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Geographic diversification of carbon risk—A methodology for assessing carbon investments using eddy correlation measurements

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Abstract

In the context of the international market for greenhouse gas emissions, I examine applications of portfolio theory for investment decisions regarding biological carbon sequestration projects. Using ecosystem-scale eddy correlation carbon flux measurements, I show how to determine how much financial risk of carbon is diversifiable. This method allows a quantitative assessment of the potential for geographical diversification of carbon sink investments. In a case study of six ecosystems in the temperate Northern hemisphere, a significant benefit from diversification is demonstrated even among sites that seem to have broadly similar characteristics. This benefit derives in part from differences in ecosystem response to varying weather conditions and differences in ecosystem type, both of which affect the sites' covariances. In providing a quantitative common language for scientific and corporate uncertainties, the concept of carbon financial risk provides an opportunity for expanding communication between these elements essential to successful climate policy.
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1. Introduction

Anthropogenic climate change challenges society to balance long-term, uncertain, and potentially serious risks against more immediate concerns. Success in this task depends on several kinds of scientific inputs such as estimates of climate sensitivity and potential impacts, projections of future variability and change, and, importantly, estimates of the uncertainty and risks posed by such changes (Sarewitz et al., 2003, Mastrandrea and Schneider, 2004, Patt and Schrag, 2003). Parallel to this interest in the scientific communication of geophysical risk has been a growing interest in the connections between climate change and financial risks. Building on conceptions of risk within the scientific literature that involve a probability and a geophysical consequence, financial risks further denote the chance for a financial gain or loss. At their best, these financial interpretations of risk could allow firms to incorporate scientific understanding of climate risks into their existing decision processes.

Climate-related financial risks come in three distinct forms (Table 1). First, firms that profit from activities or products that create climate hazards bear some associated regulatory, economic, and possibly legal risks; whether oil producers will ever be legally liable for endangerment is unclear, but a carbon-constrained economy would necessarily dent their core market (Cogan, 2004). Second, changes in the physical climate can incur extra risks for firms, such as insurers, whose profits depend on stable climate services (Intergovernmental Panel on Climate Change, 2001, Chapter 8; Michaels et al., 1997, Murnane, 2004). Finally, firms that intend to profit from the expanding markets for greenhouse gas emissions reductions incur a number of risks that depend on the regulatory environment and on the performance of their individual investments. This paper discusses the third, investment-related risk: specifically, it outlines a method for appraising a specific kind of risk—the risk inherent in a portfolio of biological sequestration projects.

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Table 1
Risk taxonomy for projects that generate carbon credits, drawing on Streck (2004a) and Laurikka and Springer (2003)

Term	Description
Project risk	Project failure
Quantity	Project does not generate anticipated credits
Delivery	Project developer does not transfer credits
Political	Problems with implementation
Cost	Abatement costs higher than expected
Price risk	Carbon price fluctuates beyond expectations
Policy risk	Rules for credits change
Other "traditional" risks	Currency, country, etc.

Risks listed are not necessarily independent; for example, because the demand for carbon credits is a direct function of policy decisions, the price and policy risks are linked. The case study presented in this paper addresses quantity risk.

One of the leading policy proposals to control greenhouse gas emissions is emissions trading. In addition to the Kyoto Protocol, which will govern international trading among countries in the EU, Japan, Canada, and many developing countries, several significant GHG trading systems parallel to Kyoto have emerged. In 2002, the United Kingdom introduced the first legally binding GHG trading system that covered a substantial part of a country's economy (Bourn et al., 2004, Radov and Klevnäs, 2004), followed in 2005 by the European Union's community-wide emissions trading system (European Parliament, 2003, Pew Center on Global Climate Change, 2005). The entry-into-force of the Kyoto Protocol has further solidified expectations for the long-term viability of an international carbon market (Sandor et al., 2002, Hultman, 2004, Lecocq and Capoor, 2005).

In this context, investors in projects that reduce or mitigate carbon emissions will be interested in maximizing their financial returns for a given level of risk. Each project will itself come with associated uncertainties that could affect its ability to deliver the anticipated number of credits and thus its profitability (Streck, 2004b). Moreover, buyers of carbon credits will want assurances that their purchases will be legally valid (Haites and Missfeldt, 2001). Managing these carbon-related financial risks presents some familiar challenges as well as some new ones.

Financial theories on risk and diversification can improve carbon investment techniques (Laurikka and Springer, 2003). Fundamentally, financial risks can be managed either by pooling them in a portfolio or transferring them through markets (Chichilnisky and Heal, 1998). Evaluating carbon risk quantitatively poses many challenges, though the difficulty in developing risk management strategies stems primarily from two factors. First, until the price data are readily transparent and available, the ability to use even existing markets for analysis will be limited. Second, as in any new industry, the technical aspects of carbon reductions themselves require a high degree of expertise. Both mitigation and sequestration projects are linked to engineering or scientific knowledge that has been historically outside the purview of standard financial management knowledge. Data on proprietary carbon reduction projects and carbon credit transactions have been similarly elusive for analysts, often forcing them to use model data to draw preliminary conclusions about portfolio construction.

One unexplored window on assessing carbon risk is described in this paper. It focuses on biological sequestration projects which currently provide some of the lowest-cost carbon credits (Richards and Stokes, 2004, Scott et al., 2004, Plantinga and Mauldin, 2001). Yet many questions remain about the robustness of such sequestration programs. One of the most uncertain aspects of GHG reduction projects is the risk of impermanence in carbon forestry projects (Breshears and Allen, 2002). Subak (2003) reviews three commonly discussed approaches to address this potential impermanence of sequestered carbon: carbon insurance, land reserves, and the use of expiring credits. Carbon insurance, which would transfer the risk of underperformance to a third party, is an underdeveloped product but one with analogues in the market for insuring forests for pulp and wood products. Land reserves set a fraction of land that must be set aside in case of underperformance. The Kyoto agreements detail an expiring credits system with "temporary" and "long-term" categories of credits available under the Clean Development Mechanism (Chen, 2003). Another option is diversification. An understudied but essential element of all these approaches is knowledge of how to reduce risk by pooling sequestration projects.

This paper presents an option for understanding the level of diversification necessary for constructing a portfolio of biological sequestration projects that reduces delivery risk to the investor. Because of past data collection campaigns, high-resolution data on ecosystem carbon fluxes have been collected and published. While not a direct measurement of actual carbon sequestration projects, these data can be used in a way similar to that of an asset price in traditional financial analysis. In this case, though, the data represent quantities and not prices, so they are removed by one step of integration from an asset value. Nevertheless, these data allow an estimate of diversifiability of carbon risk in forestry projects. This information then allows an estimate of non-diversifiable carbon quantity risk and of possible routes to hedge this risk.

2. Managing carbon risk through diversification

Standard financial portfolio theory allows investors to assemble assets to yield a higher return for lower risk (Markowitz, 1952). This methodology allows an investor to compare the financial risks of different opportunities and to determine the most useful additions to an existing set of investments. "Risk" is assigned a mathematical definition related to its historical price volatility: the more the price has fluctuated, the more likely one is to lose (or make)

money in the future. Mathematically, this volatility is denoted as the variance of returns on the asset where the returns are defined as the relative change of the price of an asset from one period to the next. This risk, moreover, encompasses a diversifiable component (which can be eliminated by holding other assets) and an undiversifiable component.

The simplest way for a project developer to package carbon credits is to sell verified credits on the spot market once they have been produced. While this approach minimizes risk to the buyers, it requires the project developer to provide capital up front. Given that financing is often the primary barrier to implementing emission reduction projects (Bishop, 2004), this simple structure might unnecessarily limit their number and types. Alternately, deliveries of carbon can be treated as cash flows that can be packaged or securitized in a variety of ways already familiar to financial managers (See, 2001). Investors should be able to determine whether to hold credits for the future or sell them into the spot market and to understand the number of projects needed to insure investment-grade carbon assets.

Following Springer's notation (Springer, 2003), a project's carbon profit over a single time interval t is a function of the price of carbon P_c, the carbon emissions reduction Q_c, and the cost of abatement C:

$$\begin{aligned} profit &= (\text{carbon revenues}) - (\text{abatement costs}), \\ &= P_c Q_c - C. \end{aligned} \tag{1}$$

Over time, the expected profits at $t = (t_1, t_2, \ldots, t_n)$ would be discounted at the appropriate rate. For a carbon credit-generating project, Q_c is the difference between the final level of emissions E_f and the hypothetical or baseline level of emissions E_i (Springer, 2002):

$$\Pi_c = P_c(E_f - E_i) - C. \tag{2}$$

This formulation highlights three specific risks to the investing firm. First, the expected emissions reduction Q_c might not materialize or be delivered, either because of ecological factors or because of more familiar managerial mistakes or political instability. This risk has been called delivery risk, when the focus is on the transfer of credits or quantity risk with a focus on the actual generation of sufficient credits. Second, P might fluctuate beyond the expected range, potentially leading to losses. While this price risk is likely to be a dominant term as carbon markets mature, financial markets for other commodities have developed hedging techniques to address this type of uncertainty; even in the nascent European carbon market, trades are routinely settled in advance, allowing prices to be locked in by both buyer and seller.

Third, the abatement costs C of the project might prove to be higher than expected. Furthermore, implicit in the calculation of Q_c is the assumption that the data to establish the baseline and final emissions levels are of high quality and accurate (Gustavsson et al., 2000); if not, sales could be challenged legally (Karmali et al., 2000; Niles and Schwarze, 2001; Brown, 2002).

Aside from the country, currency, and other familiar investment risks, forestry projects contain some additional risks because they depend on an asset (carbon storage) that has no inherent economic value outside the legal context. For example, because of their additional uncertainty in the quantity and rates of future carbon sequestration in forestation projects, they carry an additional absorption risk that is uncontrollable. Unlike mitigation projects in which, for example, a broken wind turbine can be fixed, forestry projects' carbon offsets depend on the ecosystem's response as well as human management. In this sense, these projects carry an additional risk that poses challenges to investors, as they depend on local climatic and ecosystem characteristics.

One obvious, commonly proposed, but thinly studied tool to address these project risks is the diversification of carbon investments in a portfolio or carbon fund. Just as with a traditional financial asset with uncertain returns, the firm's risk of carbon returns can be reduced substantially by holding more than one carbon-generating asset. In addition, carbon revenues can be diversified over time: if a project has annual variations in output but is only verified over 5-year cumulative periods, the annual variations become much less important.

The existing large investment pools of carbon assets have mitigated carbon risk by diversifying their holdings. Foremost among these pools have been state-sponsored funds and the World Bank's three multilateral carbon finance funds (Lecocq and Capoor, 2005)—the Prototype Carbon Fund, BioCarbon Fund, and Community Development Carbon Fund (Prototype Carbon Fund, 2002, 2004; Community Development Carbon Fund, 2004). These pools seek to acquire carbon credits from projects that are diversified geographically and by type, and are so-called "pure carbon" funds that are interested only in the carbon-generating assets of these projects.

Though many of these investment pools are diversified across multiple projects and are thus at least moderately diversified in terms of their carbon risks, the diversification has been driven by institutional factors (Lecocq, 2003). First, the number of politically and financially acceptable projects has been low during the initial phases of market development. Second, even if the funds will have a more complete set of carbon-generating assets to choose from, the methodology for allocating systematically among carbon assets systematically is still relatively underdeveloped. Thus, while these funds' diversification may succeed in decreasing risks, it almost certainly does not provide the least risk for a given expected return.

Therefore, a more quantitative and systematic methodology for assessing risks is needed. To date, few quantitative studies of carbon diversification have been published, primarily because of the difficulties in obtaining consistent data. Laurikka and Springer (2003) present a concise theoretical review and calculate diversification

benefits based on voluntary reporting across different types of projects (e.g. sequestration, methane capture, or renewable energy). Springer's studies of international diversification demonstrate some risk reduction benefits, although many of the countries yield very little diversification benefit compared to investments in the USA and China (Springer, 2002, 2003).

3. Reducing carbon quantity risk with geographical diversification

As the number of projects available for investment increases, so too does the value of understanding the individual contributions to diversification. This study posits a portfolio of biological sequestration projects in order to refine our understanding of how to assess these benefits quantitatively. One problem, for example, is that in some ecosystems, particularly those that are subject to drought stress, fluctuations in precipitation and temperature can significantly affect annual carbon sequestration rates (Law et al., 2000; Goldstein et al., 2000). These ecological characteristics raise several questions for project investors, such as which ecosystem type and weather regimes are most volatile; how diversifying across ecosystems and climates can reduce investment risk; whether the remaining, non-diversifiable risk might be hedged using existing financial instruments; and whether new financial products designed specifically for carbon projects might be useful.

The risk of a forestry project's carbon absorption depends on the averaging time and on environmental factors that might influence carbon uptake on intermediate time scales.

Because of interannual variations in carbon sequestration, individual forest plots will generate a variable carbon income stream. The present value of this income depends directly on the amount of carbon absorbed in each future period, the price of carbon in each period, and on the opportunity cost of capital r for the project. Natural resource economists have developed detailed models of optimal harvesting for individual stands which are functions of the ecosystem growth curve, the discount rate, and even the risk of fire and price fluctuations (Parks et al., 1997; Hanley et al., 1997, pp. 340–346). These models are useful in determining the rotation schedule for a single plot but do not provide enough information on *which* forests to hold for a firm interested in reducing risk to carbon credits (van Kooten et al., 1995). The economic return characteristics of one plot do not adequately capture any meaningful data on risks to a firm that invests in credits from multiple plots.

Consistent, quantitative data are essential to assess the potential carbon risk and return characteristics of different ecosystem types. Several methods exist for estimating ecosystem carbon exchange (Brown, 2002; Intergovernmental Panel on Climate Change, 2000, pp. 90–102). Ecological field techniques rely on periodic measurements of biomass, detritus, tree dimensions, and other variables that can then be statistically scaled to represent the full ecosystem. Burrows et al. (2003), for example, applied these techniques to assess the spatial variability of ecosystem production. The micrometeorological technique of eddy covariance (Baldocchi and Myers, 1988, Baldocchi, 1997, Moncrieff et al., 1996, Baldocchi, 2003) provides an alternative approach. Routinely used to measure ecosystem CO_2 and water vapor (latent heat) fluxes, as well as terms important to the local energy budget such as sensible heat and momentum fluxes, this technique can give a measurement of the flux of a trace gas into an ecosystem. Eddy covariance works by correlating ~10 Hz measurements of a trace gas concentration (such as CO_2) with ~10 Hz measurements of wind velocity; if higher concentrations are measured with an upward wind velocity, the procedure can calculate a net flux out of the ecosystem. When measuring carbon, eddy covariance thus provides a measure of net ecosystem exchange (NEE), equivalent to the algebraic sum of photosynthetic fixation P of carbon and respiration R_e from all organisms in the ecosystem. Note that P is equivalent to gross primary productivity (GPP), and that here a positive flux is defined as out of the canopy. Because they capture entire ecosystem fluxes rather than simply carbon storage in trees, analyses based on NEE data may yield slightly different results than analyses based on ecological field techniques (Ehman et al., 2002) or on harvestable woody biomass.

While this method is not sufficient for estimating fluxes over large landscape or continental scales (Körner, 2003; Dolman et al., 2003), comparing the exchange characteristics across several field sites can allow for a more detailed understanding of the relative behaviors of different ecosystem types. The Fluxnet consortium (Baldocchi et al., 2001) has become the primary venue for consolidating and harmonizing much of the available eddy covariance data. Gaps in datasets are filled according to four alternate methods and are made available through Fluxnet for research (Falge et al., 2001a,b). In analyzing the diversification opportunities for carbon sequestration, one would prefer data from regions most likely to host forestry or agricultural carbon absorption projects—namely, central and South America, Southeast Asia, and sub-Saharan Africa. Unfortunately, because eddy correlation equipment requires large investments and highly skilled labor, these regions have until recently had limited coverage in these areas. Thus, this case study is best viewed as a development of assessment methodology rather than as a prediction of how investments should or will be implemented.

Quantitative portfolio methods require consistent datasets over significant time periods. Eddy correlation measurements contain enough detail to satisfy the first requirement; however, the second element—the timescale—depends on the application. Carbon projects will not be assessed more frequently than annually; not only would the cost of such frequent monitoring and verification be prohibitively expensive, but also the ecosystem carbon

variance over sub-annual timescales is for most ecosystems far larger than the average annual sequestration rate.

At the time of this analysis, only six sites in the published dataset had three or more years of simultaneous, continuous data available through Fluxnet. These six sites therefore provide the data for this analysis, which covers the 3 years for which data are available for all of the sites. The selected sites are divided equally between North America and Europe and are detailed in Fig. 1. All sites are in the northern hemisphere. Five are forests, and one (Site 1, Bondville, IL, USA) is a cropland/grassland site that exhibits characteristics similar to potential agricultural sequestration projects. Sites 2 (Hesse Forest, France), 3 (Harvard Forest, MA, USA), and 4 (Soroe, Denmark) are different types of deciduous broadleaf forests (Granier et al., 2000; Barford et al., 2001; Pilegaard et al., 2001, 2003). Site 5 (Tharandt, Germany) is a temperate evergreen coniferous forest (Fruhauf et al., 1999, Feigenwinter et al., 2004), and Site 6 (WLEF Tower, WI, USA) covers a larger area that is at the ecotone between boreal coniferous forest and deciduous broadleaf forest (Davis et al., 2003) (Table 2).

Other than the seasonal oscillation, patterns of carbon absorption vary in timing and magnitude across the six sites. Fig. 2 plots the NEE vectors for each site for the 3 years of this study (1997–1999). The instantaneous flux points in Fig. 2 can be summed to give a cumulative uptake number for each day relative to $t = 0$; these cumulative uptake plots are shown in Fig. 3. The cumulative uptake figures give a better picture of the relative magnitude of the integrated change in carbon storage at each site. For example, the coniferous evergreen site at Tharandt (Site 5) shows the most cumulative sequestration over the study period. Sites 2 and 4 exhibited some similarities in timing although the magnitudes of uptake varied slightly (Granier et al., 2002). Site 6 experienced a small decrease in carbon over the measurement period.

With the corrected and filled NEE vectors, one can investigate the characteristics of a hypothetical investment across a sample of the measured forests. Four diversification analyses were done for this portfolio of six forests. Two calculations, hereafter referred to as Portfolios P_1 and P_2, were performed using the seasonally adjusted NEE vectors described below. Portfolio weights in calculation P_1

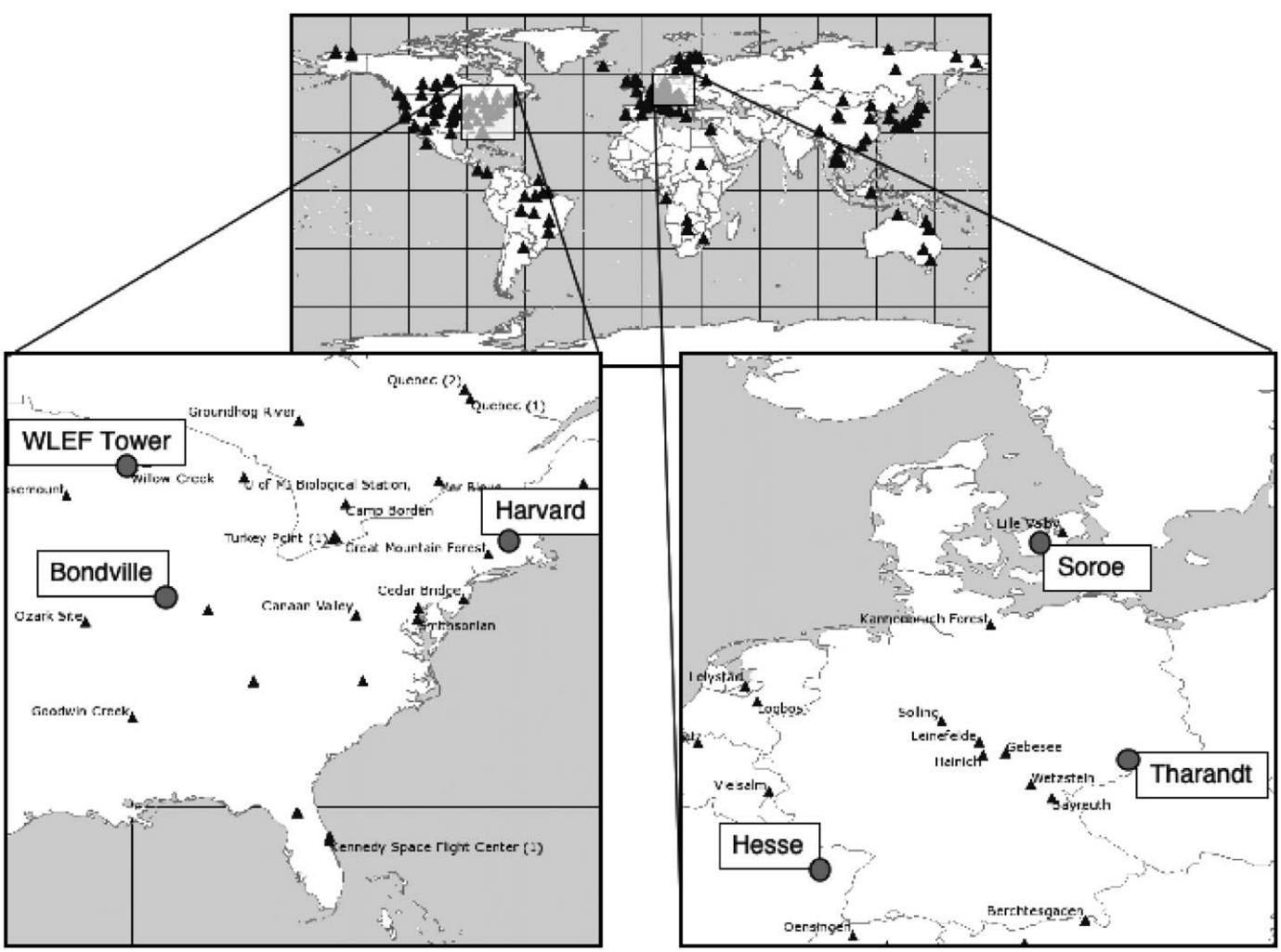

Fig. 1. FLUXNET sites used in this study are marked by gray circles. Modified from Fluxnet Consortium (2005).

allow only positive or zero values and weights in calculation P_2 allow positive, zero, or negative values. Calculation P_2 is therefore equivalent to the situation in developed, liquid markets in which actors can sell assets that they do not own, a process known as short-selling or simply shorting. In the context of carbon, a short sale

Table 2
Characteristics of selected sites; temperatures in degrees C and rainfall in cm (modified from Fluxnet Consortium, 2005)

Site	Name	Location	Biome	Climate	Ave T	Ave P	Dominant Spp.
1	Bondville	IL, USA	Gropland, no-till	Temperate	11.2	954	Z. mays, G. max
2	Hesse	France	Decid, broadleaf	Temperate	8.5–9.8	820	F. sylvatica, T. cordata, Q. petraea, B. alba
3	Harvard	MA, USA	Decid, broadleaf	Temperate	7.8	625–437	Q. rubra, A. rubrum, B. lenta, P. strobes
4	Soroe	Denmark	Decid, broadleaf	Temperate	~7	441–700	F. sylvatica
5	Tharandt	Germany	Evergreen coniferous	Temperate	7.5	824	P. abies
6	WLEF Tower	WI, USA	Boreal/decid broadleaf	Boreal/temperate	4.5–6.6	810–825	Betula, Fagus, Acer, Quercus, P. strobes, P. resinosa

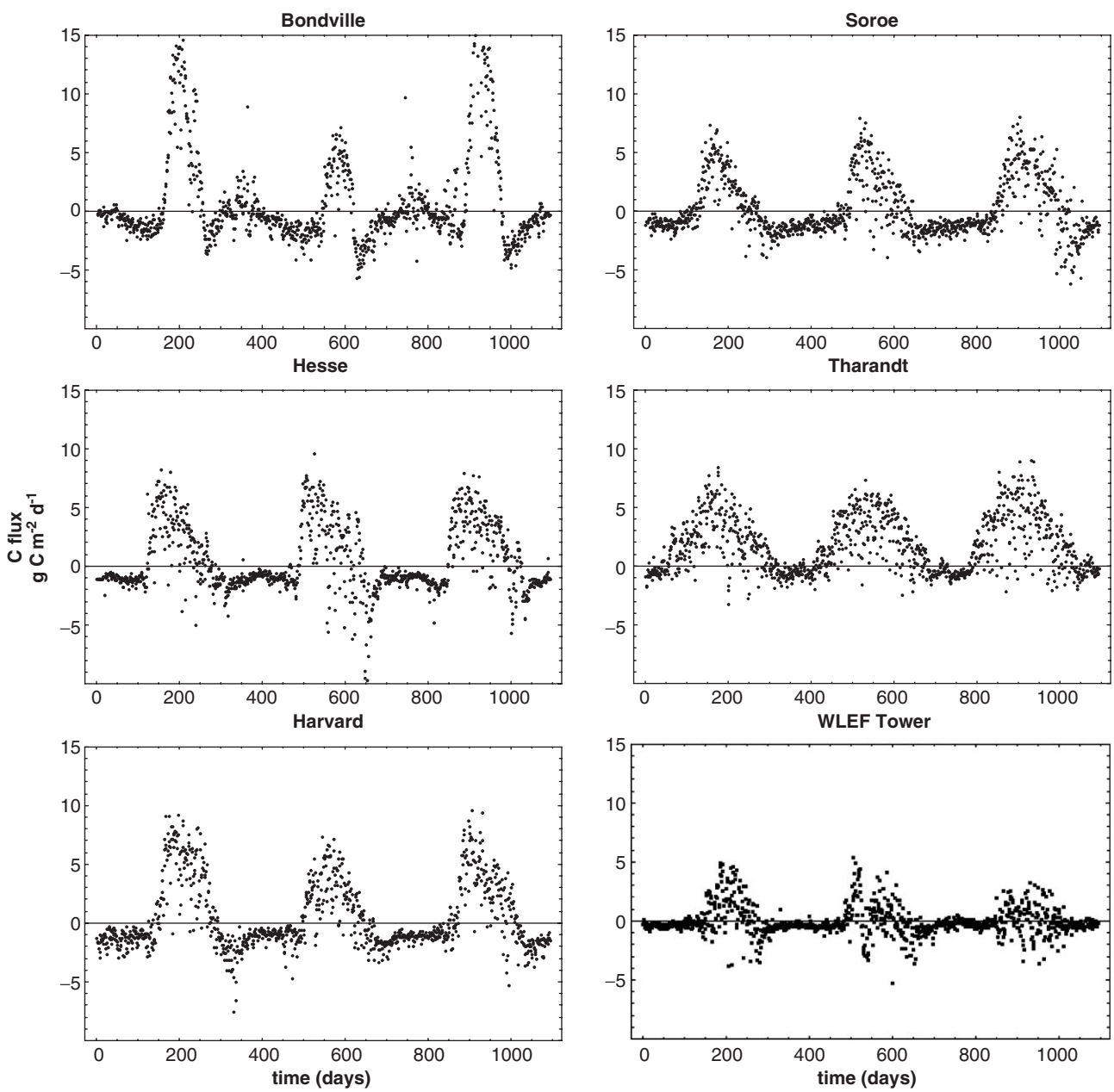

Fig. 2. Carbon flux (NEE) vectors for selected sites, 1997–1999 (Day 1 = 1 January 1997) Units are g (C) $m^{-2} d^{-1}$.

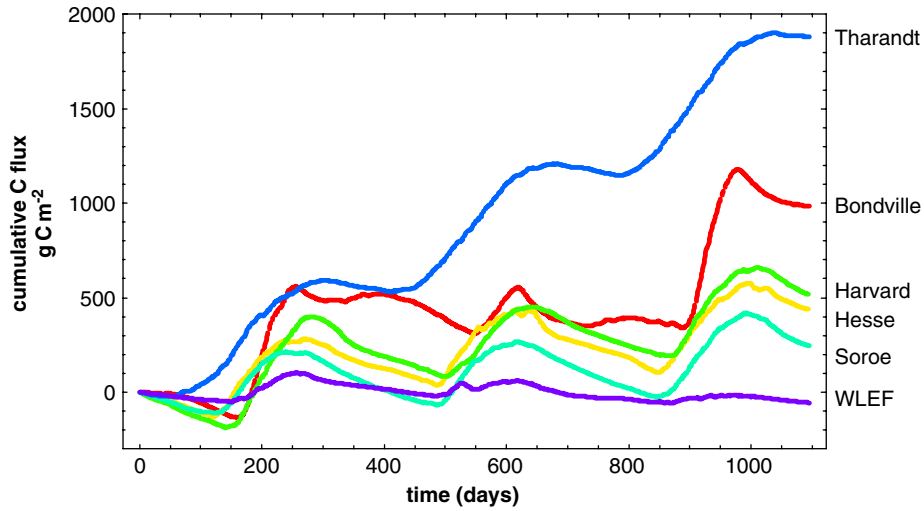

Fig. 3. Cumulative NEE for selected sites, 1997–1999 (Day 1 = 1 January 1997). Units are g (C) m^{-2}.

would be equivalent to an actor's selling a carbon credit from when that actor did not have the credit in possession yet. If the market price for the credit were to fall, the actor could buy it more cheaply later.

Because of seasonal variations in NEE (with photosynthetic uptake dominant in summer and respiration dominant during winter), most of the carbon stock fluctuations are expected. These fluctuations therefore do not represent true risks as they are predictable and would not matter over multiple years. Fig. 4 shows cumulative uptake curves for the six sites; while these data are the same as plotted in Fig. 3, here the site data from each of the 3 years are plotted on the same 365-day axis to illustrate the differences in uptake for different years. This analysis focuses only on these unpredictable risks that reflect deviations from expected seasonal NEE patterns resulting from climate variability. I define these expected patterns simply as the average pattern over the 3 years, as shown by the heavy curve Fig. 4.

More formally, I define the measured NEE vector as the sum of the average NEE (written as *NEE*) plus a residual or deviation NEE′. The true variability in the site, then, is contained in the newly defined NEE′ vector. Using these residual vectors, we can eliminate the large seasonal signal for each site and focus on the variations in uptake around that signal. Fig. 5 shows the resulting residual (NEE′) vectors (plotted as cumulative sums) for each of the six sites. While there is some similarity across several sites, the patterns for the residual are much less correlated and the true variabilities of each site are much clearer. Note that the residuals are large for Site 1 (Bondville) and rather small for Site 6 (WLEF Tower).

Assembling these residual, non-seasonal NEE′ vectors in different linear combinations results in portfolios that each have a different risk and expected return. The variance σ_p^2 of the combination or portfolio is the sum of the covariances of each vector with all vectors in the group:

$$\sigma_p^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} X_i\sigma_{ij} = X_1\sigma_{11} + X_1\sigma_{12} + \cdots X_2\sigma_{11} + X_2\sigma_{12} + \cdots + X_n\sigma_r. \quad (3)$$

With large data sets, we can define the covariance matrix M_{cov} as

$$M_{\mathrm{cov}} \equiv \begin{pmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1n} \\ \sigma_{21} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \sigma_{n1} & \cdots & \cdots & \sigma_{nn} \end{pmatrix} \quad (4)$$

and the vector **x** of portfolio fractions X_i as

$$\vec{X} \equiv X_i|_{i=1}^{n} = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{pmatrix}. \quad (5)$$

Note that M_{cov} contains both variances and covariances. The portfolio variance is then

$$\sigma_p^2 = M_{\mathrm{cov}} \cdot \vec{X} \cdot \vec{X}. \quad (6)$$

By varying the portfolio fractions x, one can optimize the portfolio[1] to produce a minimum variance for a given level of expected return. Iterating for different levels of expected return traces out optimal portfolio diversification curves. Note that these curves represent combinations of assets that provide the minimum risk for a given expected return

[1]This optimization can be carried out using specific tools for financial portfolio analysis or with more general optimization algorithms. This study used Excel Solver and Mathematica Financial Analysis Toolpack.

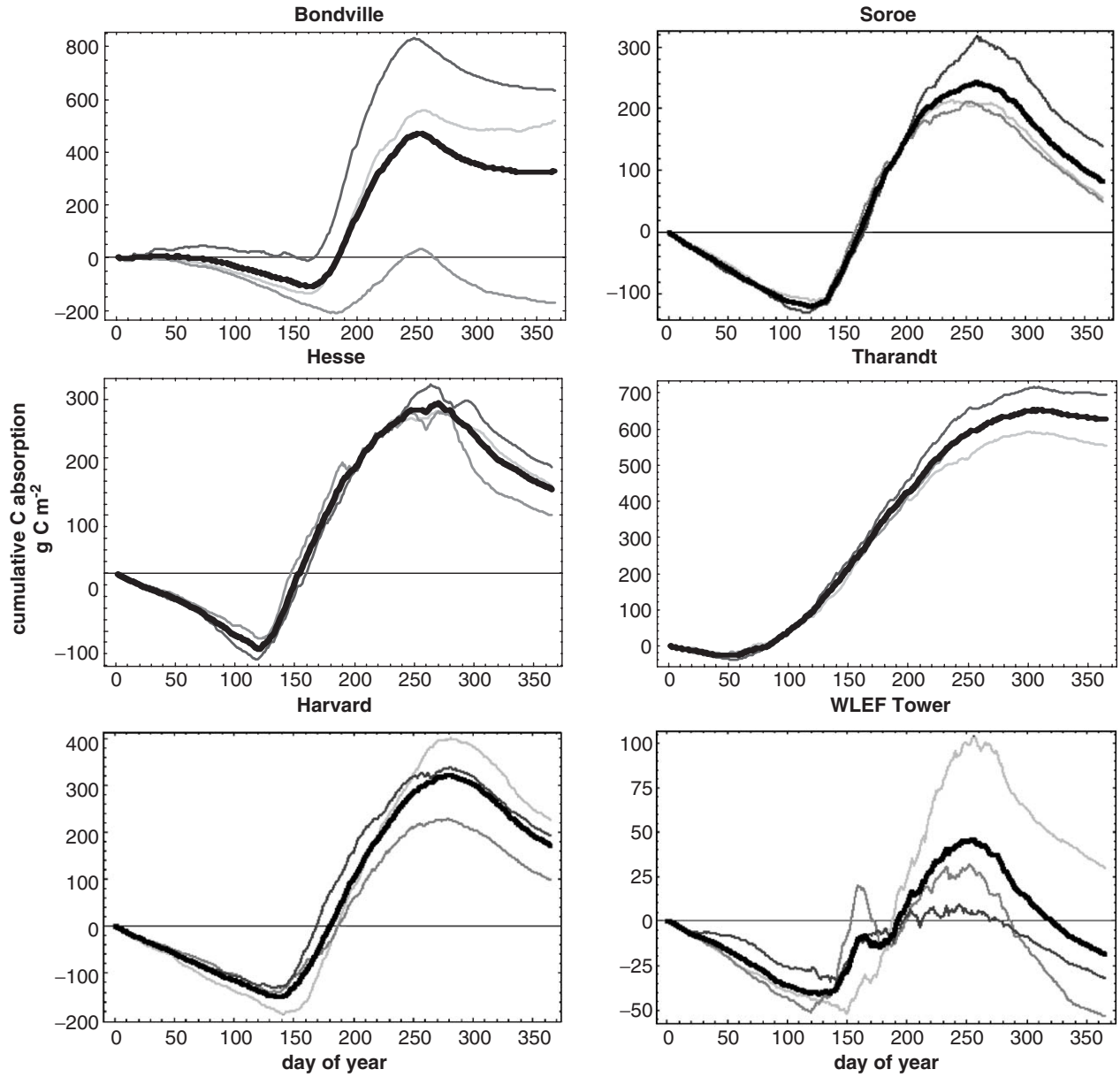

Fig. 4. Average annual cumulative uptake for each site (thick black curve) along with the three years of data that make up the average (years 1, 2, 3 = light, med, dark gray). Note that the sites vary considerably in how much they diverge from the average. This kind of variability is the unexpected change that is most helpful to diversify. Units are g (C) m^{-2}.

and are unlikely to be selected randomly. The results of the calculations for P_1 and P_2 are shown in Figs. 6 and 7.

The curves show the expected benefits of diversification: portfolio risks are minimized in both portfolios as expected annual carbon returns increase from zero toward around 175 g (C) m^{-2}. Beyond this point, returns increase as well, but only with a corresponding increase in portfolio variance. The portfolio weightings in Fig. 7 illustrate the relative fraction of each ecosystem that is required to generate the curves in Fig. 6. Note that the assets are held in different quantities for the optimal portfolio; this family of plots could be helpful in identifying a strategy that maximizes carbon absorption while minimizing risk. Fig. 8 shows these potential benefits of diversification over the performance of single assets in the portfolio. In real investments, investors will have different risk preferences and many may choose to situate themselves more aggressively on this curve, taking additional risk for additional return. The benefits of this more targeted approach accrue not only to the investor but also to the climate.

Because I have separated out one particular risk (quantity risk in delivery) from several risks that impact a project's profitability, it is impossible to assess a final dollar or percent financial return as the data say nothing about the carbon price or the costs of implementing each project.

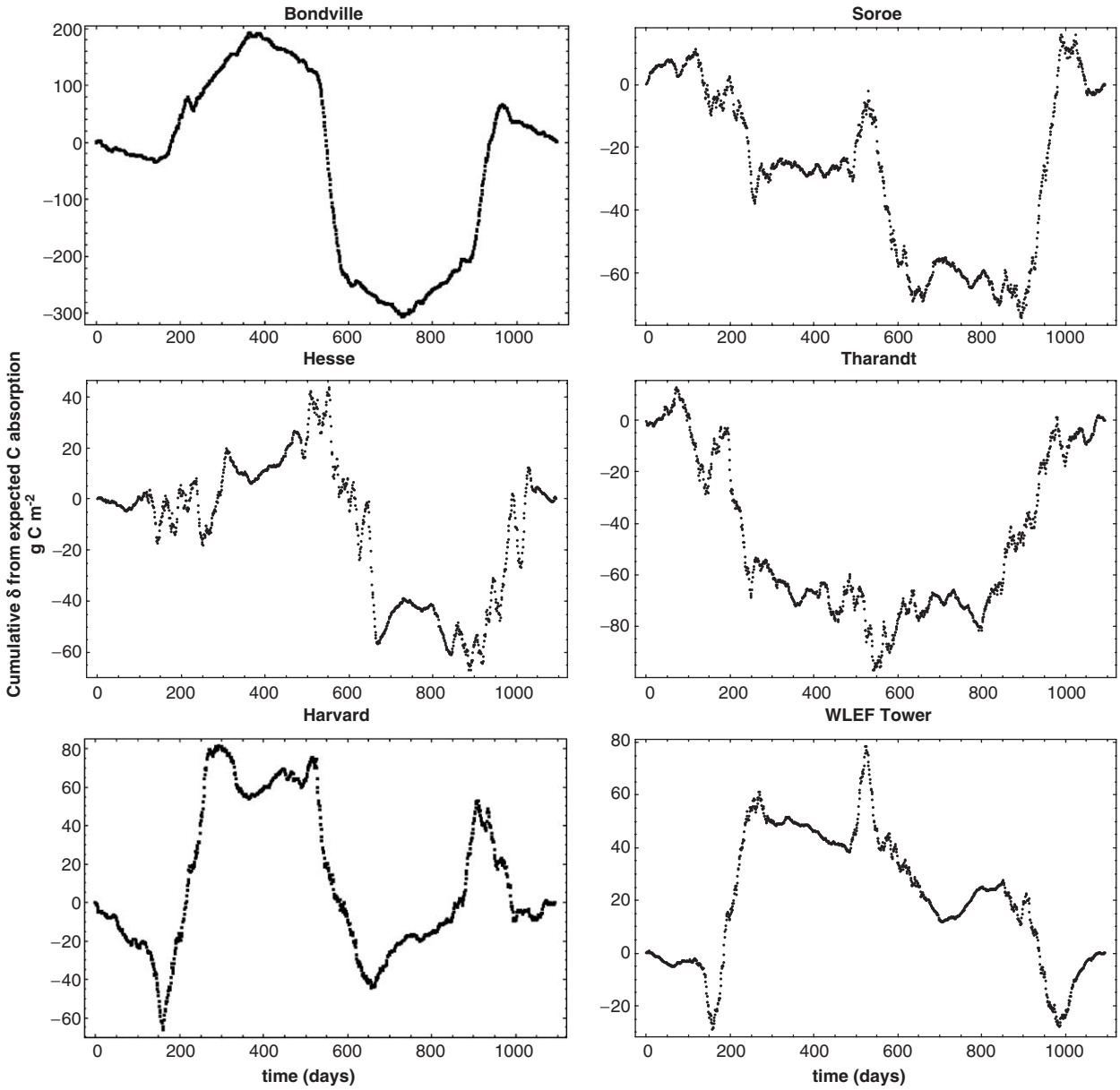

Fig. 5. Cumulative sums of the deviation from expected flux for each site, derived using methods described in text. Units are g (C) m^{-2} and necessarily sum to zero at $t = t_{final}$. Vertical scales are adjusted to show relative variability; note the significant differences in site characteristics with the seasonal signal removed.

Both of these additional elements would be required to compare a hypothetical project's total return relative to a safe financial asset such as a US Treasury. However, in practice, given recent experience with the new European emissions trading system, an investor or project developer with knowledge of project costs C could use historical prices to bracket the expected financial returns. This solution, while imperfect, would allow some assessment of the likely financial return. Alternatively, to reduce the price risk, the investor could lock in a price upfront using a futures contract; careful selection of project sites according to methods in this study or others would allow the investor to sell more carbon assets upfront and thus increase returns.

4. Undiversifiable carbon risk

This study describes techniques to reduce the diversifiable risks inherent in selling or buying carbon credits. Yet risk is never fully diversifiable. In the case of the carbon forestry developer, a number of scenarios exist for which even a diverse set of forestry projects distributed across geography might not be able to hedge a shortfall risk. Undiversifiable carbon risk is likely to appear in mitigation projects as well. While mitigation is not usually affected by correlated climatic changes, it is vulnerable to familiar global economic factors that could affect the carbon price or the costs of abatement. Nevertheless, the only carbon quantity risk for mitigation projects is really the risk to

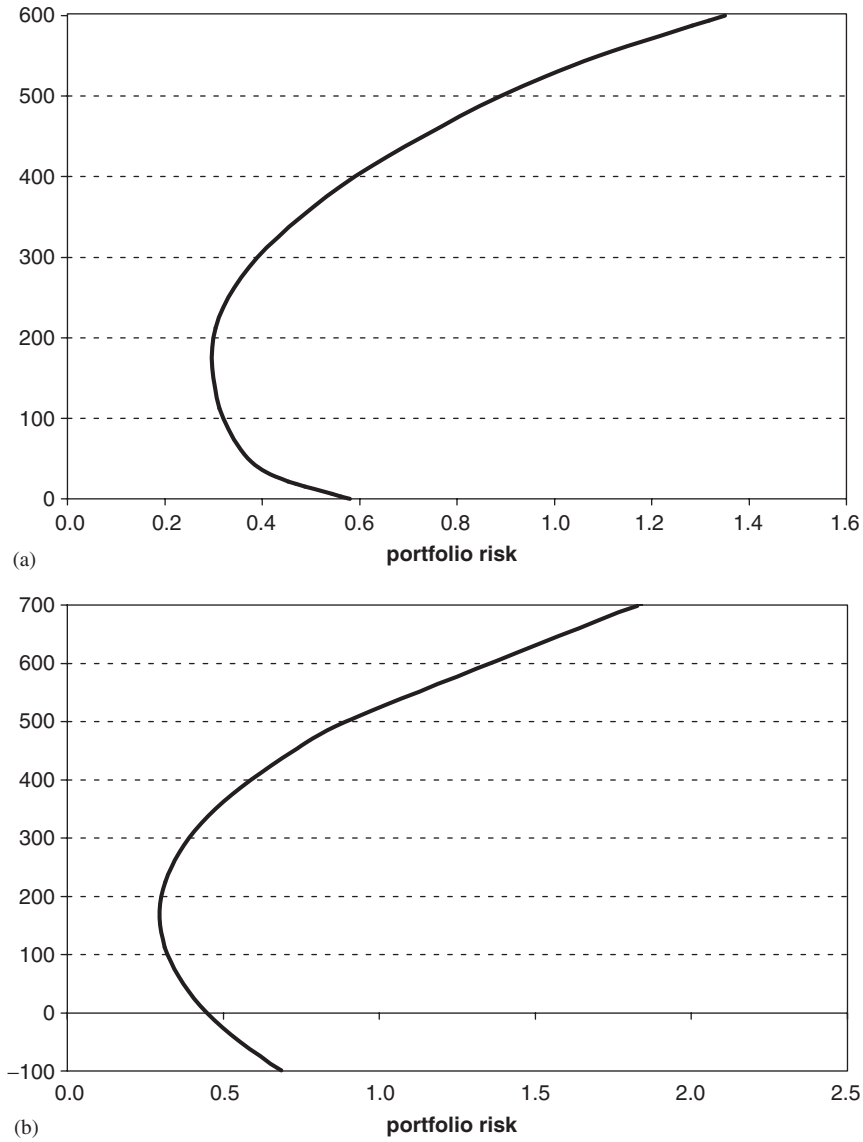

Fig. 6. Minimum variance frontier for portfolio of six selected sites, adjusted for expected seasonality. Return is defined as an absolute quantity per unit area rather than a relative return, and risk is defined as the variance of modeled portfolio. (a) shows the MVF without shorting; (b) allows shorting. Expected return in units of g (C) m^{-2} y^{-1}.

projects that depend on natural inputs (like solar, wind, or hydro) for generation. In this sense, mitigation projects are potentially subject to the same climatic correlations that sequestration projects are, although with much less sensitivity.

Thus, some undiversifiable carbon risk that is *not* part of normal market risk is linked strongly to weather and climate. One possibility for hedging weather risk is using weather derivatives that provide payouts under different weather scenarios. For example, citrus farmers can hedge against a crop not ripening by entering into an agreement that pays if a certain number of degree-heating days is not reached. Alternately, many power companies selling into the spot market use weather derivatives to hedge against low demand (Pilipovic, 1998; Dischel, 2002). The secondary weather derivative market, however, has been plagued with extremely poor liquidity. Part of this failure stems from a high amount of basis risk, but some is also related to the poor selection of available indexes to trade. Yet most weather hedging is done on a custom basis and with high transactions costs.

Most secondary market weather indexes are based on simple temperature deviation from a 65 °F baseline. Yet this rough measurement might not fit some large end-uses. Agricultural applications, including carbon forestry projects, depend not only on temperature but also very sensitively on rainfall. Several risk-management firms are developing alternate types of index that they hope will be more useful, such as regional averages, that would reduce basis risk (Saunderson, 2002). The possibility of a large set of carbon-related projects could lead to a larger market for such derivatives, and this area deserves further study.

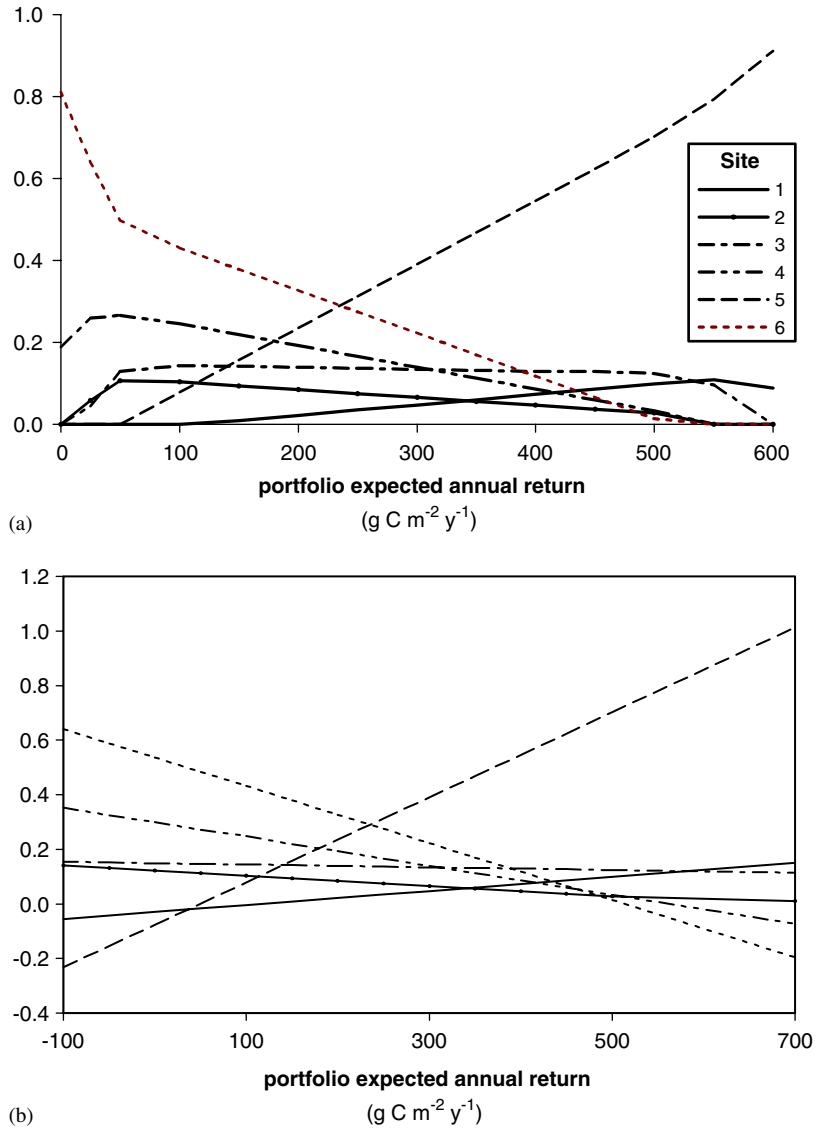

Fig. 7. Portfolio weightings (a) for non-shorting portfolio and (b) shorting portfolio, used to create curves in Fig. 6.

In addition to turning to the weather markets to mitigate quantity risk, carbon project developers can, for example, reduce the risk of carbon prices by structuring hedges that are denominated in carbon rather than in dollars or euros (Weinstein, 2001). Because payments and liabilities are all in terms of carbon, this method keeps the "currency" identical across risks and thus eliminates the risk in converting carbon to dollars. For example, a coal plant will emit more on hot days and can hedge with a carbon-denominated temperature swap based on a standard temperature index. In markets with green certificate requirements or renewables portfolio standards, a wind power project can hedge against a wind index with a carbon put or carbon futures, thereby allowing it to cover any potential shortfall due to low wind conditions. Similarly, carbon-denominated swaps could be applied to forestry projects to eliminate shortfall risk entirely.

The sensitivities to meteorological conditions in particular suggest the possibility of hedging carbon risk with weather derivatives. Carbon uptake in drought-stressed ecosystems—like many in sub-Saharan Africa, for example—is vulnerable to extreme weather events like mid-summer droughts or heat waves. If such forests experience a higher than expected occurrence of these kinds of events (either because of natural variation or human-induced climate change), the forest's rate of carbon absorption could slow significantly even over relatively long averaging times like 5 or 10 years. Were these events to happen early in the project, the financial attractiveness would be reduced because of discounting.

These kinds of sensitivities suggest that hedging against extreme temperatures and low soil moisture events is a more useful practice than targeting temperature averages or cumulative heating-degree days. Insurance or weather derivatives that incorporate these kinds of meteorological

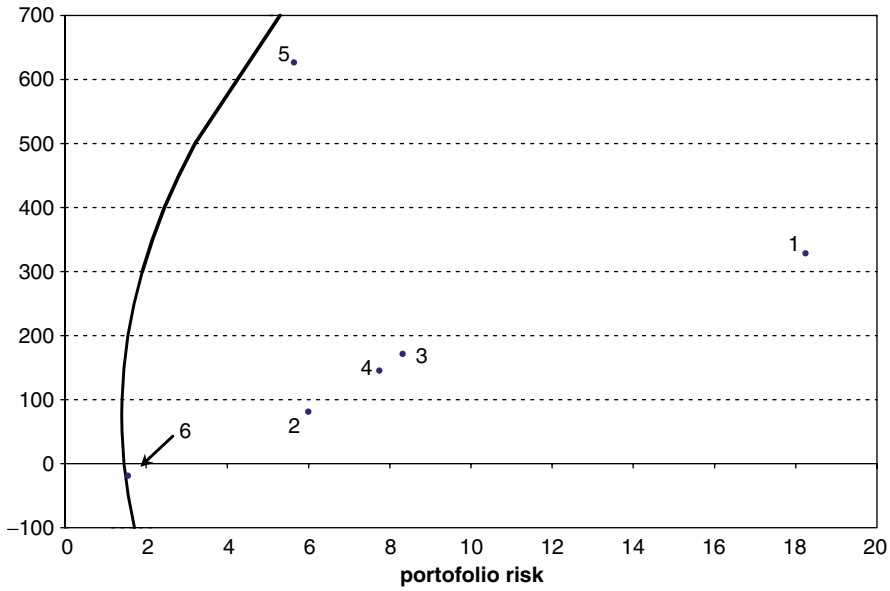

Fig. 8. Minimum variance frontier plotted with risk and return characteristics for individual sites.

phenomena would likely look attractive to investors wishing to ensure their profitability. Until the market is large enough to support extensive use of these products, though, carbon-denominated hedging would likely dominate the market for forestry credits.

One additional question raised by this analysis is the extent to which this particular carbon risk is important relative to other risks undertaken by project developers. Agricultural producers, for example, face not only their own quantity risk in the production of their commodity but also face similar risks in price movements and basis risk for hedging (Moschini and Lapan, 1995). Thus, while it is unlikely that carbon absorption risk will be the dominant risk to a firm, having a methodology to evaluate it is the first step in assessing the need to hedge. The fact that so many producers of agricultural commodities choose to hedge their production is a good indication that carbon risk will justify similar measures.

5. Conclusion

These calculations show that diversification, even within similar ecosystems in similar latitudinal zones, could have significant, quantifiable risk-reduction benefits. While the basic benefits of diversification are expected, the calculations based on the non-seasonal NEE vectors were somewhat surprising in that they provided a much stronger diversification benefit based on their low covariances than one might expect. This kind of portfolio analysis provides a way to assess the value of potential new projects. If suitable proxies can be located, the same methodology would yield insights into the usefulness of additional investments in each location. Importantly, what matters for sales depends not only on the amount of carbon sequestered but also on the trading regime's rules for crediting carbon. This analysis also provides an assessment of the diversifiability of carbon risks by biological sequestration. It therefore provides the basis for calculating the additional hedging that a firm could carry out to offset its remaining non-diversifiable risks. Deliberate and careful geographical diversification using this technique or other assessments of better portfolio construction can therefore not only reduce the risk to project developers and financers but also will make these projects a more attractive and therefore more effective mitigation option. However, while knowing how the risks from different regions can be offset may lead people to choose one site over another if all else is equal, carbon investments, like other investments, will continue to be made based on the institutional and legal climate in the host countries.

While long-term climate change could also have a significant effect on carbon dynamics, discounting and difficulty of reliably forecasting the ecological impacts of such changes decrease the usefulness of considering such scenarios in the present context. Nevertheless, as a larger policy question it does present important challenges. The current political situation moreover limits diversification to specific participating countries—excluding, for example, the United States. In addition, while this paper has largely avoided the important questions about the social contexts of individual projects, these aspects are important not only ethically but also for the success of the project. While carbon credits may be seen as a new "cash crop" and thus must be approached with caution, forestry projects as well as mitigation projects can also have significant co-benefits for participants (Plantinga and Wu, 2003). As the carbon market matures, project design should include not only better financial diversification but also ensure that the local communities are appropriately included in project implementation and benefit sharing.

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