatly improve confidence in the results.

By October 2004 we should have an excellent understanding of the effect of stand age on carbon balance, and will turn our attention to another outstanding issue - the effect of soil drainage on carbon balance. Poorly drained stands have very large stocks of soil carbon (Trumbore and Harden 1997). We will focus our efforts on understanding whether poorly drained stands are currently sequestering carbon, and whether the carbon in wet areas could be lost with a change in climate. We have recently begun to suspect that poorly drained stands play a dominant role in the regional carbon budget. Research by Tom Gower and Ben Bond-Lamberty indicates that poorly-drained stands are stronger carbon sinks than well-drained stands. Bond-Lamberty et al (2003) used inventories to calculate the carbon balance of age sequences in both well-drained and poorly-drained sites. Some of Bond-Lamberty et al's upland sites are co-located with our tower sites, and the two types of measurements agree that these areas are accumulating on average ~0.5 tC ha^{-1} yr^{-1} (see Progress to date section below). By contrast, Bond-Lamberty et al report that most of their poorly-drained stands are strong carbon sinks, with an average uptake of 1.4 tC ha^{-1} yr^{-1}, and no obvious trend with time since fire. Our research thus far has largely disregarded poorly drained stands, whereas Bond-Lamberty et al's results provide strong motivation for shifting attention to these areas. Hence, we propose to make tower flux measurements in a poorly drained site beginning in October 2004.

III. Progress to date: Research findings during initial period of TCP support

A. Specific activities

We are pleased with our progress during the last two and a half years. Our original proposal described three milestones. (1) During summer 2001 we planned to collect at least one month of growing-season flux data at each site using a pair of portable systems. (2) From summer 2001 to summer 2002 we planned to design and test a new eddy covariance system for year-round use. (3) Beginning in summer 2002 we planned to continuously operate six eddy covariance towers at forested stands that differ in time since fire in order to quantify the patterns of NEP, GEP, ecosystem respiration, energy balance and microclimate. We have achieved all of these milestones, in many cases 12 months ahead of schedule. The rapid notification of anticipated funding that we received from DOE in July 2000 permitted us to get an early start on milestone #2. This allowed us to winter test our equipment in 2000-2001, which, in turn, allowed us to deploy and begin operating four eddy covariance towers in summer 2001, a year ahead of schedule.

B. Methodological development

Our original proposal promised methodological progress in two areas.

1. Develop an eddy flux system for year-round measurements at remote Canadian sites

One of our goals was to develop a comparatively inexpensive eddy covariance system for year-round operation in Manitoba. Steve Wofsy's group demonstrated in the 1990s that year-round eddy flux measurements are possible in this extreme environment, given access to a climate-controlled instrument building and ample power from diesel generators. Our goal was to reduce the infrastructure needed for year-round operation. Table 2 summarizes our operational strategy, and Figure 2 presents our flux data through March 2003. The data sets at two of the sites are nearly continuous (1963, 1989), except for gaps in mid winter caused by persistent cloud cover and low battery charge. The data gaps at most of the other sites are due to specific faults that have been corrected, and are not expected to recur. For example, the gap in Sept 01 at the 1981 site was caused by a manufacturing defect in the flash RAM; The gap in May 02 at the 1981 site was caused by inadequate battery ventilation and a hydrogen explosion.

2. Demonstration of an economy of scale for tower operation

Past AmeriFlux research has focused on understanding individual sites, whereas our goal was to understand the differences and similarities among six sites arrayed across the landscape. Our success depended on establishing an economy of scale for the operation of eddy covariance towers, a goal we achieved by: (1) fully matching the towers, so that identical equipment and programs are used at all sites, and (2) designing a data acquisition architecture so that data collection and calculation are fully automated. One of the keys to our success has been the use of satellite radios at all of the sites to transmit flux and system status data every hour. This allows us to continuously confirm site operation and, if necessary, diagnose problems.

C. Measuring the changes in CO_2 exchange during secondary succession

We have operated towers at four sites for ~21 months and two more sites for ~10 months. Our CO_2 flux data are shown in Figure 2, in decreasing order of stand age. Significant findings include:

1. Large differences in seasonality

There are large differences on seasonality between sites, with the younger sites having comparatively short growing seasons (Fig 2). Differences in seasonality are apparent at both the beginning and end of the growing season. The 70-year old site, which is dominated by evergreen black spruce, began active photosynthesis in May,

Table 2: Tower design considerations

Problem	**Issues**	**Solutions**
Site selection	Experiment requires sites that are matched for micrometeorological suitability and for ecological comparability.	Candidate sites identified from satellite images, fire history maps, aerial photographs, geological survey maps, topographic maps, and forest resource maps. Final selection of sites made during site visits.
Site access	Experiment requires well-matched sites, but roads are scarce, sharply limiting the number of accessible candidate sites.	Day-to-day access to all sites is by hiking trail; equipment installation is by helicopter. The added flexibility provided by the helicopter allowed us to identify a well-matched chronsequence.
Site infrastructure	The heavy infrastructure at most AmeriFlux sites would cost too much for use in an experiment comparing six sites.	Adopt the philosophy that a lighter infrastructure can cut the cost of tower sites. Key savings include (1) The use of a 60 to 80' scientist-installed telescoping aluminum tower rather than a contractor-installed tower. (2) The use of a small enclosure to house the equipment, rather than a contractor-installed hut. (3) The use of a solar system for power, rather than a diesel generator or line power.
Dealing with the cold	Equipment/system must function in extreme cold (nighttime temperatures of –40°C or below).	Insulate and bury instrument box. Adjust the insulation so that the internal box temperature is 20°C above ambient, resulting in an internal box temperature that remains above 10°C even during extreme cold.
Data collection, analysis and management	Remote sites limit opportunities for data collection, opening the danger of extended down periods between visits.	Design data acquisition system to include (1) frequent satellite transmissions confirming system operation and (2) storage of raw data for subsequent collection and full processing. CR5000 datalogger calculates half hour statistics of all observations for transmission to UCI via GOES radio every hour. Flash RAM stores raw data for collection every 1 to 4 months.
Equipment maintenance	Equipment will require periodic maintenance and repair.	Automated calibrations using CO_2 standards. Site visits for repairs as indicated by GOES transmission. Additional visits for routine service. The day-to-day operation of the site is managed by the datalogger, which, for example, shuts down equipment to save power if the battery voltages is too low.

whereas the 13-year-old site, which is dominated by aspen and other deciduous plants, did not begin active photosynthesis until June. Similarly, the younger stands (4- and 13-year old) curtailed photosynthesis in September, whereas the older stands (70- and 150-year old) remained active until October. The black spruce stands take advantage of the longest growing season possible, beginning photosynthesis a few days after the nighttime temperatures remain above freezing, and continuing photosynthesis as long as daytime temperatures remain above freezing. In contrast, the deciduous plants lose about a month for leaf growth at the beginning of the season, and a month for leaf senescence at the end of the season.

These differences in seasonality are likely important for the stand carbon balances, and for the competitive relationships between species. These observations contradict Zimov et al's (1999) suggestion that vegetative shifts caused by recent changes in disturbance are responsible for the observed advance in spring CO_2 drawdown at high latitude. Our observations imply the opposite - recent disturbance should increase the fractional coverage of deciduous vegetation and delay the seasonal drawdown of atmospheric CO_2.

2. No major differences in rates of daytime CO_2 uptake and nocturnal respiration

We had expected midday CO_2 uptake and evaporation would be reduced at the youngest sites, due to the loss of vegetation with disturbance and a delay in LAI reestablishment. However, the maximum rates of midday CO_2 uptake are remarkably similar from site to site - approximately 12 to 18 μmol m^{-2} s^{-1} (Fig 2). Likewise, we had expected nocturnal respiration would be increased at the youngest sites due to the

Fig 2

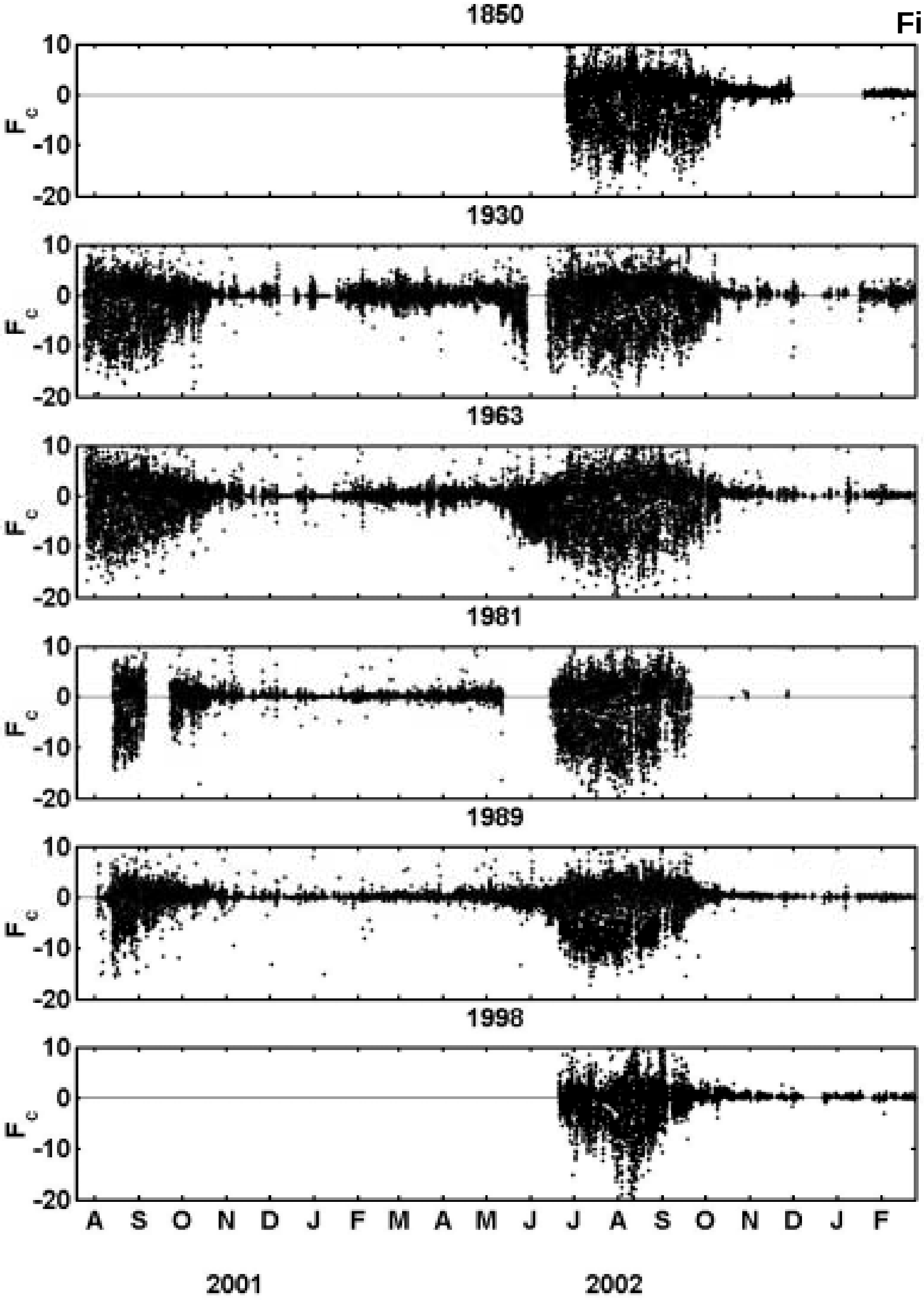


Figure 2. Net CO_2 exchange at six sites that differ in time since fire.

decomposition of fire residue. However, the maximum nocturnal respiration is 5 to 10 μmol m^{-2} s^{-1} at all sites, with no indication of accelerated respiration at the youngest sites.

3. The expected trend in C balance with age (Fig 1) is not observed

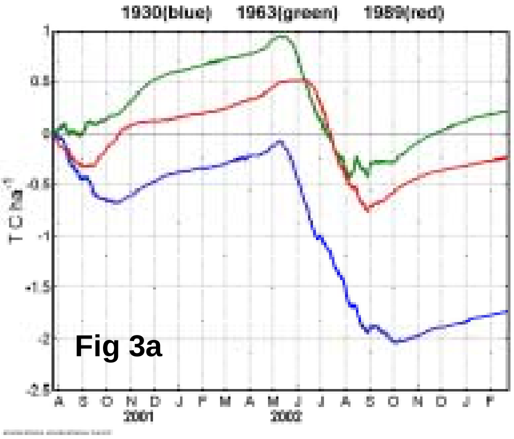
Our data sets are just reaching the length where we can calculate carbon balances (Fig 2, 3). The data sets at the 1930, 1963, and 1989 sites provide the best estimates of carbon balance, with the 1930 site acting as a moderate carbon sink (~1 tC ha^{-1} yr^{-1}), and the 1963 and 1989 sites relatively close to carbon balance (Fig 3a). The data sets for the other sites are either still too short (1998, 1850) or too fragmented (1981) to reliably estimate annual carbon balance. Nonetheless, preliminary estimates indicate the 1998 site is probably a small carbon source and the 1981 and 1850 sites are probably modest carbon sinks (Fig 3b). These observations differ from our expectations (Fig 1a). We had expected the 1998 and 1989 sites would be large carbon sources; the 1963 and 1930 sites would be large carbon sinks; and the 1850 site would be in approximate balance. However, the rate of carbon loss by the young stands is much smaller than expected; the rate of carbon accumulation by the middle-aged stands is less than expected; and the rate of carbon uptake by the oldest stand is greater than expected.

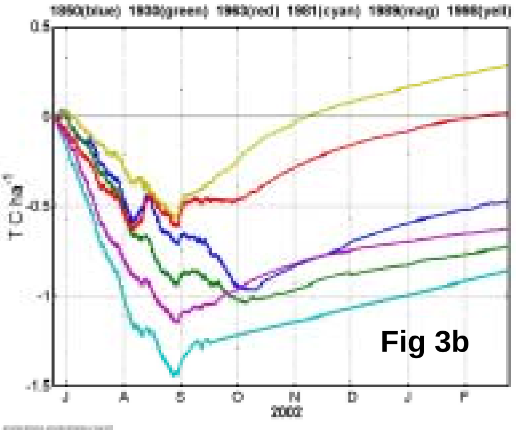
4. Explanation for lack of increased respiration by young stands

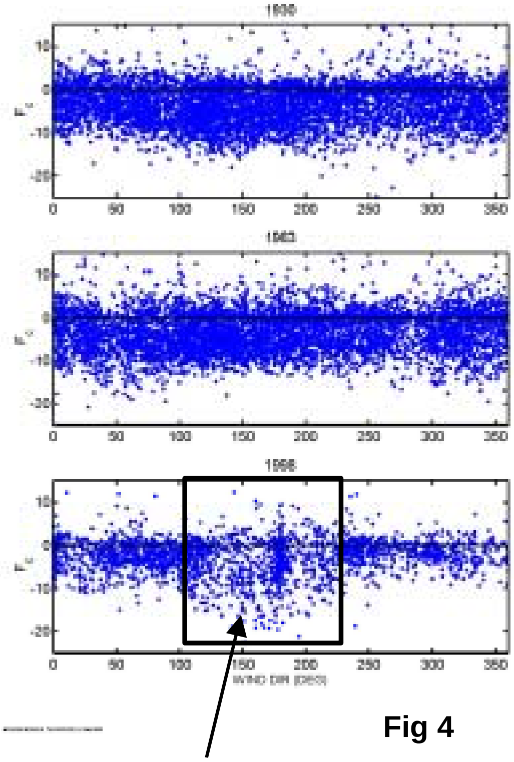
The lack of an initial increase in respiration (Fig 2) has important implications for the carbon balance during succession (Fig 3). The prevailing theory assumes fire debris decomposes rapidly, resulting in increased respiration and carbon loss. The tower data indicate this is not the case, a pattern consistent with direct observations of the disappearance of woody debris with time. Visual observations indicate most of the debris at the 1998 site is solid and still standing, and most of the debris at the 1989 and 1981 sites is solid and has recently fallen but is not fully contacting the ground. By contrast, most of the debris at the 1963 site is in close contact with the ground, and is partially decayed, and most of the debris at the 1930 site is covered by moss and has decayed almost entirely. Previous reports confirm that standing debris, or debris that has fallen but is not in close contact with the ground, decays slowly due to the lack of moisture. In contrast, debris that is in close contact with the ground, and therefore moist and easily colonized by microbes, decays rapidly. This phenomenon appears to be the main reason the young sites do not have high rates of respiration and carbon loss.

5. Explanation for high rates of canopy gas exchange by young stands

We had expected midday CO_2 uptake and evaporation would be reduced at the young sites. However, we found that the midsummer rates of CO_2 uptake and evaporation by the 4-year-old stand had already recovered to a level comparable to that of the older stands (Fig 2). This surprisingly high rate of gas exchange was a result of rapid growth by herbaceous weeds (fireweed, grass and horsetail) and resprouting alder (Van Cleve et al 1986). A fortuitous tower position illustrates the importance of fireweed. We attempted to choose a tower site that was homogenous in all directions, but our selection was made before leaf-out, and patchiness in the distribution of deciduous LAI was not visible. Subsequent observations after leaf out revealed considerable patchiness in deciduous vegetation, with a dense patch of fireweed beginning ~20 m from the tower and continuing for several hundred meters at 100 to 240 degrees from the tower. The







Dense fireweed

Figure 3. Cumulative net CO_2 exchange calculated from data shown in Fig 2. The fluxes have been filtered for a u_* threshold of 0.2 ms^{-1}.

Figure 4. Net CO_2 exchange during summer 2002 as a function of wind direction for the 1930, 1963 and 1998 sites. The CO_2 exchange for the oldest two sites was comparatively constant with wind direction, whereas the uptake at the youngest site was anomalously high when the wind originated from 120 to 220°, an area with a dense patch of fireweed.

mid-summer rates of gas exchange when the tower footprint samples this patch of fire weed are very high, with peak rates of CO_2 uptake that equal or exceed those measured at any of the other sites (Fig 4). The rates of respiration in this direction are also very high, almost certainly due to increased autotrophic respiration.

The speed of ecosystem recovery surprised us. This recovery is probably part of the reason we did not see a large loss of carbon by the young sites (Fig 3), though further analyses will be required to test this point. The recovery reflects important plant ecological processes that control species composition (Grime 2001, Bazzaz 1979), and affect the mass and energy budgets and microclimate (Van Cleve et al 1986). The rapid recovery of productive capacity is presumably important for the long-term maintenance of nutrient stocks and ecosystem function (Marks 1974).

6. No midsummer increase in respiration with deep soil thaw

Goulden et al (1998) studied a 90 to 150-year-old stand of black spruce near our study area, and concluded that the soil carbon is vulnerable to an increase in soil thaw. Goulden et al's conclusions were based on tower observations of a midsummer increase in respiration and shift from carbon sink to carbon source, which coincided with soil thaw at 50 cm depth (see also Hirsch et al 2002). In contrast with Goulden et al's (1998) observations, most of our sites do not show a midsummer change in carbon balance or increase in respiration (Fig 2, 3). The main difference between these studies is that our towers are measuring only well-drained areas, whereas Goulden et al's (1998) tower measured a mix of well and poorly drained stands. Goulden et al's observations were made from a tower that extended ~15 m above the canopy and was near a border between well and poorly drained areas. The fluxes reported here were made with towers that extend ~4 m above the canopy and are centered in large well-drained stands. This leads us to suspect that the seasonal increase in decomposition with deep soil warming described by Goulden et al is greatest in poorly drained areas.

This conclusion has implications for the work we propose. The soil carbon stocks in poorly drained areas are much larger than in well-drained areas (Trumbore and Harden 1997). Moreover, Bond-Lamberty et al (2003) report evidence that these sites are currently accumulating large amounts of carbon. At the same time, a change in water table depth, or a change in soil temperature and the distribution of frost, may lead to a loss of carbon from poorly drained areas (e.g., Goulden et al 1998, Hirsch et al 2002, Diomouva et al 2002).

D. Publications and data submitted to archives

We have published three papers with TCP support (Litvak et al (2003), Hirsch et al (2002), Diomouva et al (2002)), and have submitted preliminary data to the ORNL DAAC via the AmeriFlux website. We have presented our results at workshops and conferences, including the 2001 TCP/AmeriFlux meeting at Argonne (M. Goulden), the 2002 Fluxnet meeting in Orvieto (S. Miller), the 2002 AmeriFlux meeting in Boulder (M. Goulden), and the 2002 AGU meeting in San Francisco (M. Goulden).

IV. Research planned for Renewal period

A. Continue tower measurements along chronosequence until October 2004

Renewed support from TCP will allow us to continue making tower measurements past summer 2003. We believe another year of observations is crucial for understanding the effects of stand age of CO_2 exchange. In the absence of continuing TCP support, we will remove our tower-flux equipment in August 2003. Our original proposals to DOE and NSF promised one year of tower observations at six sites along the age sequence, and we will have accomplished this goal by summer 2003. The removal of equipment is extremely expensive, with large costs for travel, shipping, customs fees, extra labor, and helicopter transport. Our NSF grant, which continues until August 2004, does not have sufficient funds in 2004 for equipment removal or the continued operation of all six towers. This will force us to remove our equipment in summer 2003 if TCP support is discontinued.

B. Cease measurements at most chronosequence sites in October 2004

We plan to cease operation at most of the well-drained sites in October 2004. We have discussed the possibility of continuing observations at all of our sites past October 2004, and have decided against this option for the following reasons.

1. We will have answered most of our questions by this point

Our work is going well (Fig 2), and we expect we will have addressed most of our initial questions by the end of the 2004 growing season (Tab 1). There is no doubt that long tower data sets are extremely valuable (e.g., Harvard Forest, as demonstrated by Barford et al 2001). At the same time, there is little doubt that the first few years of a data set yield the greatest science return per effort.

2. Other researchers are already collecting long data sets in Canada

A great deal is already known about the interannual and longer patterns of tower flux in Canadian boreal forest. Steve Wofsy's group has been collecting data at the original BOREAS OBS site since 1994 (OBS is less than 1 km from our 1850 site), and Andy Black and colleagues have been making measurements at other former BOREAS sites for nearly as long (the BERMS sites). Fluxnet-Canada is ramping up an impressive operation, which includes long-term measurements at many sites in Canada, and will further contribute to understanding of interannual variability in boreal forest. The Wofsy and BERMS data sets have remarkable longevity and precision. We are skeptical that the continuation of our sites past 2 or 3 years will contribute much further to understanding long-term patterns.

3. Costs are prohibitive

The majority of our support (63%) has come from NSF's IRCEB program; TCP provided 37% of the funds. NSF no longer runs the IRCEB program, and we will have to rely fully on DOE support after our NSF grant expires in August 2004. Running six sites is expensive, even with the efficiencies we have in place. The continued operation of all sites would require a large increase in TCP funding. Instead, we would like to keep our funding approximately level, and scale back the number of towers we operate. We plan to operate two towers after 2004, which is in proportion to the original purchase of equipment (TCP paid for 2 towers) and also the original support (TCP provided 37% of the funds for the operation of 6 towers).

4. Other issues need attention

The best reason for reducing operation along the age sequence is to allow us to concentrate on further, pressing questions. In particular, we plan to focus on the carbon balance of poorly-drained areas.

C. Begin measurements in a poorly-drained area in October 2004

We will begin work in a poorly-drained area to address the following questions.

1. Are poorly-drained sites large carbon sinks?

Our results from Phase I indicate that upland areas are not large carbon sinks. The largest sink measured will likely be less than 1.5 tC ha^{-1} yr^{-1}, and several of the sites appear to be in approximate carbon balance (Fig 3). Preliminary analyses indicate that after factoring in the loss of carbon during fire, it appears unlikely that the overall balance of upland areas is significantly different from zero. This pattern is consistent with the simple observation that the carbon stocks of upland areas are not that large. In contrast, the carbon stocks of the poorly-drained areas can be quite large. While the NPP of muskeg is likely less than in the upland areas, the high water table reduces decomposition to the point that extremely large stocks of carbon may accumulate. Moreover, the fire frequency in poorly-drained areas is lower than in the upland areas, reducing the loss carbon loss from combustion.

These results, and Bond-Lamberty et al's (2003) observations, underscore the importance of beginning tower measurements in a muskeg area. We propose to begin making measurements in October 2004 at a muskeg site that is close to one of our currently operating, well-drained sites. Candidate sites with large poorly-drained areas within 1 km of our current towers include the 1963 and 1930 burns. We will select one of these sites based on field surveys, and begin year-round tower measurements in October 2004. We will continue to operate the nearby well-drained tower past October 2004. We will then compare the fluxes measured by the two sites, and determine whether the poorly drained site is accumulating more carbon than the well-drained site.

2. Is the carbon balance in poorly-drained areas vulnerable to a change in climate?

In earlier work in the area as part of BOREAS, Goulden et al (1998) reported on the sensitivity of soil carbon to soil thaw. As discussed in Section IIIC6, we now believe this vulnerability is greatest in poorly drained areas. Our parallel tower-flux observations above well- and poorly-drained stands will allow us to test this hypothesis. We predict that the poorly-drained stand will show a marked increase in respiration during mid summer, in parallel with the local thaw of deep soil, whereas the well-drained stand will show a relatively constant rate of respiration. If confirmed, we will follow the approaches used by Goulden et al (1998) and Hirsch et al (2002) to further quantify and compare the rates of deep decomposition in the well and poorly drained areas.

D. Time line

Table 3 shows our expected rate of progress.

Table 3: Timeline

Task	6/1/03	6/1/04	6/1/05	6/1/06
Field measurements (in Manitoba)				
Ecological field measurements along age sequence (See Table 4 for list of measurements)	XXXX	XXXX	X X	X X
Operate 6 towers along well-drained age sequence	XXXXXXXXXXXXXXX			
Select a poorly-drained site for study	X			
Ecological field measurements comparing well- and poorly-drained areas (See Table 4 for list of measurements)	X X	X X	XXXX	XXXX
Remove 5 towers, continue operation of 1 original well-drained tower and set up a new tower in a nearby poorly drained site		X		
Operate 2 towers - one in well drained and one in poorly drained area		XXXXXXXXXXXXXXXXXXXXX		
Data analysis and submission (at UCI)				
Analyze age sequence flux data	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX			
Submit preliminary age sequence data to archive	X	X		
Submit age-sequence manuscripts		X	X	
Submit final age sequence data to archive			X	
Analyze soil drainage flux data			XXXXXXXXXXXXXXXXX	
Submit preliminary soil drainage data to archive				X
Submit soil drainage manuscripts				X
Submit final soil drainage data to archive				X

Table 4: Measurements by UCI (many additional measurements available from Gower et al and Harden et al)

What	Method
Species composition	Transect (all sites) and grid (1998) surveys
Aboveground NPP	Ring width and allometry for trees, sequential clipping or measurement for herbs, litter fall
Tree biomass	Inventories along transects, Allometric equations from Gower et al
Leaf area index	LI2000 along established transects. Repeated visits to sites
Year-round tower measurements	FCO_2, H, LE, PPFD↑↓, K↑↓, Q*, ρ_{ϖ}, Tair, Tsoil, H_2Osoil

V. Relevance to TCP, The US Carbon Cycle Science Plan (CCSP), and The North American Carbon Program (NACP)

Our past and proposed research is highly relevant to the goals of TCP, CCSP, and NACP. Our design, testing, and demonstration of a lightweight, portable eddy flux system that allows inexpensive year-round measurements of CO_2 exchange at almost any micrometeorologically-suitable site is responsive to Goal 1b(3) of the CCSP (page 29), and is among the priority enabling developments for the NACP (page 4). The operation of multiple matched towers along a gradient in land cover (6 towers along an age gradient) is a new experimental paradigm for eddy covariance, which is expected to find wide use in the NACP. Similarly, our focus on the effect of recovery from fire is responsive to Goal 4 of the CCSP (page 9). Finally, our planned focus on the effects of drainage on carbon balance, and on the possible vulnerability of soil carbon in wet areas, is in line with the recommendations at the recent NACP planning workshop in Washington DC, May 12-14, 2003.

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