SCIENCE PLAN & IMPLEMENTATION STRATEGY

David M. Lapola & Richard J. Norby (Coordinators)

AMAZON FACE

Assessing the effects of increased atmospheric CO_2 on the ecology and resilience of the Amazon forest

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Front cover picture: View of top forest canopy as seen from the ZF2 km 34 flux tower.

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PREFACE

What does the future hold for the Amazon rainforest?

What does the future hold for the Amazon rainforest?

The Amazon rainforest functions as a climate regulator at the regional and even global scale. It is the largest rainforest in the world, encompassing eight countries. The Amazon rainforest contains the largest reservoir of biodiversity on the planet and in addition is the river basin with the largest contribution of fresh water worldwide. Most of the Amazon basin is in Brazil, representing nearly 50 percent of the country's territory. In that region resides a population of over 26 million Brazilians and the area is also one of the few left in the world where primitive societies can still be found. With great agricultural and livestock potential, the Amazon region receives important projects of energy generation and infrastructure development. The wealth of Its subsoil has not yet been entirely measured.

What will remain of all this physical and human wealth if the global environmental changes, particularly climate change and the increase in the amount of atmospheric carbon dioxide, projected for the coming decades, really cause a catastrophic change in the functioning of the ecosystems, with possible loss of forest biomass and biodiversity, as some studies predict?

The emission of carbon dioxide (CO_2) from human activities is the main cause of climate change. On the other hand, the increase of atmospheric CO_2 concentration may, ironically, also be the factor that holds the balance to keep the forest intact. This is because CO_2 is the main element to primary productivity through photosynthesis. Although the increased emission of atmospheric CO_2 causes climate change, such as rising temperatures and increased occurrence of extreme phenomena that threaten the Amazon ecosystems, on the other hand, it can result in increased forest productivity, known as the effect of CO_2 "fertilization", which in principle could make the Amazonian ecosystems less vulnerable to further impacts of climate change.

In addition, there is the possibility that the fertilization effect may not be sufficient to maintain the stability of the vegetation cover in an atmosphere considerably warmer or that the effect on photosynthesis may eliminate productivity gains beyond a certain temperature level. In this scenario, there is a risk of the Amazonian biome becoming a CO_2 source rather than a sink.

Reducing uncertainty about the future of Amazonian ecosystems necessarily involves answering how these ecosystems respond to conditions of elevated atmospheric CO_2 and higher temperatures, simulating the conditions expected in the future. This is the starting point for the experiment presented here, which received the name of "Free-Air Carbon Enhancement Experiment in the Amazon / Amazon-FACE" with the main objective of studying and assessing the existence and magnitude of the effect of CO_2 "fertilization" in the Amazon rainforest.

One of the most awaited scientific experiments in this area, Amazon-FACE is the result of a partnership between the Ministry of Science, Technology and Innovation (MCTI) and the Inter-American Development Bank (IDB). This partnership initiated in 2012, during the Rio+20, and was reinforced in 2013 during the scientific workshop held at IDB headquarters in Washington DC, USA, which marked the beginning of the development of the scientific plan of this experiment, presented in this document.

The preparation of the scientific plan involved more than 40 scientists from Brazil, USA, Europe and Australia. Amazon-FACE represents excellence in science at global scale through international cooperation. It will generate scientific results and form highly qualified personnel, enabling all of society to benefit from its results. Amazon-Face follows the successful tradition of the Large Scale Biosphere-Atmosphere Experiment in Amazonia, still considered the most important scientific activity conducted about the Humid Tropics up to today.

Amazon-FACE is not limited to a simple scientific experiment. It is a platform for research on the impacts of climate change in Amazonia, assisting economic planning and sustainable regional development. The Brazilian government, through the MCTI, believes that the new partnership with the IDB is a bet on the importance of science, technology and innovation for the conservation and sustainable use of the largest tropical forest of the planet and in the improvement of the standard of living of the Amazonian populations, whilst preserving the functionality of ecosystems and biodiversity. The IDB believes that the results of this research are key towards the arguments for Amazon biome conservation and the efforts to control the destabilization of climate at a global scale.

Carlos A Nobre
MCTI

Walter Vergara
BID

PREFÁCIO

O que o futuro reserva para a Amazônia?

A Amazônia funciona como reguladora do clima em escala regional e até mesmo global. É a maior floresta tropical do planeta e distribui-se por oito países. A Amazônia contem o maior reservatório de biodiversidade do planeta e além disso é a bacia com a maior contribuição de água doce a nível mundial. A maior parte da bacia Amazônica está em território brasileiro, representando quase 50 por cento do território do país. Ali vive uma população de mais de 26 milhões de brasileiros e a área é também uma das únicas do mundo onde ainda vivem povos primitivos. Com grande potencial agropecuário, recebe importantes projetos de produção de energia e de implantação de infraestrutura. Seu subsolo guarda riquezas ainda não totalmente mensuradas.

O que restará de toda essa riqueza física e humana caso as mudanças ambientais globais, especialmente as mudanças climáticas e o aumento da quantidade de gás carbônico atmosférico, projetadas para as próximas décadas, realmente causem uma catastrófica alteração no funcionamento dos ecossistemas, com possível perda da biomassa da floresta e de biodiversidade, como preveem alguns estudos?

A emissão de gás carbônico (CO_2) por atividades humanas é a principal causa das mudanças climáticas. Por outro lado, o aumento da concentração atmosférica de CO_2 pode, ironicamente, também ser o fiel da balança para manter a floresta intacta. Isso porque o CO_2 é também o principal elemento para produtividade primária por meio da fotossíntese. Embora o aumento da emissão do CO_2 atmosférico provoque mudanças climáticas, como aumento da temperatura e maior ocorrência de fenômenos extremos que ameaçam os ecossistemas Amazônicos, por outro lado, pode resultar no aumento da produtividade florestal, fenômeno conhecido como efeito de "fertilização" por CO_2, o que em princípio poderia tornar os ecossistemas Amazônicos menos vulneráveis aos demais impactos das mudanças climáticas.

Ademais, existe a possibilidade de que o efeito de fertilização não seja suficiente para manter a estabilidade da cobertura vegetal num clima consideravelmente mais quente ou que o efeito na fotossíntese elimine os ganhos em produtividade além de um certo nível de temperatura. Neste cenário existe um risco do bioma amazônico se tornar uma fonte ao invés de um sumidouro de CO_2.

Reduzir as incertezas sobre o futuro dos ecossistemas Amazônicos passa necessariamente por responder como estes ecossistemas reagem a condições de elevado CO_2 atmosférico, a temperaturas mais elevadas que as atuais, simulando condições prevalentes no futuro. É este o ponto de partida para a realização do experimento aqui apresentado, o qual recebeu o nome de "Free-Air Carbon Enhancement Experiment in the Amazon—Amazon FACE", com o objetivo principal de estudar e avaliar a existência e magnitude do efeito de "fertilização" por CO_2 na floresta amazônica.

Um dos mais esperados experimentos científicos nessa área, o Amazon-FACE resulta de parceria entre o Ministério de Ciência, Tecnologia e Inovação (MCTI) e o Banco Interamericano de Desenvolvimento (BID). Essa parceria nasceu em 2012, durante a Rio+20, e foi reforçada em 2013 durante workshop científico na sede do BID em Washington DC, EUA, que marcou o início do planejamento do plano científico deste Experimento, apresentado neste documento

A elaboração do plano científico envolveu mais de 40 cientistas do Brasil, EUA, Europa e Austrália. O Amazon FACE é ciência de excelência em escala global e através da cooperação internacional. Vai gerar resultados científicos e formar pessoal de alta qualificação, possibilitando que toda a sociedade se beneficie dos seus resultados. Segue na bem sucedida tradição do Experimento de Grande Escala da Biosfera-Atmosfera na Amazônia, considerado ainda a mais importante atividade científica realizada sobre os Trópicos Úmidos até hoje.

O Amazon-FACE não se limita a ser um simples experimento científico. É uma plataforma de pesquisas sobre os impactos das mudanças climáticas na Amazônia, favorecendo o planejamento da economia e o desenvolvimento regional sustentável. O governo brasileiro, por intermédio do MCTI, considera que a nova parceria com o BID é uma aposta na importância da ciência, da tecnologia e da inovação na preservação e uso sustentável da maior floresta tropical do planeta e na melhoria das condições de vida das populações amazônicas, com preservação da funcionalidade dos ecossistemas e da biodiversidade. O BID considera que os resultados desta pesquisa são centrais aos argumentos para a conservação do bioma amazônico e aos esforços para controlar a desestabilização do clima a nível global.

Carlos A Nobre
MCTI

Walter Vergara
BID

Executive Summary

A CO_2 enrichment experiment of unprecedented scope and importance is proposed for a primary, old-growth forest of the Amazon basin. The experiment will simulate the atmospheric CO_2 composition of the future in order to help answer the question: "How will rising atmospheric CO_2 affect the resilience of the Amazon forest, the biodiversity it harbors, and the ecosystem services it provides?"

Rapid changes in the Earth's climate caused by burning of fossil fuels and deforestation pose a severe threat to the forests of the Amazon basin. Warmer temperatures and drier conditions have been predicted to cause widespread forest dieback, but the impacts of such a climate change on the Amazon forest are highly uncertain – especially due to a conspicuous lack of knowledge on the effects of increasing atmospheric CO_2 concentrations on tropical forests. Reducing this uncertainty is therefore critical for assessing the future of the Amazon region and other tropical ecosystems in light of global climate change. The research agenda proposed in this science plan is directed toward resolving a key source of uncertainty: the potential for rising atmospheric CO_2 concentrations to buffer tropical forests against the potentially deleterious effects of climate change by stimulating forest growth and resilience to drought.

We propose to establish a free-air CO_2 enrichment (FACE) experiment in an old-growth forest in the Amazon basin near Manaus, Brazil. FACE technology has proven to be a valuable method to determine long-term, ecosystem-scale responses of forests to elevated CO_2 in temperate regions. However, no such experiment has ever been attempted in a tropical forest, despite the long-standing recognition in science and policy communities of the need for such an experiment.

We will begin with a pilot experiment of two 30-m diameter plots; the final experimental design will encompass four pairs of plots maintained at ambient or elevated CO_2 concentrations for at least 10 years. The research site is a plateau at the ZF2 site within the Cuieiras Biological Reserve, an area that is representative of a dominant fraction of the forests of Amazonia. Experimental plots will comprise stands of 30-m tall trees on deep, well-drained clay soils. Managed by Brazil's National Institute for Amazonia Research (INPA), the site has supported a long tradition of research on tropical forest ecology, forest management and biosphere-atmosphere interactions.

Five research questions that focus on carbon metabolism and cycling, water use, nutrient cycling, forest community composition, and interactions with environmental stressors will be the focus of the experiment. A multi-disciplinary team of scientists will employ state-of-the-art tools from deep in the soil to above the forest canopy. The resulting data sets will be valuable resources for a broad community of scientists. Significant scientific products from this experimental effort will derive from a strong interaction between data from the experiment and modeling.

The Amazon-FACE experiment will be a flagship scientific endeavor that will stimulate the scientific empowerment of research institutions in Brazil as well as strengthen cooperation with US and European research groups in the science of carbon cycle, ecosystem function and ecosystem-climate interactions in the Amazon.

Results from this project will be disseminated through peer-reviewed scientific journals, communicated to the general public, and prepared for government agencies and decision-making bodies with the goal of reducing uncertainty about the vulnerability to climate change of the Amazon forest and helping to steer future development policies for the Amazon region.

Sumário Executivo

Propõe-se neste plano a implementação de um experimento de enriquecimento por CO_2 - de importância e abrangência sem precedentes - em uma floresta primária da bacia Amazônica. O experimento irá simular uma composição atmosférica futura de CO_2 de modo a avançar na resposta da questão: "Como o aumento do CO_2 atmosférico afeta a resiliência da floresta Amazônica, a biodiversidade que ela abriga, e os serviços ecossistêmicos que ela provê?".

As aceleradas mudanças do clima planetário, causadas pela queima de combustíveis fósseis e desmatamento, representam uma séria ameaça para as florestas da bacia Amazônica. Prevê-se que temperaturas mais elevadas e condições mais secas possam causar uma grande perda da biomassa florestal ("forest dieback"), embora os impactos dessas mudanças climáticas sobre a floresta Amazônica sejam ainda bastante incertos – devido especialmente à uma conspícua falta de conhecimento sobre os efeitos do aumento de CO_2 atmosférico sobre florestas tropicais. A redução dessas incertezas é então fundamental para se avaliar o futuro da região Amazônica e outros ecossistemas tropicais frente às mudanças climáticas globais. A agenda de pesquisas proposta neste plano científico tem foco na resolução de uma das principais fontes de incerteza: o potencial do aumento das concentrações atmosféricas de CO_2 para amortecer os potenciais efeitos deletérios da mudança climática nas florestas tropicais, estimulando o crescimento e a resistência à seca das florestas.

Propõe-se a implementação de um experimento tipo FACE (Free-Air CO_2 Enrichment) em uma floresta madura da bacia Amazônica, próxima à Manaus, Brasil. A tecnologia FACE já provou ser um método valioso para determinar as respostas de longo prazo, em escala ecossistêmica, de florestas temperadas ao aumento de CO_2. Entretanto, nunca tal experimento foi conduzido em uma floresta tropical, apesar de já há tempos se reconhecer sua importância e necessidade nos círculos científico e político. O experimento terá início com um piloto consistindo de duas parcelas de 30 m de diâmetro por 35 m de altura; o experimento final compreenderá quatro pares de parcelas mantidas em concentrações de CO_2 ambiente ou elevada por ao menos 10 anos. O local de pesquisa será um platô na estrada ZF2, dentro da Reserva Biológica Cuieiras – área representativa de uma fração dominante das florestas da Amazônia. As parcelas experimentais, com biomassa elevada, incluirão árvores de 30 m de altura em solos argilosos profundos em bem drenados. O local de estudo é administrado pelo Instituto Nacional de Pesquisas da Amazônia (INPA) e já tem uma longo histórico de pesquisas em ecologia de florestas tropicais, manejo florestal e interações biosfera-atmosfera.

Cinco questões focando no metabolismo e ciclagem de carbono, uso de água, ciclagem de nutrientes, composição da comunidade florestal e interações com variáveis ambientais serão o foco do experimento. Um time multidisciplinar de cientistas empregará o estado-da-arte em ferramentas para investigar desde os impactos profundos no solo como no topo do dossel da floresta. Os dados resultantes do experimentos servirão à uma ampla comunidade de cientistas. Muitos dos avanços científicos deste experimento serão fruto de uma forte interação entre dados experimentais e modelagem.

O experimento Amazon-FACE será um grande esforço científico que irá estimular a capacitação científica de instituições de pesquisa no Brasil, bem como reforçar a cooperação com grupos de pesquisa dos Estados Unidos e da Europa na ciência do ciclo de carbono, da função do ecossistema e nas interações ecossistema-clima na Amazônia. Os resultados do projeto serão divulgados através de revistas e jornais científicos, e comunicados ao público em geral através de workshops e relatórios para agências governamentais e órgãos de tomada de decisão, com o objetivo de reduzir a incerteza sobre a vulnerabilidade da floresta Amazônica às mudanças climáticas e ajudando a orientar políticas de desenvolvimento futuro para a região.

1. The Scientific Basis

1.1 RISING ATMOSPHERIC CO_2 AND THE AMAZON FOREST

The rapid and unprecedented rise in atmospheric CO_2 concentration [CO_2] over the past century is an unambiguous indication of human influence on the global environment. Most recent projections—based on assumptions about energy use, population growth, and other physical, biological, and socioeconomic factors—indicate that atmospheric [CO_2] could increase from its present day value of nearly 400 parts per million (ppm) to more than 900 ppm by 2100[1]. Because atmospheric CO_2 is the primary basis for all terrestrial productivity, this substantial increase undoubtedly will affect the metabolism of the forests of Amazonia and tropical forests worldwide. The qualitative and quantitative expression of the effects, however, is largely unknown, representing a major source of uncertainty that limits the capacity to understand tropical ecosystem processes, assess their vulnerabilities to climate change, and improve the representation of these processes in Earth system models. The uncertainty surrounding tropical forest responses to atmospheric and climatic change is especially critical given the large impact that the forests of the Amazon basin have on global carbon cycling and climate, as well as harboring a considerable fraction of the world's biodiversity and providing substantial additional ecosystem services to humankind. **Future climate change may be particularly severe in the Amazon region[2,3], compromising the provision of those services[4,5]. The so-called CO_2 fertilization effect, however, could have an important buffering effect on regional temperature/rainfall changes[6-9], and as such it must be evaluated.**

Much is known about the effects of elevated concentrations of CO_2 (hereafter e[CO_2]) on biochemical and physiological processes in leaves, including leaves of tropical trees under tropical conditions[10]. However, the primary responses to e[CO_2] (e.g., stimulation of photosynthesis) do not reveal the integrated responses of ecosystem productivity, carbon cycling, and biotic interactions. Free-air CO_2 enrichment (FACE) experiments in temperate forests have revealed many higher-order responses and emphasized the importance of interactions and feedbacks between CO_2 and other environmental resources, stand development, and integration across time and space[11]. No such experiments have ever been conducted in a tropical forest. Tropical and temperate forests differ substantially in the plant species, forest structure, soils, and climate. These differences severely limit our ability to use results from temperate zone studies to predict tropical forest responses (Hickler et al. 2008). Hence, land surface schemes and vegetation models are highly uncertain with respect to their representation of tropical forests, and confidence remains low in their predictions of tropical forest responses to rising CO_2 and the feedback that vegetation-e[CO_2] interaction provides to the climate system.

Nevertheless, analysis of the vertical profile of CO_2 concentration in the atmosphere (Stephens et al 2007), which

provides a large-scale constraint on carbon cycle models, now indicates that tropical ecosystems are a strong sink for CO_2 and, through their biological productivity, provide an important negative feedback to the accumulation of CO_2 in the atmosphere. The importance of this feedback for understanding the escalation of climate change and ultimately human welfare over this century is indisputable, and the need for direct observational evidence to test the likely extent of this feedback is compelling.

1.2 WHY IN AMAZONIA?

Research on responses to rising atmospheric [CO_2] concentration and ecosystem feedbacks with the atmospheric and climatic systems is needed in tropical ecosystems. The Amazon forest is widely agreed to be the best region to initiate this research program for several reasons:

- The forests of the Amazon basin—the largest extent of tropical forest in the world—have a large impact on the global atmosphere and carbon cycle, comprise the world's largest repository of biodiversity, and provide substantial ecosystem services to humankind. For example the Amazon River outflow represents 20% of the global flow of fresh water to the oceans[5]. All of these functions will be affected by e[CO_2] in some way and, as such, it is important to predict the role Amazonia will play in the next decades for the global carbon cycle, climate regulation and biodiversity conservation.

- Future climate change may be particularly severe in the region, putting considerable additional pressure on the Amazon system (along with deforestation, logging and increased fire frequency) [14]. Furthermore, the Amazon rainforest is considered an important tipping point element in the Earth system, where "tipping point" refers to a critical threshold at which a small perturbation can considerably alter the state of large-scale components of the Earth system[15]. The CO_2 fertilization effect could have a buffering effect and alter the occurrence of this tipping point. Modeling studies[6-9] indicate that the effects of higher temperature and decreased precipitation alone tend to favor the dieback of Amazonian forest, while the CO_2 fertilization effects counteract the deleterious effects of climate change and favor the long-term permanence of the forest.

- The Amazon basin is home to about 25 million people, and if the forest dieback indeed takes place, there will be considerable consequences for the region's social welfare and Brazil's economy.

- Existing data and infrastructure: There is already a well-maintained, coherent set of forest plots in which biodiversity, tree growth and forest dynamics have been studied. These plots are also co-located with the eddy flux towers used in the large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) project.

- Institutional capacity: The Amazon region and Brazil as a whole have built top-quality expertise in the field of biosphere-atmosphere interactions in tropical forests during recent decades, with strong scientific collaborations with US and European institutions and research groups.

1.3 KNOWLEGDE GAPS ON TROPICAL FOREST RESPONSES TO ELEVATED CO_2

Experimental evidence.

Although there have been no FACE experiments in the tropics, the lessons from temperate FACE experiments[11] can highlight some critical areas of uncertainty that must be resolved to improve predictions of tropical ecosystem responses to atmospheric and climatic change. A stimulation of photosynthetic CO_2 uptake is the initial interaction between rising e[CO_2] and a forest tree, but the relative allocation of carbon to production of leaves, wood, or roots, to storage compounds, or to respiration or other losses must be understood to assess e[CO_2] effects on net primary productivity (NPP). NPP represents the input of organic matter into an ecosystem but by itself does not predict ecosystem carbon storage, a process dependent on how carbon is partitioned to different plant and soil pools and the turnover times of those pools. An important uncertainty that must be resolved is whether NPP stimulation in the tropics results primarily in increases in woody biomass or as increased detrital input into soil. Our understanding of root system responses in tropical forests is especially weak and must be improved given the many intersection points among roots, plant growth, carbon, water, and nutrient cycles in tropical forest ecosystems.

Observations of increased growth and recruitment rates recorded in tropical forests over the last three decades are currently best explained by the hypothesis of the combined effects of elevated [CO_2] and increases in incident radiation[16-22]. Other studies have concluded that different factors are more likely causes of biomass increases observed at the plot scale[23-24]. Attributing the driver of past changes in forest biomass is never straightforward because of multiple, uncontrolled environmental and stand development factors that are confounded with past increases in atmospheric [CO_2].

Temperate-zone experiments revealed the importance of nutrient availability and feedbacks between carbon and nitrogen cycles in modifying responses to e[CO_2]. Many tropical forests may not be nitrogen limited, but strong evidence indicates that photosynthesis and respiration in tropical rain forests are phosphorus (P) limited[25-29]. New observational data are thus needed to inform the incorporation of P dynamics into models of tropical photosynthesis to simulate phosphorus availability[30] and the ability of trees to increase access to less available forms of phosphorus under e[CO_2][31-33].

Interactions between e[CO_2] and the water cycle could be very important to tropical forests in a future high-CO_2 world. By increasing photosynthesis and/or decreasing water use via reductions in stomatal conductance, water-use efficiency

(WUE; carbon uptake per unit water loss) usually increases in response to e[CO_2]. Depending on other factors, especially responses in total leaf area, increased WUE may or may not result in decreased water use[11], but increased WUE potentially could confer increased drought tolerance to trees in e[CO_2][34]. Increased soil moisture has been associated with e[CO_2] in some experiments, with subsequent effects on soil respiration and nutrient turnover[35].

Interactions between CO_2 and light derive from the ability of e[CO_2] to increase light use efficiency in photosynthesis and decrease the photosynthetic light compensation point[36]. Although plants in the deep shade of a closed tropical forest will have slow growth, their relative response to e[CO_2] can be dramatic[37]. Hence, e[CO_2] has the potential to facilitate the expansion of plants into deeper shade[38] and alter the species composition that results after a canopy opening. This issue is important in determining the response of leaf area index (LAI, m^2 leaf area per m^2 ground area), and the associated change in land-atmosphere interactions under e[CO_2] conditions.

Few data are available describing the differential sensitivity to e[CO_2] among tropical species, but if important differences exist at large scales, they could represent a significant influence on forest structure resulting from re-vegetation of a forest gap or abandoned agricultural land. Lianas (woody vines) are increasing in Neotropical forests, representing one of the first large-scale compositional changes documented for old-growth tropical forests. Some research indicates lianas and woody legumes may be particularly sensitive to e[CO_2][39-43], and this could potentially have far-reaching consequences for ecosystem carbon storage.

Insights from Models.

Models are the primary tools for interpreting ecosystem measurements, understanding their relationship to environmental variables, and placing those observations in a larger spatial and temporal context. Models have been used to interpret past and current responses to atmospheric [CO_2], and they are especially useful for projecting responses to future scenarios of e[CO_2] and their feedbacks to the atmosphere and climate. Confidence in such model predictions depends on the models being well informed by both process-level and large-scale observations and responses to experimental manipulations.

Global models that incorporate a whole-ecosystem heuristic illustrate the potential importance of e[CO_2] to tropical carbon cycling and

the feedbacks from the tropics to the global climate. Carbon cycle predictions of different dynamic global vegetation models (DGVMs) are consistent with contemporary global land carbon budgets but can diverge considerably when forced with the future climate predicted by general circulation models (GCMs), CO_2 emission scenarios and different parameterizations on the effects of increasing atmospheric [CO_2] on photosynthesis and photosynthetic water-use efficiency by plants.

A recent study[8] constrained the likely range of sensitivities of tropical land carbon fluxes to climate change by current observations, suggesting that tropical forests, and especially the Amazon forest, are more resilient to climate change than previously thought assuming CO_2 fertilization effects are as large as suggested by current vegetation models. In the LPJ DGVM the enhancement of NPP driven by e[CO_2] was shown be more pronounced in the tropics (35% NPP enhancement) than in temperate forests (26% NPP enhancement) at an atmospheric CO_2 concentration of 550 ppm relative to that at 370 ppm[12]. This latter result derived primarily from the expression of photosynthesis in the model, which shows greater stimulation by e[CO_2] at higher temperatures; potential nutrient limitations were not included in the model. Other studies using different vegetation models have highlighted the key role of the CO_2 fertilization effect for counteracting the likely deleterious effects of climate change on vegetation, maintaining the tropical forest biomass relatively unchanged and resulting in the tropical land being predicted to be a net sink for carbon rather than a net source over the 21st century[6,7,9,44,45]. Exceptions were found for extreme climate scenarios—extreme increases in temperature or decreases in annual rainfall—for which the modelled CO_2 fertilization effect is not sufficient to avoid the modelled loss of biomass. **Thus, the possibility of climate change causing a substantial loss of Amazon rainforest cover and carbon stocks, and amplifying the climate-carbon cycle feedback—the so-called "Amazon forest dieback"[46,47]—is still an open question because of the potential resilience that e[CO_2] might confer to vegetation and the lack of experimental field studies to constrain the vegetation models with respect to this resilience.**

However, many uncertainties related to the effects of e[CO_2] remain to be addressed by models, such as the limitation of NPP increase by nutrient availability[48], especially phosphorus in tropical forests[49], or impacts on species composition[45]. Currently these model predictions are based on limited information and omit what are likely to be critical modifying processes. But importantly, the use of models can guide experimental design through the testing of hypotheses[34]. Understanding the major points of uncertainty in the models with regard to representation of e[CO_2] responses will help identify the highest priority research needs. That approach will be followed in the implementation of this scientific plan.

2. Justification for the Amazon-FACE Experiment

The need to address the many substantial scientific issues concerning the response of the Amazon forest to rising atmospheric CO_2 is the primary justification for a long-term and large-scale FACE experiment in the Amazon. Modeling studies indicate that there is a substantial, though uncertain, risk of wide-spread die-back of the Amazon rainforest under future climate change. This occurrence would have an unprecedented impact on the natural resources base of Latin America and would represent a significant threat to the region's economy, via changes in regional and global water circulation patterns, agricultural output and hydropower supply[50]. As outlined above, some of the deleterious effects of climate change on forests can be mitigated by the CO_2 fertilization effect by stimulating forest growth and increasing resilience to drought. However, if mitigation through CO_2 fertilization does not occur, then tropical forests are predicted to be much more vulnerable to climate change, and the risk of forest die-back would increase. Reducing uncertainty in this area is critical to steer future development policies for the Amazon region.

The responses of forests to e[CO_2] have not been tested in the Amazon or anywhere else in the tropics, and there is a compelling need to reduce this uncertainty. A FACE experiment is the most direct and robust scientific approach for accomplishing this. The FACE experiment proposed here will provide primary scientific information that advances our knowledge and understanding of the physiological and ecological effects of e[CO_2] in tropical forests. It will provide data needed for parameterizing and improving predictive models of the long-term effects of elevated CO_2 on carbon cycle and climate feedbacks.

Amazon-FACE will be a flagship scientific endeavor with high visibility in the international scientific community. In addition to the primary scientific justification for the proposed experiment, there are numerous ancillary benefits that should accrue. The analysis of the CO_2 fertilization effect in the Amazon forest should have many significant economic and environmental implications for the Amazon basin and for global carbon and water cycles. It is expected that the experiment will also have many passive implications for issues such as biological conservation, forestry practices, land use policy, and the provision of ecosystem services from the Amazon forest. The multi-disciplinary research team that will be required for the project will advance scientific empowerment of developing nations through education and training, hands-on research experience, and international collaboration. The experiment will provide a forum for outreach and education on climate change issues and Amazon rainforest ecology for stakeholders, policy makers, and the general public.

3. Major Objectives and Research Questions

The major objective of this science plan is to establish a research agenda on the implications of rising atmospheric CO_2 concentration on the functioning and resilience of the Amazon forest, the biodiversity it harbors, and the environmental services it provides in light of projected climatic changes.

In April 3-4, 2013, the "Workshop on how to assess the impact of high CO_2 environment on the stability of the Amazon forest" took place at the Inter-American Development Bank (IDB) headquarters in Washington DC, USA[51] (hereafter referred as the DC-Workshop). The DC-Workshop gathered a group of about 30 scientists to discuss the best ways to establish a comprehensive experiment on the issue, and the discussions held there – as well as extensive discussions with the scientific community in other forums – served as a basis for this science plan. It was agreed that the efforts should be directed towards the implementation of a FACE-type experiment, aiming at the provision of high-quality observational data for the improvement of vegetation models, to ultimately enhance our projections of the future of Amazonian forests in the light of climate change. Instead of forest plantations, the experiment should target mature forest, aiming at the up-scaling of its results to the entire Amazon basin later on. Moreover, ecosystem level studies should be given priority over, for example, experiments focused on individual trees or sapling stands.

Amazon-FACE should then allow advancement in five relevant research areas, expressed as the following questions:

- 1. Does e[CO_2] affect fluxes of carbon to and from the plant-soil system, and what are the consequences of changes in carbon allocation, turnover, and carbohydrate metabolism to long-term carbon storage within the ecosystem?

- 2. How are water use of vegetation and soil water status affected by e[CO_2]?

- 3. How are the availability, uptake, and use of nutrients, especially nitrogen and phosphorus, by vegetation affected by e[CO_2]?

- 4. How does variation in plant functional traits lead to alterations in plant community composition under e[CO_2], and how will changes in community composition alter ecosystem metabolism?

- 5. How do environmental stressors such as high temperature, drought, and nutrient limitation alter the responses of tropical forests to e[CO_2]?

These questions shall be pursued within four coordinated and cross-linking "tasks", which are addressed in more details in Sections 6.1 to 6.4.

4. Expected Outcomes

The major expected outcome of this project will be an improvement of our scientific knowledge about the fate of the Amazon forest in the context of atmospheric and climatic change.

This improved knowledge will be delivered through multiple products. Data sets describing physiological and ecological responses will be made publicly available and will be used as valuable inputs for parameterizing, testing, and improving land surface models used to predict terrestrial responses to e[CO_2], climate change, and disturbance. Results of experimental and modeling activities will be published in peer-reviewed scientific journals. Initial publications will emerge after the first year of funding describing the research site in detail, including novel observations such as root distribution and microbial populations, as well as a comprehensive assessment of vegetation models at the local/regional scale forced with the experiment target CO_2 concentration. As the project proceeds, technical reports describing responses to the CO_2 treatment will be published, followed by synthesis papers in high-visibility international journals (e.g. most of the current debate about the Amazon forest dieback is taking place in the leading scientific journal Nature). Previous FACE experiments have been very successful in generating a great many publications – approximately 70 per experiment along ~12 years of experiment*, including highly cited papers that were important references in IPCC Assessment Reports.

The scientific products also will be prepared in close collaboration with scientific press professionals in a format appropriate for informing government decision makers and providing input into sustainability initiatives in the Amazon.

Another important outcome of this science program will be in the scientific training of Brazilian students and capacity building of Brazilian institutions. Successful implementation of this project will require the participation of many students in various disciplines: plant biology, experimental field ecology, soil science, microbiology, meteorology, data analysis, engineering and scientific and public communication, to name a few. Students trained through this project will be prepared to use these skills, for example, in future research programs, government policy analysis and nonprofit organizations promoting sustainability. The project will also require the cooperation among multiple Brazilian institutions and between Brazilian and international organizations (see Section 12), thereby increasing the capacity for future scientific and educational endeavors, as well as advancing technological developments in experimental manipulation and environmental monitoring.

*See http://face.ornl.gov/pubs.html and http://face.env.duke.edu/publications.cfm

5. Implementation Strategy

5.1 Study Area and Available Infrastructure

The experiment will be implemented in the Central Amazon at the Experimental Station of Tropical Forestry (Estação Experimental de Silvicultura Tropical – EEST) bordered on the north by the ZF2 (Zona Franca 2) road, and located approximately 60 km north of Manaus. The proposed FACE site has access via the BR-174 paved road (50 km) and the ZF2 unpaved road (~35 km). The site is administered by Brazil's National Institute for Amazonia Research (INPA) and has a long tradition of research in tropical forest ecology, forest management and biosphere-atmosphere interactions. Long-term projects at the EEST started in 1979. and have resulted in a large body of scientific literature about the site. For example, the LBA (Large Scale Biosphere-Atmosphere Experiment in the Amazon) project activities started in the 1990's, and since 1999 there has been nearly constant monitoring of the forest-atmosphere exchange of CO_2, water vapor, sensible and latent heat, momentum transfer, and other meteorological variables from flux towers installed in the site[52]. There is also valuable knowledge on the site's soil composition[53] and soil CO_2 efflux characteristics[54], long-term trends in forest structure and dynamics[55-58], basic leaf physiology[59], and water balance[60].

The vegetation is old-growth closed-canopy terra firme (non-flooded) forest. The forest type (formally classified as Lowland Dense Ombrophylous Forest) and soil found on plateau forests along ZF2 (Ferralsol / Oxisol) are representative of ~32% of the forests occurring in the Amazon basin (~60% of Brazilian Amazonia)[61-63]. Local variations in soil type, topography and drainage status have created distinct patterns in forest vegetation composition. On the plateaus, well-drained clay soils favor high biomass forests 30–40 m in height with emergent trees over 45 m tall: typical terra firme forest. Along the slopes, where a layer of sandy soil deepens towards the valley bottom, forest biomass is lower and canopy height is around 20–35 m with few emerging trees. In the valleys, the sandy soils are poorly drained and usually remain waterlogged during the rainy season, supporting lower biomass and lower tree height (20–35 m), with very few emerging trees. Mean air temperature is 26 °C and average annual rainfall is about 2400 mm, with a distinct dry season during July, August, and September when there is less than 100 mm rainfall per month[52,64-66].

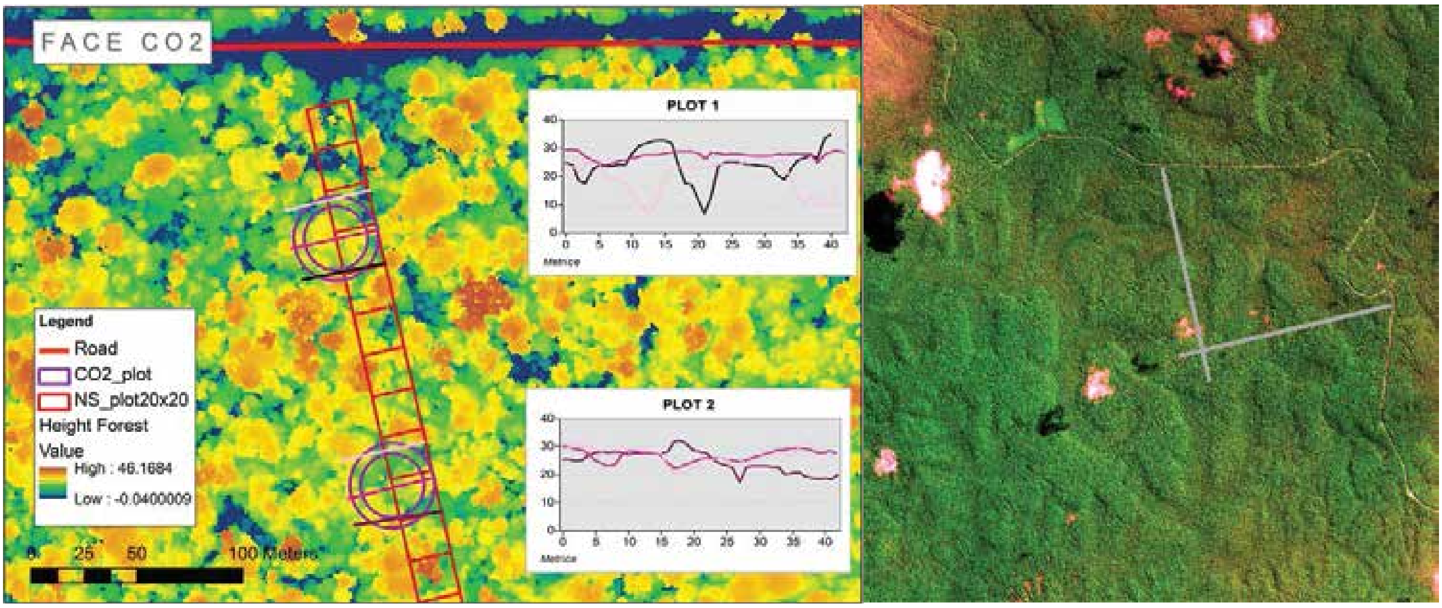
The proximity to Manaus (a city of 1.8 million inhabitants, with a large industrial park, an international airport, and research institutions) makes ZF2 an attractive option for locating the experiment when considering the provision and transport of the CO_2 needed for the experiment (see Section 5.3). The proximity of INPA is also an advantage for both the scientific and technical management of the experiment. Additionally, there are two large and well-equipped research stations (camps) at ZF2, one at the unpaved road's km 23 and the other at km 34, which can host groups of scientists and students. The camp at km 23 is extremely well-equipped for extended stays, and includes very comfortable sleeping quarters and showers, a diesel generator to supply power, cell phone service, a classroom with a computer projection system. The camp at km 34 (which is adjacent to the proposed experimental site) has two diesel-powered generators of approximately 100 kWh, ~ 70% of which is currently in use. This capacity can, however, be increased with the acquisition of new generators. The nearest power grid line at the ZF2 site is located ~35 km to the East, along BR-174 paved road. Initial estimates indicate that the costs for pulling an electrical cable from BR-174 over the entire unpaved road would be far more elevated than using diesel-powered generators. The road conditions can be challenging during the rainy season, which is particularly a problem if CO_2 is brought to the site by heavy trucks.

Options to overcome this problem are either the improvement of this road (by graveling its worst parts) or the piping of CO_2 from the beginning of the unpaved road to the experiment location.

Other options for locating the experiment are considered to be either logistically complex (e.g., Tapajós National Forest – CO_2 sources are too far away), problematic from a security point of view (the Adolpho Ducke Forest Reserve for instance is too close to Manaus urban area and there could be interference with or theft of equipment), or they simply do not have research facilities and sufficient previous studies that could provide background data for the experiment.

The proposed location of the experimental pilot plots for Amazon-FACE is shown in Fig. 1. These FACE plots will take advantage of a long term study initiated in 1996 by the Jacaranda Project (a collaboration between INPA and Japan International cooperation Agency – JICA). That project included two transect plots each comprising a 5 ha (10 ha total) permanent plots oriented in north-south (NS) and east-west (EW) directions (Fig. 2). The plots were designed to representatively sample the local undulating topography with high-clay Oxisol soils on plateaus, transitioning to Ultisols on slopes with an increasing sand content, and then to high-sand Spodosols associated with perennial steams in the valley bottoms ("baixios"). The FACE plots will be located on the plateau adjacent to the ZF2 road.

In 2011 the transect plots contained a total of 5885 trees (NS 3042; EW 2843) larger than 10 cm diameter (Diameter at Breast Height - DBH). The plots were initially censused in 1996, and recensused in 2000, 2002, 2004, 2006, 2008, 2010, 2011, 2012, and 2013 for a total of 10 inventories. Each tree has been identified to species or morphotype and is marked with a permanent numbered tag. At each recensus, new trees that



(a) (b)

Fig 1. (a) Subplots (20 x 20m) of the North-South (NS) transect plot (red boxes) and the proposed placement of the experimental FACE plots (30 m inner diameter circle, with a 5 m buffer radius). Cross-section lidar height profiles (background colors blue to red) for canopy height are shown in the inset plots. The entrance to the NS transect plot is located at: -2° 35' 40.29", -60° 12' 28.69" off the ZF2 road shown as the thick red line.

(b) The ZF2 Transect permanent plots (grey tracks) located on a false-color IKONOS image (green NIR band 4, red SWIR band 7). Each plot is 20 m x 2,500 m (5 ha) divided into 20 x 20 subplots. The plots capture the prevalent undulating topography were plateaus are dissected by small streams with local relief of 50 m. Plateau soils are rich in kaolinitic clay, while valleys ("baixios") with a surficial water table grade to almost pure white sand (referred to as Manaus Spodosol). Leafless drought deciduous trees are evident (red crowns) in this July 2001 image, and the ZF2 road is a clear feature.

grow into the 10 cm DBH class are added to the inventory, the DBH of each tree is remeasured to calculate growth rates, and trees that die are tabulated as mortality. A subset of trees has been outfitted with dendrometer bands, which are measured monthly to estimate seasonal variation in growth rates[56]. **As a consequence, whilst our FACE plots will necessarily be relatively small in size (30 m diameter), our study will sample forest that has been examined and measured in great detail for nearly 20 years, enabling us to account as well as possible for natural regional variation in tree growth and ecosystem process characteristics relevant to the FACE experiment results.**

Many other projects have been carried out on these transect plots including an ecosystem respiration study and comparison with tower-based eddy covariance data[67]; a characterization of soil properties and soil carbon cycling dynamics at plateau (Oxisol) and valley (baixio) (Spodosol) sites[53]; a pan-Amazon comparative study of forest structure and above-ground carbon cycling dynamics[55]; a tree growth rate and radiocarbon age-structure study[68]; and a variety of synthesis studies, technical reports, and INPA Masters and Ph.D. theses. This previous work will serve as an excellent foundation for the proposed Amazon-FACE experiment.

5.2 FACE Technology

Free Air CO_2 Enrichment (FACE) is a technology that allows elevation of the atmospheric CO_2 concentration in large field plots with minimal disturbance to the natural ecosystem[69,70]. This is done by releasing CO_2 on the upwind side of a circular research plot and allowing that CO_2 to be carried across the plot and diluted by ambient wind. Computer controlled feed-back and feed-forward algorithms maintain a target CO_2 concentration within the plot.

The first successful application of FACE technology to a tall forest was accomplished in 1994 by Brookhaven National Laboratory (BNL) at the Duke University Research Forest in North Carolina, USA. This initial study was expanded to a fully replicated experiment that operated from 1996 to 2010[71]. Additional temperate forest FACE facilities were constructed using this design in Oak Ridge, Tennessee, USA[72], and Rhinelander, Wisconsin, USA[73]. BNL recently updated the FACE facility design for use in a Eucalyptus forest in New South Wales, Australia, where CO_2 enrichment treatments began in September of 2012 (the EucFACE project). The FACE technology used in the Amazon forest FACE experiment will be designed by BNL in cooperation with Brazilian engineers based on technologies and equipment that have been proven to work in these prior experiments.

The diameter of 30m chosen for the Amazon-FACE plots is a good trade-off between costs (of towers and CO_2) and potential results that can be achieved with the FACE technology available now. New technologies would have to be engineered for plots larger that 30m in diameter, to guarantee, for example, homogenization of the aspersed CO_2 in the central parts of the experimental plot.

5.3 CO_2 Provision

The CO_2 requirements for a single FACE plot (pilot project) with a diameter of 30 m, a canopy height of 35 m, a CO_2 treatment of 200 ppm above ambient, daytime only treatment, and average wind speed above the canopy of 1.25 m s^{-1} is estimated to be 3.7 Mg (= metric tons) per day or approximately 1350 Mg per year. These quantities are based on actual CO_2 use rates at three FACE experiments with plot dimensions similar to those planned for this study. Taking 1350 Mg per plot per year as a reference value, the CO_2 requirements for the long-term full experiment (four FACE plots with elevated CO_2) would reach 5400 Mg y^{-1}. Currently there is only one CO_2 production plant in Manaus, called CarboMan, which produces CO_2 out of the burning of natural gas. Although it is the easiest way for acquiring CO_2 for the pilot experiment, their price as in April 2013 (1 USD = 2.3 BRL) was in the order of USD $1000 per Mg of CO_2. That value would reduce to US$740 Mg^{-1} CO_2 in case natural gas is donated – by Petrobras for example. Although CarboMan is not capable today of providing the quantity of CO_2 required for the full-long term experiment their production capacity could be enhanced in the next few years.

Alternatively, there have been discussions with representatives of Amazonas Energia, the local electric generating company, and international CO_2 vendors with interests in expanding their presence in the Manaus market. The possibility of one of these vendors implementing a CO_2 plant that benefits from the exhaust gases from a thermoelectric power plant is being explored. In that case CO_2 costs could lower up to approximately US$200 Mg^{-1} CO_2.

The vaporizer banks will be sized for the pilot experiment and, as with the storage tanks, additional units will be added as needed for the full experiment. Depending on the CO_2 vendor and economic considerations, the CO_2 storage tanks and vaporizers may be leased from the vendor or purchased outright.

5.4 Cranes & Towers

Each experimental plot will be equipped with a crane to assist in constructing the plot hardware and to provide scientists with canopy access during the experiment. These cranes will provide access to most of the forest canopy as well as the elevated portions of the FACE facility, improving both the efficiency and safety of research and maintenance activities performed at height. Cranes have not been used at most FACE experiments due to their cost, but they are being used to great advantage at the EucFACE experiment and at other forest canopy research sites (e.g., webFACE in Switzerland). The use of construction cranes will be greatly beneficial for this and other research projects at the experimental area that may require access to upper forest canopy. A walkup style (scaffold) tower will be placed in the plot center to allow placement of the required sensors and instruments within and above the canopy (Section 5.5). Additional towers will be installed around the periphery of the plots to support the pipes used to deliver CO_2 to the forest canopy.

5.5 Meteorological Measurements

Meteorological variables will be measured continuously. An instrument package mounted above the canopy will include sensors for air temperature and relative humidity, global and diffuse radiation, photosynthetically active radiation (PAR), wind speed and direction, and precipitation. An additional sensor package will be installed below the canopy in each plot to measure air temperature, relative humidity, soil temperature, PAR, and throughfall precipitation. In addition to monitoring of CO_2 concentration as part of the FACE control package, a multiport sampling system will be deployed to measure [CO_2] throughout the 3-dimensional space of the plot. All of these meteorological measurements will be managed with data loggers and immediately uploaded to a central computer accessible to all project participants.

5.6 Project Phasing

Phase I: Pre-experimental Measurements.

It is extremely important to build a comprehensive set of observational data from aboveground and belowground forest processes before the atmospheric CO_2 concentration in the experimental site is increased in order to assess properly the effects of e[CO_2] on the forest ecosystem. These measurements (biological and non-biological) are basically the same as should be conducted inside the research plots after treatments begin. One of the advantages of the selected research site is a long history of observations of many of the trees within the study area, which will continue throughout the project duration. Nevertheless, other measurements are also needed. These measurements, of forest ecosystem physico-chemical characteristics, physiology, growth and dynamics should include foliar photosynthetic and respiratory activity, tree and sapling growth, soil moisture, fine-root development, etc. A detailed list of the measurements necessary for the Amazon-FACE study site is given in Appendix A.

Phase II: Pilot Experiment.

The Amazon-FACE project will start with a short-term pilot experiment, running for at least 2 years following a 1.5 year construction and pre-treatment measurement period. The pilot experiment will consist of two 30 m diameter plots, one receiving CO_2-enriched air and the other with all of the FACE equipment but receiving only ambient air. These plots will be used to study the performance of the FACE facility under local conditions to improve estimates of performance and CO_2 use in the fully replicated experiment. The prototype plots will also allow the scientists to test and perfect their sampling techniques and research plans under actual experimental conditions. The micrometerology of the control plot (Section 5.5) will be studied with and without the dilution caused by air blowers to document any machine effects due to installation and operation of the FACE equipment. The findings from these studies will be used when deciding whether or not fully instrumented control plots are needed in the replicated experiment. The results of this pilot study will lead to testable hypotheses for the subsequent long-term, fully replicated experiment.

Phase III: Full-Scale Long-Term Experiment.

The long-term, fully replicated Amazon forest FACE experiment will begin after the successful conclusion of the pilot study. It will be designed to run for at least 10 years to capture the response of ecosystem processes including slow dynamics such as soil carbon turnover. The experimental design will comprise four CO_2 enrichment plots and four control plots installed in the same area used in the prototype study and incorporating the prototype treatment and control plots as part of the study. The establishment and monitoring of the sampling transect has provided a basis for using a fully replicated, complete block experimental design, using the presence or absence of routine tree sampling as the block. Based on prior experience with FACE plot spacing, treatment plots will be separated from adjacent treatment and control plots by at least four plot diameters between plot centers. The selection of plot locations will also be adjusted to accommodate local topography and the presence of emergent trees that significantly exceed the height of the surrounding canopy.

The CO_2 enrichment target will be 200 ppm ($\mu mol\ mol^{-1}$) above ambient concentration, measured at the top of the forest canopy. Enrichment will occur during daylight hours throughout the year. An examination of historical wind events will be used to determine the need for an upper wind speed cutoff to reduce CO_2 consumption during extreme wind events. The target enrichment of 200 ppm is chosen to result in an atmospheric concentration similar to what is predicted to occur in about 50 years by the Representative Concentration Pathway (RCP)-8.5 emissions scenario used by the IPCC (or by 2100 in the RCP-6.0)[1], and it is consistent with the concentration used in other FACE experiments, facilitating comparison of results.

16. Project Timeline

APR/2014	SEP/2015	SEP/2016

Project phase 1: Pre-Experimental Measurements & Pilot Plots Construction

Project phase 2: Pilot Experiment (two FACE plots (1 control + 1 treatment)

Full experiment

SEP/2017	OCT/2017	SEP/2027
plots construction		
	Project phase 3: Full-Scale Long Term Experiment (six additional FACE plots [3 control + 3 treatment])	

7. Science Tasks

TASK 1 - ABOVEGROUND PROCESSES

Task 1 deals with all aboveground processes in the experimental plots and is addressed in a series of linked science questions. The tables in Appendix A, Section 13.1 summarise the questions, data needs and equipment requirements, for both the pilot experiment and the full FACE experiment*. The outcomes of this work will address the individual science questions and will also be needed to inform the modeling of the response by trees and the ecosystem to e[CO_2] at multiple scales. Two challenges for this task are: (i) representing the short and long term physiological and growth responses to e[CO_2] in leaves, stems and whole trees; and (ii) accounting for the high species diversity present. The two challenges will be addressed by measurement of processes, stocks and tissue composition and through analysis of the variance in trait characteristics and process responses among individuals and species. Model-based analyses of the responses to e[CO_2] comprise aboveground and belowground elements and hence the work of Task 1 will be closely linked with that of Tasks 2 and 3, both empirically and through simulation.

T1-A. How does photosynthesis respond to elevated CO_2 in tropical trees, especially in relation to nutrient constraints?

There is evidence from temperate FACE experiments that long term enhancement of photosynthesis through exposure to e[CO_2] may be strongly constrained by nitrogen (N) availability. There is also evidence that photosynthetic capacity (and productivity) at sites with weathered oxisols such as the chosen study site are naturally constrained by low phosphorus (P) availability, and that the relationship between photosynthetic parameters and leaf N differs from that observed for temperate forests. Uncertainties include whether: e[CO_2] results in sustained increased photosynthetic rates, whether this is constrained by P availability (and other nutrients), and whether e[CO_2] results in relatively more P acquired by some or all plant species[12,48,49,59,62,74,75].

T1-B. What are the responses of stomatal conductance (g_s), photosynthesis and respiration to elevated leaf temperature and elevated CO_2?

The warm ambient temperatures of tropical forests, and the potential for sun leaf temperature to rise to critically high levels, have potentially large consequences for net carbon gain via stomatal, mesophyll and non-stomatal (e.g. biochemical) limitations. At e[CO_2] some of these limitations may be ameliorated, but the extent and nature of the combined response to e[CO_2] and warming remains a large uncertainty. Analysis of the variance in these gas exchange responses across plant traits (e.g. leaf mass per unit area, leaf nutrient concentration, leaf longevity, woody tissue density etc), and among plant functional groups, will inform empirical or model-based scaling from leaf-level process understanding to the canopy[12,19,76-82].

* Open-top chamber (OTC) studies may be available to extend the FACE, with better-replicated understory physiology and carbohydrate analysis as a focus. This opportunity is of interest, but is not yet developed here. Questions T1-A to T1-E are relevant to OTC studies, as in Task 2.

T1-C. Does leaf area index increase under elevated CO_2? What phenological changes occur under elevated CO_2, and what physiological information do they provide?

An increased carbon resource at e[CO_2] has been modelled to result in increased leaf area index (LAI) because of increased water use efficiency, with recent remote sensing-based global time-series observations supporting this view for dry environments. A change in LAI under e[CO_2] may also be affected by possible alterations to leaf mass per unit area occurring in response to altered nutrient and carbon supply to the canopy. Further, light-limited leaves near the canopy-bottom may be favourably affected by e[CO_2] or certain species groups (lianas) may benefit disproportionately; and there may be a positive impact on allocation of photosynthate to reproduction. There is the potential to detect physiological processes and phenological changes in the canopy using remote sensing methods as well as automated or regularly-implemented ground-based methods, and these offer potential for understanding e[CO_2] effects on structure and process at leaf and canopy scales. [11,37,83,84,85,86]

T1-D. Will a reduction in g_s and/or increase in LAI influence whole-plant water use and soil water balance?

Modelled and empirical temperate e[CO_2] studies suggest the potential for reduced water use by vegetation and subsequent impacts on soil moisture and run-off. This implied water savings could have important implications for tropical forest structure and function, but the idea has not yet been tested in tropical forests. [43,87,88,89]

T1-E. How does aboveground growth respond to elevated [CO_2] in different size classes and functional groups?

The growth response in stems to e[CO_2] by different plant functional groups may not correspond to alterations in photosynthesis or, for example, tissue carbohydrate concentration. Growth may instead respond through changes in the patterns of allocation to different components of the vegetation, above- and below-ground

Differences in stem growth responses among functional groups may occur, depending on growth form (lianas/trees), capacity to fix nitrogen, successional status (pioneer/climax) and size or canopy position (seedling/understory). [34,48,90,91,92]

If resources allow we will also develop a focus on the physiology, growth and phenology of trees and lianas in the understory. Competition in the understory partly determines the future composition of any forest canopy, so understanding the response among species to elevated CO_2 concentration, especially where light availability is limited, may be important for understanding the long term response of the forest. Understory plants are more numerous and more easily accessed than full canopy trees, and so this approach will also enable sub-project studies with fuller species replication and easier implementation of some of the more technically-demanding measurements.

TASK 2 - BELOWGROUND PROCESSES

The work plan for Task 2 has also been designed to address a series of science questions, and to help develop the mechanistic understanding required to interpret the responses of belowground processes to elevated CO_2 at the ecosystem level. Four specific challenges of this task are: (i) quantifying root production as a component of NPP, and the turnover and distribution of roots in the soil profile; (ii) identifying potential nutrient limitations and the potential mechanisms through which the limitations may be alleviated; (iii) quantifying changes in decomposition rates; and (iv) determining impacts on soil water movements. These challenges will be addressed by a range of field and laboratory measurements (summarized in Appendix A, Section 13.2 together with equipment and personnel requirements), which integrate strongly with the Task 1 measurements (see section 6.1) and provide data directly to Earth System modellers.

T2-A. Does elevated [CO_2] increase root growth throughout the soil profile?

CO_2 enrichment has been demonstrated in temperate ecosystems to shift biomass allocation patterns toward increased root production in a trade off with longer living woody tissues[34,48,90]. Ephemeral or 'fine' plant roots are important for nutrient and water acquisition, and contribute a substantial input of C and nutrients to the soil because the average lifespan of the fine-root population is less than 1 year[93]. One of the most consistent responses of temperate forests to elevated [CO_2] has been increased allocation of C belowground to the production of fine roots, especially deeper in the soil profile[33]. An increased root to shoot ratio has also been observed in seedlings of tropical trees exposed to elevated [CO_2][94]. Increased production of fine roots could increase tree access to available soil nutrients[95], and also lead to increased C storage in long-lived soil pools[96]. However, there are few fine-scale measurements of fine-root production and distribution in tropical ecosystems[93,97]. Quantification of root production is an important component of the ecosystem carbon budget, including NPP and belowground respiration, and measurements of root dynamics, morphology, depth distribution, and mycorrhizal colonization will substantially improve our understanding of belowground processes in tropical ecosystems, and their responses to environmental perturbation.

T2-B. Does nutrient availability limit the CO_2 fertilization effect?

Low nutrient availability reduces the percentage growth response to e[CO_2][98], and it is likely that nutrient availability may constrain the response of tropical forests to e[CO_2]. While N is abundant in most lowland forests in Amazonia[99], rock derived nutrients such as phosphorus and base cations are usually found in very low concentrations due to the effects of continuous weathering over millions of years[62]. Forest productivity is generally considered to be P limited across Amazonia[100]. However, P limitation could be alleviated under e[CO_2] through increased carbon allocation to roots and associated mycorrhizal fungi[32], as well as the production of extra-cellular phosphatase enzymes[31] and exudation of organic acids[101]. Other elements such as calcium, potassium and molybdenum may also be limiting in Amazonian soils, and their availability could constrain responses to e[CO_2]. Even N could become limiting since it holds interdependences with P and carbon turnover[49,62,102]. Understanding nutrient limitation and the mechanisms for improving nutrient acquisition are of fundamental importance to predicting the response of Amazonia to e[CO_2].

T2-C. Will growth under e[CO_2] result in greater soil water availability?

Task 1-D identifies the potential for stomatal conductance to decline and tree water-use efficiency to increase under e[CO_2][143]. It is important to determine whether this effect is large

enough to alter soil water availability at different depths, especially during periods of low rainfall. As well as the direct benefits to the trees in terms of reduced vulnerability to drought, greater soil moisture content could also potentially facilitate microbial activity and nutrient uptake[103]. This extra soil water availability may also result in greater deep soil drainage and, if associated with increased plant tissue turnover, result in greater DOC and losses of dissolved organic nutrients.

T2-D. How will e[CO_2] affect litter dynamics?

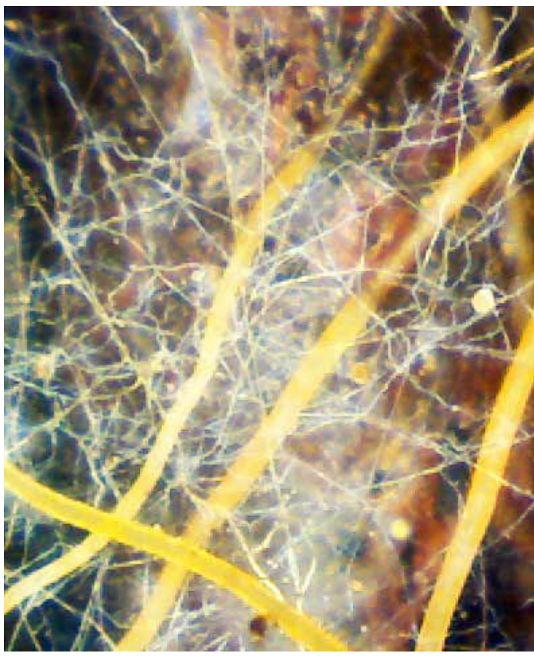
Increases in plant growth following e[CO_2] under the limited nutrient supply typical of Central Amazonia could result in changes in the quantity and quality of aboveground and belowground litter. Litter inputs will increase if canopy and root productivity are enhanced under e[CO_2], while potential changes in quality include alterations in nutrient stoichiometry and concentrations of defence and structural compounds (i.e. lignin, tannins, cellulose). A detailed understanding of litter biogeochemistry and its association with microbial dynamics, decomposition/mineralization rates, and the fraction of decomposing litter leaching into mineral soil is needed to understand the effect of e[CO_2] on below-ground processes.

T2-E. Does e[CO_2] affect decomposition rates; priming effects versus soil C stabilisation?

Predictions of the response of soil organic carbon to e[CO_2] vary widely because of the complex range of impacts. For example, while soil C inputs may increase, decomposition rates may also be enhanced following an increase in microbial activity[101]; this being particularly relevant if allocation is directed to roots instead of long lived woody biomass. Increased delivery of high quality organic carbon to soils may enhance degradation of previously stabilized C ('priming'). Furthermore, changes in the proportion of physically or chemically stabilized soil organic matter could also occur[104,105]. Therefore, it is important to measure the capacity of tropical forest soils to stabilize C, which if already saturated, could imply greater DOC losses and transfer of C deeper into soil profiles.

T2-F. How does e[CO_2] influence the structure and function of the soil microbial community?

Alleviating nutrient limitation of the plant growth response (T2-B), changes in litter decomposition (T2-D) and soil organic matter priming and stabilization effects (T2-E) are all mediated, at least partly, through soil microbial community responses. As mentioned above, one group of microbes which may benefit under e[CO_2] is mycorrhizal fungi[106], and changes in competition between these symbiotic fungi and free-living micro-organisms may have major implications for microbial community structure and carbon and nutrient dynamics[105,107], with knock-on implications for interactions between different plant species[108]. Furthermore, an overall increase in the rate of soil C input, including litter production, root and mycorrhizal biomass turnover and root exudation, may increase overall microbial biomass and alter community structure by favoring certain groups of soil microbes. The production of important C and nutrient cycle enzymes may be affected, with consequences for rates of decomposition, soil respiration and greenhouse gas production.



TASK 3 - ECOSYSTEM MODELING

An immediate goal of the modeling task is to guide the measurements and observations in the experimental plots and the data structure for those observations. The longer-term goal is to use the experimental results to test relevant model assumptions and improve process-level algorithms, thereby reducing uncertainties in the representation of tropical forests and their long-term responses to environmental change in Earth System Models. The three major challenges to be undertaken by the modeling task are:

T3-A. Generating model predictions to be tested by the experiment.

Existing models encompass the current hypotheses on e[CO_2] effects. Model testing will evaluate the validity and relative importance of these hypotheses, guiding and fine-tuning the analysis of processes and variables addressed in the questions of tasks 1 and 2. A number of dynamic vegetation models will be run using the data collected in the LBA network of flux towers across the Amazon for site-specific model forcing and validation (sites providing parameter values, but with particular focus on the Amazon-FACE experimental site) forced with current and elevated CO_2 conditions. The employed models shall comprise as many different approaches and features to model vegetation (e.g. consideration of nutrient cycling) as possible, as a way to assure this project task can fully support and benefit from the experimental outcomes. The modeling protocol will be designed to standardize the model simulations as much as possible. Model testing against site data (biomass, canopy fluxes), against each other, as well as sensitivity analysis on selected process parameters will help to focus field research questions and to guide in structuring output of the experimental analyses. The modeling exercise will strongly benefit from collaboration with other projects: the choice of models and the modeling protocol can rely on the FACE-Model Intercomparison Project (FACE-MIP)[109] and also on the LBA-Data MIP[110]. A list of variables as well as parameters to be used in model simulations will be established based on these previous modeling efforts. The provision of input data for the vegetation models will strongly benefit from existing projects (such as AMAZALERT, LBA, TRY, RAINFOR) and from existing measurements from the LBA project, data on site-specific climate, carbon fluxes (NEE, GPP derived from eddy covariance measurements), biomass (AGB, increment), soil nutrient availability (N, P) and vegetation structure (age structure, species abundance, functional traits).

T3-B. Improving vegetation models through better process representation or new model approaches.

Developing new process representation or model approaches is not a trivial task but regarding the project's time horizon of 10 years, it is a feasible task. As a first step, the improved processes and components needed for the Amazon-FACE modeling framework will be determined through development of a conceptual model. Then, processes currently considered in existing models will be evaluated and improved and new processes and components will be developed. Modeling approaches and model improvements are not necessarily focusing solely on the parts of the model that concern CO_2 fertilization directly. Based upon current insights on the major model deficiencies, it is likely that these improvements will focus on those processes already identified under tasks 1 and 2, but will also need to scale up the experimental work to enable assessment of whole-ecosystem response to the combined effects of e[CO_2] and other global change factors. Model development and experimental work will go hand in hand, in an iterative way. In particular future model development should focus in the following priority areas:

- Interaction of e[CO_2], nutrient limitation, temperature, water (and light) use efficiency and water stress affecting primary productivity. Stomatal responses to CO_2 and water stress, photosynthetic and respiratory response to temperature and nutrient allocation are still poorly represented in vegetation models[78,109,111].
- Allocation of photosynthate under changing productivity and stress, which currently relies too heavily on fixed, empirical allocation ratios and long time scales[34,112,113].
- Representing the variety of soil biological processes in nutrient (N and P) acquisition, liberation and occlusion, that are currently not or only rudimentarily represented in vegetation and soil models[48,113,114].
- Different responses of ecological or functional groups in the above processes, potentially leading to changing species composition and biodiversity, with potential feedbacks to ecosystem response.
- The combined effects of direct anthropogenic activities over the forest structure and dynamics such as degradation, deforestation, and fires will need to be linked with the above listed processes and the potentially enhanced resilience through e[CO_2][115].

T3-C. Reduction of e[CO_2]-related uncertainties in projections of long-term changes in tropical forest ecosystems.

This is a goal during the entire duration of the Amazon-FACE experiment and will be necessarily linked to uncertainties in other interlinked model processes. Reduced uncertainty will be achieved through improvement in process representation as detailed above, by applying modified vegetation models and the most up-to-date scenarios of future climate change, such as those currently generated for CMIP5 (Coupled [General Circulation] Model Intercomparison Project 5). Several model improvements will, if relevant for collaborating groups, also be incorporated in and contribute to the development of next-generation global Earth System Models (ESMs). Long-term forecasts of such ESMs will ultimately generate answers to the overall question whether e[CO_2] will, through enhancing ecosystem resilience, reduce the deleterious impacts of increased temperatures, more frequent droughts and direct anthropogenic disturbances[114].

TASK 4 - DATA INTEGRATION AND SYNTHESIS

Many significant results from this experimental effort will derive from a strong interaction between experimental data and modeling, and the most important experimental responses for evaluating models are ecosystem-level responses that require an integration of different data streams. Experience in other large-scale climate change experiments has shown the importance of initiating the model-data interaction in the earliest phases of project planning, and that integration will be an important objective in this experiment. Discussions between modelers and empirical scientists will define the most important measurements needed for model parameterization and set standards for data formats.

T4-A. How will net primary productivity (NPP), allocation and carbon-use efficiency respond to elevated CO_2?

One of the most important outputs from temperate forest FACE experiments, both for tracking ecosystem-level responses and for comparisons with models, has been quantifying changes in NPP[12,116]. This requires integration of aboveground and belowground measurements, with rates of stem growth, canopy production and root production all needing to be determined.

Comparing rates of above versus belowground NPP can also be very informative. CO_2 enrichment has been demonstrated to shift biomass allocation patterns toward increased root production in temperate ecosystems in a trade off with longer living woody tissues[34,48,90], therefore having the potential to decrease woody biomass growth and increase the portion of non-respiratory carbon losses. However, increased fine-root production also increases the input of root detritus into soil, with the potential for increased carbon storage in soil organic matter[96], and provides a mechanism for alleviation of nutrient limitation[117]. Furthermore, existing allocation studies in tropical forests suggest an emphasis on fine root-stem trade-offs, with allocation to the canopy a less variable component of NPP. Changes in allocation between roots and stems may also alter susceptibility to other environmental factors such as drought.

Finally, NPP measurements need to be placed into the context of total photosynthesis (gross primary productivity, GPP), allowing carbon-use efficiency (the proportion of C assimilated by GPP that is retained in biomass; CUE), to be calculated. Overall, CUE may be relatively low in tropical forests (0.3 vs 0.5 in temperate forests), and it has been suggested that differences in growth rates between Amazonian forests may be related more to differences in CUE than GPP[118]. Many physiological processes contributing to gross CUE and component-scale carbon allocation may be sensitive to e[CO_2][23,48,119,120] and, thus, determining the impacts of e[CO_2] on CUE is essential for modeling. Determination of GPP is best made using more than one method and we will use new and established approaches based on modeling and measurement[83,84,120-123].

T4-B. What is the impact of e[CO_2] on carbon storage?

Earth System models predict that e[CO_2] will result in a substantial and sustained increase in C storage in tropical forests in the absence of nutrient limitation[12,35]. While aboveground biomass changes may be measureable remotely (at a coarse resolution), changes in belowground C storage, up to 50% of the C stock in many Amazon forests[62,63], can only be determined in situ. Thus, it is essential to quantify the responses of all components of forest C storage (stems, leaves, roots, and soil organic matter) to e[CO_2], with these data being particularly important if e[CO_2] affects C allocation aboveground versus belowground and C storage in soils.

T4-C. How do nutrient and water budgets change with CO_2 enrichment?

As with carbon budgets, an ecosystem-scale analysis of water and nutrient budgets requires an integration of data from multiple sources and tasks. N and P budgets (stocks and fluxes) will be constructed from data on elemental concentrations in leaves, wood, fine roots, and leaf litter combined with the standing biomass of those tissues and their fraction of NPP. Net nutrient uptake will be calculated as in the work by Finzi et al.[117]. Nutrient fluxes will be interpreted in relation to nutrient availability in soil. Hydrologic budgets will include data on stomatal conductance, sap flux, vapour pressure deficit, precipitation, throughfall, evaporation, and soil water content[124].

T4-D. Synthesis of data and integration of results.

This task aims to answer cross-linking questions as raised above and to assure data flow between the project partners. In addition to these cross-linking questions, a project website and data repository will be established. Sharing of standardized data among project participants is important for advancing the science product in a consistent way, most efficiently moving data to models, and avoiding both redundant and missing measurements. Guidelines for data sharing will be established that all project participants will be expected to follow. Similar guidelines will be established for dissemination of model results. Workshops will be organized regularly to serve as a basis for communication between modelers and experimentalists. As the experiment proceeds, team leaders will confer regularly via conference call to ensure that all project participants know what measurements are being made, when they are being made, and how one activity could impact another.

8. Evaluation and Dissemination

The Amazon-FACE Scientific Steering Committee (SSC) will comprise the project coordinators (2), task leaders (2+2+2), two scientists responsible for the site engineering and instrumentation, and the project officer (1), totaling 11 members (see section 11). This SSC will confer every second month by conference calls to ensure coordination and collaboration among tasks, and to identify and resolve problems as they develop.

An advisory board will be established with approximately five senior scientists with expertise in tropical forest ecology, modeling of terrestrial ecosystems, elevated CO_2 research, or other topics closely related to the projects. This advisory panel, including scientists based in Brazil and abroad, will be assembled annually to review progress, critique experimental approaches, identify new opportunities for research and collaborations, and help disseminate and publicize results.

Primary outlets for dissemination of results from the Amazon-FACE project will be through peer-reviewed scientific journals and conferences. In addition, we will pursue opportunities for outreach to the general public through popular media (e.g. the project website: http://www.labterra.net.br/amazon-face) and educational outlets (e.g. training courses at the experimental site). Reports will be prepared for government agencies and decision-making bodies as opportunities arise on the overall effects of climate change on the resilience of the Amazon forest.

9. Broader impacts

The research agenda proposed in this plan will stimulate the scientific empowerment of research groups in Brazil as well as strengthen cooperation with North American and European research groups in science of the carbon cycle in the Amazon. Previous large-scale experiments have provided the wider scientific community an opportunity to become skilled at project management, and have generated unprecedented opportunities for the training of new, young scientists to work in a highly collaborative environment. The latter has particularly been the case for LBA and the Brazilian community.

Analysis of the CO_2 fertilization effect in the Amazon forest is of great scientific interest but will primarily have significant economic and environmental implications for the Amazon basin and for global carbon and water cycles. **If the Amazon forest dieback indeed occurs at large scale, this would represent a significant threat to the region's economy via changes in the regional and global rainfall patterns, agricultural losses and impairment of hydropower supply. Reducing uncertainty in this area is critical to steer future development policies for the Amazon region.**

Large, integrated field experiments and infrastructures have always led to technological advances in techniques for monitoring, and Amazon-FACE can be expected to do so as well. This will stimulate development of small enterprises, especially in South America. For example, the sequence of integrated land-surface-atmosphere exchange experiments has strongly stimulated the development of micrometeorological equipment and software. New developments can be anticipated in remote sensing, automated canopy observation techniques, automated plant physiology measurement, analysis of soil and root biochemistry, and modeling soil-vegetation interactions, and these will be especially useful for Amazon-FACE. The project will actively seek collaboration with regional (Amazonian or Brazilian) engineering companies to jointly develop novel approaches in such fields.

10. General Budget and Funding Strategy

Estimated costs for the Amazon-FACE project total US$11.2 million for the pilot experiment (3 years comprising Phases I and II) and US$78.5 million for the 10 years-long full experiment (Phase III). Largest uncertainty regarding these costs is related to the cost of CO_2 to be released into the FACE plots. Assumed costs for CO_2 in such a budget are in the higher end of price estimates. As mentioned in Section 5.3 there are opportunities to reduce this cost from US$1000 to US$700 per Mg (or even less) [CO_2 requirements for each FACE plot are approximately 1345 Mg y^{-1}]. Members of the research team are currently in contact with CO_2 vendors to reduce this uncertainty related to CO_2 costs as soon as possible. Moreover, part of the infrastructure cost could be alleviated with the provision of the old FACE hardware used in previous experiments in Duke Forest and Oak Ridge.

The general strategy to cover the project expenses presented above is to have a variety of funding sources covering Phases I and II. Prospective agencies with potential for funding these two project phases include Brazil's Ministry of Science, Technology and Innovation (MCTI), the Inter-American Development Bank (IDB), Amazonas and São Paulo State Research Foundations (FAPEAM and FAPESP respectively) and others from Europe and USA.

A cooperation agreement between MCTI and IDB has already secured US$ 1.25 million for initiating the experiment's phases I and II.

Because the costs for Phase III are relatively high, there will be a submission of a funding proposal to the Amazon Fund, which is currently managed by the Brazilian Development Bank (BNDES). **The Amazon Fund currently has assets of approximately US$ 435,000,000 which can be assigned to prospective projects (Amazon Fund 2012).** The fund recently included in its funding portfolio the following project category in which Amazon-FACE fits in:

"(...) the development of methodologies for measuring carbon stocks and carbon storage capacity in the Amazon Forest biomass and mensuration of other ecosystem services" (Item 21 - Ecosystem services, from the Scientific and Technological Development in the Amazon Biome support focus).

It is noteworthy that this is a tentative funding strategy and that as of the date this plan was written no funding bodies have yet officially committed any resource for the Amazon-FACE project.

11. Institutional Arrangement and Partner Projects

Institutional coordination of the Amazon-FACE will be centered at Brazil's National Institute for Amazon Research – INPA in Manaus, Brazil. All project resources originated from funds such as Inter-American Development Bank – IADB and The Amazon Fund will be administered by the FDB (Fundação Amazônica de Defesa da Biosfera) foundation, which has administered the funds from several INPA projects.

Many other institutions will have scientists and students participating in the project such as São Paulo State University – UNESP, Oak Ridge National Laboratory, Brazil's National Institute for Space Research – INPE, Edinburgh University, Brazil's Agricultural Research Corporation – EMBRAPA, Brookhaven National Laboratory, Wageningen University, Potsdam Institute for Climate Impact Research – PIK, and the University of Exeter. For a full list of institutions that participated in the planning of the experiment, please refer to section 12.

Other ongoing scientific efforts such as the LBA program (Large Scale Biosphere-Atmosphere Experiment in the Amazon) and the Jacaranda project will support Amazon-FACE with cession of existing infrastructure and logistics, subject to a formal agreement. An official agreement between Brazilian and US institutions – such as the one that exists for the LBA program – may facilitate the exchange of equipment such as the old FACE hardware from the Duke Forest and Oak Ridge FACE experiments.

Considering the intrinsic influence of CO_2 increase on the fluxes of carbon and water, the results achieved with the Amazon-FACE experiment will foster improvements and reduction of uncertainties within the Brazilian Earth System Model – BESM, developed at INPE, Brazil.

Finally, synergies with and stimuli to other ongoing related scientific projects should be encouraged. The Amazon-FACE modeling task for instance can benefit greatly from the science being generated in AmazAlert, SecaFlor (rainfall exclusion experiment), GOAmazon (Terrestrial Ecosystem component) and ATTO (Amazon Tall-Tower Observatory) projects.

12. Description of Initial Research Team

Interim Scientific Steering Committee indicated by **

Alessandro C. Araújo**

Brazilian Agricultural Research Corporation – EMBRAPA, Belém, Brazil.

Micrometeorology of agricultural and forest ecosystems; stable carbon isotopes; plants and microclimate

Marcos S. Buckeridge

Department of Botany, University of São Paulo – USP, São Paulo, Brazil.

Plant physiology, biochemistry and molecular biology of plant growth and development and carbon metabolism.

Erika Buscardo

Large scale Biosphere-Atmosphere Experiment in the Amazon Program - LBA, National Institute for Amazon Research - INPA, Manaus, Brazil.

Soil-plant interactions; ectomycorrhizal fungi; Mediterranean forests; wildfire; maritime pine; molecular analysis.

Lucas Cernusak

School of Marine and Tropical Biology, James Cook University, Cairns, Australia.

Ecophysiology of tropical trees, including photosynthesis, respiration, water use, and responses of these processes to environmental drivers.

Jeffrey Q. Chambers

Department of Geography, University of California, Berkeley, USA.

Tropical forest ecology; forest-climate change interactions; tree ecophysiology; remote sensing.

Evan H. DeLucia

University of Illinois, Urbana-Champaign, USA.

Ecology, plant physiology, global change, carbon and nitrogen cycle, tree growth, environmental instrumentation

Tomas Ferreira Domingues

Department of Biology, University Sao Paulo Ribeirao Preto, Brazil.

Tropical plant ecology; photosynthesis; ecophysiology; forest-savannah transition; stable isotope ecology; functional diversity.

Helber Freitas

Department of Atmospheric Sciences, São Paulo University – USP.

Investigations related to exchanges of carbon, water and energy between surface (soil, natural ecosystems and plantations) and atmosphere; development of autonomus systems for long term environmental monitoring.

Anne Gander

Interamerican Development Bank – IDB, Brasília, Brazil.

Climate change, sustainability, land use and forests.

Luis Gustavo Gonçalves de Gonçalves

Center for Weather Forecast and Climate Studies – CPTEC, National Institute for Space Research – INPE, Cachoeira Paulista, Brazil.

Surface hydrology and hydrometeorology; modeling and data assimilation of the land surface and atmosphere; biosphere-atmosphere interactions.

Iain Hartley**

University of Exeter, Exeter, United Kingdom.

Terrestrial ecosystem responses to global change; manipulative field experiments; belowground and whole ecosystem responses to elevated CO_2.

Niro Higuchi

National Institute for Amazon Research – INPA, Manaus, Brazil.

Forestry; forest conservation; forest dynamics.

Marcel Hoosbeek

Wageningen University, Wageningen, Netherlands.

Impacts of global change on soil C and nutrient dynamics; impacts of elevated CO_2 on soil C stabilisation; upscaling of soil processes for use in large scale climate change models.

Hewlley M. A. Imbuzeiro

Federal University of Viçosa, Viçosa, Brazil.

Micrometeorology; interaction between Atmosphere-Biosphere; energy, water and carbon fluxes; ecosystem modeling; climate change.

Colleen Iversen

Oak Ridge National Laboratory, USA.

Ecosystem ecology; root-soil interface; responses of fine-root production to elevated CO_2 and climate change; belowground carbon and nutrient cycling.

Lars B. Johnsen

Inter-American Development Bank – IDB, Brasília, Brasil.

Infrastructure and environment.

Bart Kruijt**

Alterra, Wageningen University and Research Centre, Netherlands.

Ecophysioloy and micrometeorology; measuring and modeling carbon and water exchange in the soil-vegetation-atmosphere interface; impilcations of climate change on short- and long-term vegetation dynamics worldwide.

David M. Lapola**

Department of Ecology, São Paulo State University – UNESP, Rio Claro, Brazil.

Earth System science; integrated modeling of the Earth System; Amazon forest dieback hypothesis; assessment of impacts and vulnerability to climate change; global vegetation modeling; land-use change.

Keith F. Lewin**

Brookhaven National Laboratory, Brookhaven, USA.

Field research facility design, construction and management; climate change effects on ecosystems

Antonio Manzi

National Institute for Amazon Research – INPA, Manaus, Brazil.

Biosphere-atmosphere interactions; micrometeorology; global vegetation modeling; tropical forest responses to climate and climate change.

Patrick Meir**

University of Edinburgh, UK (permanent) and Australian National University (until Sept 2014).

Forest ecosystem science; plant ecology and environmental physiology; biogeochemical cycling; leaf, stem and soil gas exchange; tropical forest responses to climate and climate change.

Patricia Morellato

Department of Botany, São Paulo State University – UNESP, Rio Claro, Brazil.

Phenology and seasonal changes of natural vegetation; patterns of plant reproduction, pollination and seed dispersal; influence of phylogeny on phenology and methods in phenology research; effects of environmental and climatic changes on plant phenology; applications of new technologies of plant monitoring systems.

Carlos A. Nobre

Ministério de Ciência, Tecnologia e Inovação – MCTI, Brasília, Brazil

Amazonia, Biosphere-atmosphere interactions, natural disasters, climatic change, vegetation modeling

Richard Norby**

Oak Ridge National Laboratory, USA.

Responses of forests to atmospheric and climatic change; interactions between aboveground and belowground responses to elevated CO_2; principal investigator of the ORNL FACE experiment; synthesis of experimental data to inform models.

Andrea F. P. Nunes

Ministério de Ciência, Tecnologia e Inovação – MCTI, Brasília, Brazil.

Ecosystem management.

Jean Ometto**

National institute for Space Research (INPE) / Earth System Science Centre (CCST), Brazil.

Ecosystem functioning - biogeochemical cycling of carbon and nutrients in terrestrial ecosystems; forest dynamic and biomass; biosphere-atmosphere interactions and gas fluxes; ecological impacts of climate change; stable isotopes.

Ryan Pavlick

Jet Propulsion Laboratory, California Institute of Technology, United States of America

Global vegetation modeling, functional diversity and trait ecology, biogeochemical cycling, biosphere-atmosphere feedbacks

Carlos A. N. Quesada**

INPA, Manaus, Brazil.

Linking soil properties to Amazon forest function; analysis of data from fixed plots across the Amazon basin; correlations between soil fertility. forest productivity and carbon storage across Amazonia.

Anja Rammig**

Potsdam Institute for Climate Impact Research (PIK), Germany.

Ecosystem analysis and ecosystem modeling; model-data-integration; plant ecophysiology; tropical forest response to global environmental change.

Celso von Randow

Earth System Science Center - CCST, National Institute for Space Research - INPE, Cachoeira Paulista, Brazil

Land-Atmosphere Interactions; bi-directional interactions between Amazonian forest and climate; Tropical micrometeorology and Atmospheric Boundary-Layer

Susan Trumbore

Max Planck Institute for Biogeochemistry, Jean, Germany.

Isotopes and tracers to study important questions in ecology, soil biogeochemistry and terrestrial C cycling; accelerator mass spectrometry measurements of 14C to determine the impacts of elevated CO_2 on the decomposition old versus young soil C.

Walter Vergara

Climate Change and Sustainability, Inter-American Development Bank – IDB, Washington DC, USA.

Climate change, renewable energy, environmental impacts in Latin America

Anthony Walker

Oak Ridge National Laboratory, Oak Ridge, USA.

Ecosystem models; responses of forests to elevated CO_2; model-data synthesis of the results of FACE experiments.

13. Appendix A
Required Measurements

List of Measurements for Task 1
Aboveground Processes

The science questions divide into two groups: those that strongly benefit from pre-treatment data and those that can be addressed during the experiment. In general, baseline structure, tissue composition and flux data are required before treatment, whilst more focussed gas exchange or larger-scale questions can be addressed in detail in the treatment phase.

Growth/structure.

1. Litterfall, separated into leaves, stems, flowers and fruits (weekly or fortnightly) (Also listed in Task 2)
2. LAI, monthly, coupled with phenology measurements, from above the canopy and on individual branches to address leaf turnover times at different points in the canopy, different species groups. Automated measurements where possible.
3. Stem growth (Automated dendrometers on subset of trees? Manual dendrometers suitable for full census). Subplot growth studies of seedlings/understory. Ensure compatibility with other studies.
4. LIDAR: Regular measures of canopy height, structure

Fluxes.

5. Leaf gas exchange (+fluorescence) to derive: *V*cmax, *J*max, *R*dark, *R*light and temperature responses (and test generality of relationships with biophysical environment, eg leaf traits, incident light, LAI, productivity); diurnal responses of photosynthesis to couple A with g_s; determination of g_m and its relative importance for understanding responses to eCO_2.
6. Sapflow
7. Woody tissue respiration (stem, branch, coarse root) (and link with drivers, as with (5))
8. Tracing efflux of stable isotopes in gas fluxes (e.g. ^{13}C, ^{14}C), intensive during start up of fumigation; also for detailed interpretation of photosynthesis and respiration data (with Task 2, which is likely to focus on soil emissions rather than vegetation).

Tissue traits, composition, contents.

9. coupled nutrient and physical measures with leaf gas exchange (N, P, but also other nutrients; carbohydrate concentrations (simple and complex CHO); LMA, FMA, DMC; leaf thickness, toughness, size).
10. Woody tissue measurements: density, nutrients and cations, CHO; potentially xylem vulnerability
11. Tissue isotopic composition: leaf and woody tissue (and potentially of sap) ^{13}C, ^{15}N, ^{18}O.
12. Leaf water status: LWP, predawn and midday; stem hydraulics in some cases. Measurements made quarterly, and/or during leaf gas exchange measurement campaigns.

Environmental measurements in addition to weather station/FACE data, and near-field remotely-sensed measures of canopy properties and performance.

13. Hyperspectral measures of canopy properties and leaf phenology (leaf traits, function etc; also potential for exploration of change in reflectance properties in

QUESTION	PILOT (P) OR FULL EXPERIMENT (F)?	DATA NEEDS
T1 - A	P, F	5, 9, 11,12, 14, 15
T1 - B	P, F	5, 6, 9, 11, 12, 14, 15
T1 - C	P, F	1, 2, 4, 13
T1 - D	F	5, 6, 12, 15
T1 - E	P, F	3, 10, 14, 15

Table A1. Mapping science questions T1-A to T1-E to data types and experimental phase (pilot or full FACE).

response to eCO_2), and automated phenology (leaf presence/absence).

14. Canopy temperature monitoring (from central tower) by IR, plus possible manual measurements within the canopy on a quarterly basis, coupled with phenology monitoring.

15. Canopy vertical profile monitoring of radiation (PAR, Red/ Far red), leaf and air temperature, weather metrics (VPD)

Access requirements.

Canopy access crane for upper canopy, central scaffolding for mid canopy.

List of Measurements for Task 2 Belowground Processes

Due to the fact that the pilot study does not have true replication, it is essential that below-ground baseline conditions are established, allowing the impacts of elevated CO_2 to be evaluated relative to the control plot. Thus, with the exception of the continuous stable isotope measurements, wherever possible, measurements made prior to fumigation should be as detailed as those undertaken during the pilot experiment.

Field measurements.

1. Partitioning of belowground respiration into the contributions of roots, mycorrhizal fungi, and free-living heterotrophs (continuous monitoring linked to spatial surveys using soil collars with and without root or hyphal exclusion).

2. continuous monitoring of the stable isotope signature of the CO_2 released from the soil surface, with additional measurements of $^{14}CO_2$ to help determine seasonal variations in the sources of the CO_2 (the $^{13}CO_2$ measurements are particularly important during the beginning of the fumigation).

3. Measurements of soil CO_2 profiles to determine the contribution of deep layers to total efflux (continuous measurements linked to diffusion modeling).

4. In situ measurements of rates of root and mycorrhizal hyphal production (continuous monitoring at one site per plot coupled with weekly or fortnightly spatial surveys).

5. continuous logging of soil moisture contents, water movements and soil temperature.

Field sampling for laboratory analysis.

6. Rates of litterfall, separated into leaves, flower and fruits will be measured weekly or fortnightly (also listed in Task 1).

7. In situ litter stocks will also be four times per year.

8. Root samples from in-growth cores will be collected monthly.

9. Litter bags containing leaf and root will also be established to measure rates of decomposition in situ, with samples being collected after 10, 30, 60, 150 and 360 days in the field.

10. Soil samples will be collected twice a year from multiple depths.

11. Soil water samples collected weekly from multiple depths to determine leaching rates.

12. Mineralization rates of N and P will be determined by field incubation method, followed by salt extraction in the laboratory.

Laboratory analyses.

13. Root biomass, productivity, specific root length and mycorrhizal colonisation: in-growth cores will be used for quantifying rates of root production, while the other soil samples will be used to calculate biomass stocks. Roots will be manually extracted following a method that corrects for underestimates in very fine root mass, and specific root lengths calculated using root scanners. Standard staining techniques will be used to quantify rates of mycorrhizal colonisation with numbers of hyphae, arbuscules and vesicles quantified per unit root length.

14. Litter and root chemistry: the concentrations of nutrients (C:N:P:cations) will be determined,

together with measurements of different structural components (lignin, tannins, fiber and cellulose content). These will be linked to decomposition rates calculated from productivity/stock calculations, and the litter bag study.

15. Soil analyses: A complete soil organic matter fractionation scheme will be carried out, and individual fractions analyses for C and N stock. In addition, total and inorganic nutrient concentrations will be quantified for bulk samples, and a complete P fractionation scheme carried out.

16. Stable C and N isotopes will be measured for root, litter and soil samples. Radiocarbon determinations on soils, roots and litter will be carried out at the start and end of the experiment, allowing contributions of new and old C to be quantified.

17. Soil enzymes: We will measure potential activities of a range hydrolytic enzymes involved in the cycles of carbon, nitrogen, and phosphorus (including cellulase, protease and phosphatae) as indicators of biological nutrient demand. In addition, to determine the metabolic activity of intraradical and extraradical mycorrhizal mycelium, acid and alkaline phosphomonoesterase activity will be assessed for.

18. Microbial biomass C, N and P will then be measured on all soil samples and DNA will be extracted and characterization of the total soil and AM fungal communities. DNA will also be extracted from roots for the identification of colonizing AM fungi on particular host species.

Access Requirements

Soil samples will be collected from pits surrounding the experimental plots dug during the construction phase. An area of the experimental plot should be set aside where no sampling or foot traffic is permitted during the experiment. No foot traffic or sampling will be permitted where minirhizotrons are installed. Holes created by soil sampling will be refilled with soil and clearly marked to avoid subsequent sampling at the same location.

QUESTION	DATA NEEDS
T2 - A	4, 13
T2 - B	All 18 measurements
T2 - C	3, 5
T2 - D	1, 2, 4, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16
T2 - E	1, 2, 3, 6, 7, 8, 10, 13, 14, 15, 16, 17, 18

Table A2. Mapping science questions T2-A to T2-F to data types and experimental phase (pilot or full FACE).

14. Appendix B
Detailed Budget

	Pilot ($x10^3$ US$)	Full-exp. ($x10^3$ US$)
Infrastructure	1655	4485
Equipment	2779	7272
Services (excl. CO_2)	1510	4750
CO_2 provision	2690	53800
Personnel+Travel	2550	8190
GRAND TOTAL	**11184**	**78497**

Table B1. Amazon-FACE consolidated budget, according to different cost categories. Pilot experiment (Phases I and II) runs for 3 years and the full long-term experimente (Phase III) runs for 10 years.

	Item	Description	Justification	Unit/PILOT	Unit/FULL	Cost/Unit ($\times 10^3$ US$)	Pilot ($\times 10^3$ US$)	Full-exp. ($\times 10^3$ US$)
Infrastructure	1	Construction crane	Acces to upper canopy (incl. building)	2	6	180	360	1080
	2	FACE plot hardware		2	6	250	500	1500
	3	Scafold tower	Acess to lower canopy and vertical intrumentation	2	6	100	200	600
	4	Instrumentation	Miscellaneous sensors, meteorological stations	2	6	50	100	300
	5	CO_2 vaporizer		2	6-8	60	120	360
	6	Control panel	FACE control system	2	6	7,5	15	45
	7	50t CO2 storage tank	(incl. ambient pressure building vaporizer)	1	2	300	300	600
	8	Power generator (50 kVa)		2	0	30	60	0
						TOTAL	**1655**	**4485**
Services	9	FACE system maintenance		2	6	50/y	100	500
	10	Pressurized CO_2 (1345 Mg/plot/y)		2	8	1000 USD/t	2690	53800
	11	Fuel	Generator consumption	3×10^4L	18×10^4	0.85 USD/L	31	155
	12	Crane operator	See item 1	2	6	40	80	240
	13	ZF2 Road improvement	For CO_2 trucks to drive in	1	0	210	210	0
	14	ZF2 Road maintenance	For CO_2 trucks to drive in	3	6	20/y	60	200
						TOTAL	**3171**	**54895**
Personnel	15	Engineer	On-site system monitoring	1	1	35	105	350
	16	Technician	On-site system monitoring	2	2	20	120	400
	17	Project officer	On-site project management	1	1	50	150	500
						TOTAL	**375**	**1250**
Travel	18	Travel for collaboration	Technical and scientific management	6	30	8	48	240
						TOTAL	**48**	**240**
						GRAND TOTAL	**5249**	**60870**

Table B2. Amazon-FACE basic infrastructure, carbon dioxide, and other general expenses. Pilot experiment (Phases I and II) runs for 3 years and the full long-term experiment (Phase III) runs for 10 years. Personnel units are based on an anual demand.

	Item	Description	Justification	Measurement reference (Appendix A)	Cost/Unit (x10^3 US$)	Units/PILOT	Units/ FULL	Cost Pilot (x10^3 US$)	Cost Full (x10^3 US$)
Equipment	1	Li6400	Leaf gas exchange	5	84,5	4	8	338	676
	2	Walz leaf temp cham	Leaf gas exchange/T	5	49,4	2	4	99	198
	3	Walz miniPAM	Leaf gas exchange	5	33,8	2	4	68	135
	4	Heating elements, pc	Temp X CO2 effects	5	39	2	8	78	312
	5	Picarro CRDS	Isotope monitoring	9	162,5	1	1	163	163
	6	Stem resp IRGA + au	Stem resp	7	65	2	4	130	260
	7	Dendrometers	Tree growth	1,3	0,65	60	240	39	156
	8	Li2200 (pair), hemi c	Canopy leaf area	2	65	1	2	65	130
	9	IR sensors + thermal	Canopy temperature	15	84,5	0	0	169	676
	10	Sap flux sensor array	Water use metrics	6	104	2	8	208	416
	11	Pressure chambers,	Hydraulic traits	13	65	2	4	130	260
	12	Microscope	Cell structure/functio	13	45,5	2	4	91	182
	13	Leaf and woody tissu	Leaf/wood traits	10,11,12,13	91	2	4	182	728
	14	Camera+spectromet	Phenology +hypersp	14		2	8	101	452
							TOTAL	**1861**	**4744**
Services	15	Repair/spares	Repair/spares		97,5	0	0	293	975
	16	Power supply kit	Specific to Task1 equipment		32,5	1	2	33	65
	17	Shipping (repair/anal	Shipping (repair/analysis)		32,5	0	0	98	325
	18	Equipment service	Equipment service		6,5	4	8	78	520
		Ground LIDAR, available from JACARANI		4	--	--	--	--	--
							TOTAL	**502**	**1885**
Personnel	19	Senior post doc	Integrating/co-ordina	All	35	1		105	315
	20	Post doc	Litterfall, dendromete	6,10,11,12,13	35	1		105	315
	21	PhD	Litterfall, dendromete	6,10,11,12,14	20	1		60	180
	22	Post doc	Leaf gas exchange, i	5,9,10,12	35	1		105	315
	23	PhD	Leaf gas exchange, i	5,9,10,13	20	1		60	180
	24	Post doc	Stem gas exchange,	7,10,11,12	35	1		105	315
	25	Post doc	Sap flow, leaf and ste	6,10,11,12,13	35	1		105	315
	26	PhD	Sap flow, leaf and ste	6,10,11,12,14	**20**	1		60	180
	27	Post doc	Remote sensing of p	7,9,13	35	1		105	315
	28	PhD	Remote sensing of p	7,9,14	20	1		60	180
	29	Technician	Senior science techn	Equip./Data	20	1		60	180
							TOTAL	**930**	**2790**
Travel	30	Travel for collaborati	Site visits and coordination workshops		8	20	90	135	450
							TOTAL	**135**	**450**
							GRAND TOTAL	**3428**	**9869**

Table B3. Detailed budget for Amazon-FACE science Task 1 - Aboveground Processes. Pilot experiment (Phases I and II) runs for 3 years and the full long-term experimente (Phase III) runs for 10 years. Personnel units are based on an anual demand.

	Item	Description	Justification	Measurement reference (Appendix A)	Cost/Unit ($x10^3$ US$)	Unit/PILOT	Unit/FULL	Cost Pilot ($x10^3$ US$)	Cost Full ($x10^3$ US$)
Equipment	1	LiCor 8100	Soil CO_2 efflux	1	200	2	6	400	1200
	2	Picarro system	Continuous isotopic monitoring	2	150	1	3	150	450
	3	Vaisalla probes	CO_2 profiling probes	3	1	40	120	40	120
	4	Automated Minirhizotron	Minirhizotron systems	4	80	2	6	160	480
	5	Manual Minirhizotron	Root growth	4	30	1	1	30	30
	6	Tensiometers and moisture probes	Tensiometers and moisture probes	5	0,5	48	144	24	72
	7	Soil temperature probes and loggers	Soil temperature probes and loggers	5	0,2	20	60	4	12
	8	Staatliche Porzellan-Manufaktur	Suction-cup lysimeters	11	1	24	72	48	72
	9		Materials for ingrowth cores, litter traps, litter bags	6,7,8,9,13	10	1	4	10	40
						TOTAL		**866**	**2476**
Services	10	Litter, soil and water analysis	Nutrient and carbon concentration and isotopes	out/16				100	400
	11	Micorbial community structure	Impacts on micorbial function	13,17,18				300	1000
	12	Repair/spares	Repair/replacement of other equipment					50	150
	13	Shipping	Shipping of materials for repair or additional analysis		40			40	100
	14	Repair/service	Maintenance of gas exchange equip		4			32	100
						TOTAL		**522**	**1750**
Personnel	15	Post-doc fellowship	Soil CO2 flux, gaseous isotopes and CO2 profiles	1,2,3	35	1	1	105	350
	16	Post-doc fellowship	Mini-rhizotrons and root in-growth core	4,8	35	1	1	105	350
	17	Technian	Soil water movements and nutrient leaching	5,11,12	20	2	2	120	400
	18	Technician	Litter, root and soil chemistry	10, 13-16	20	2	2	120	400
	19	Post-doc fellowship	Soil microbial community structure and enzyme activity	17,18	35	1	1	105	350
	20	PhD student	Litter dynamics	6,7,9	20	1	1	60	200
						TOTAL		**615**	**2050**
Travel	21	Travel for collaborators	Site visits and coordination workshops		8	15	60	120	480
							TOTAL	**120**	**480**
							GRAND TOTAL	**2123**	**6756**

Table B4. Detailed budget for Amazon-FACE science Task 2 - Belowground Processes. Pilot experiment (Phases I and II) runs for 3 years and the full long-term experiment (Phase III) runs for 10 years. Personnel units are based on an anual demand.

	Item	Description	Justification	Cost/Unit ($x10^3$ US$)	Unit/PILOT	Unit/FULL	Cost Pilot ($x10^3$ US$)	Cost Full ($x10^3$ US$)
Equipment	1	High performance workstation	Model development and application	2	8	8	32	32
						TOTAL	**32**	**32**
Services	2	Repair/spares	Computer repair				5	20
						TOTAL	**5**	**20**
Personnel	3	Post-doc fellowship	Integrating/co-ordinating researcher	35	2		210	700
	4	PhD fellowship	Model development and application	20	4		240	800
						TOTAL	**450**	**1500**
Travel	5	Travel for collaborators	Coordination workshops	8	10	60	80	480
						TOTAL	**80**	**480**
						GRAND TOTAL	**567**	**2032**

Table B5. Detailed budget for Amazon-FACE science Task 3 - Ecosystem Modelling. Pilot experiment (Phases I and II) runs for 3 years and the full long-term experimente (Phase III) runs for 10 years. Personnel units are based on an anual demand.

	Item	Description	Justification	Cost/Unit ($x10^3$ US$)	Unit/PILOT	Unit/FULL	Cost Pilot ($x10^3$ US$)	Cost Full ($x10^3$ US$)
Equipment	1	Central data server	Data storage	20	1	1	20	20
						TOTAL	**20**	**20**
Personnel	2	Technician	Data storage and management, data integratio Website administration Data webportal management	25	1	1	75	250
	3	Post-doc fellowship	Integrating/co-ordinating researcher	35	1	1	105	350
						TOTAL	**180**	**600**
Travel	4	Organisation of workshops		50	3	10	150	500
						TOTAL	**150**	**500**
						GRAND TOTAL	**350**	**1120**

Table B6. Detailed budget for Amazon-FACE science Task 4 - Data Integration and Synthesis. Pilot experiment (Phases I and II) runs for 3 years and the full long-term experimente (Phase III) runs for 10 years. Personnel units are based on an anual demand.

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