Harvesting the Greenhouse:
Comparing Biological Sequestration with Emissions Offsets

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Emerging policies directed toward greenhouse gas (GHG) emission (GHGE) reductions are causing governments and industries to consider the merits of GHGE mitigation possibilities[1]. Land-based biological sequestration (LBS) along with other sequestration options is being evaluated as potential ways to achieve net GHGE reductions. Some have argued that LBS strategies are relatively inexpensive ways of lessening GHG mitigation costs, as well as ways of increasing economic opportunities for farmers and foresters (Dixon et al 1993; Sampson and Sedjo 1997; Marland and Schlamadinger 1999). Direct emissions reductions are also under consideration. Here we investigate the relative value of each considering important differences in their characteristics relative to saturation and permanence. We show cases exist where tons of carbon from LBS may be worth half or less of an equivalent tonnage from emissions reduction.

Sequestration and emission offsets have contrasting characteristics. Emissions offsets are implemented by either reducing the scale of the emitting activity (e.g. reducing the production of emitting products) or by altering the mix of fuel inputs (e.g. increasing fuel use efficiency or switching fuels). Sequestration offsets involve the capture of GHGs by either industrial processes or biological means. Industrial sequestration involves separating GHGs, then injecting the carbon into soils, aquifers, oceans or geological formations for permanent storage. LBS generally refers to the absorption of carbon dioxide from the atmosphere through photosynthetic processes by plants or trees and subsequent fixation into soils, plants or trees. GHGE offsets reduce the actual quantity of emissions while sequestration involves absorption of previously

[1]The policy and strategy attention is principally stimulated by the link between GHGs and projected global warming (Intergovernmental Panel on Climate Change-IPPC, 2001). But numerous other forces are at work stimulating this interest including emerging international agreements on GHG emissions (GHGE) reductions (e.g the Kyoto Protocol to the United Nations Framework Convention on Climate Change), GHGE related regulatory efforts in some countries (e.g., carbon emission taxes in Norway or potential multi pollutant electric utility regulation in the U.S.), and unilateral GHGE reduction efforts by private companies (e.g., British Petroleum has a major effort).

emitted gases and subsequent storage of those gases. Note that an emissions offset through fuel use reduction involves a lack of withdrawal of fossil fuels from underground storage. In principle, these below-ground stocks can be used in the future for energy and thus emissions may simply be delayed rather than completely avoided.

Sequestration activities exhibit saturation when storage reservoirs fill up due to physical or biological capacity. LBS sequestered carbon is also commonly thought of as not being permanent since its storage form is often volatile and subject to subsequent release through land use change, tillage change, harvesting, fires, or other natural and anthropogenic disturbances. For example cutting down a LBS-developed forest and plowing the soil up for farmland quickly releases much of the sequestered carbon. Replacing no-till agriculture with a mold board plowing system also quickly releases carbon.. In terms of costs, emission and sequestration efforts involve both

1) an initial outlay for development and implementation of the activity and
2) operating expenses for keeping the activity going over time.

However the combination of saturation and volatility for LBS strategies also introduces a potential third cost item which is a

3) maintenance cost to keep the carbon sequestered possibly even after saturation has been achieved.

Here we examine the relative value of sequestration and emission offsets given their differing saturation and volatility characteristics. Specifically, we estimate the relative value to a carbon purchaser of LBS and emission offsets as they arise over time. We will also treat the concept regarding the rental of LBS generated sequestered carbon and the bridge to the future concept involved with future paths of carbon prices.

Context for Greenhouse Gas Emission Offset Purchases

Before proceeding with the technical analysis, it is useful to consider the context for GHGE offset purchases. Consider a firm or country which, due to international treaties, domestic policies, or voluntary programs, has a limited amount of GHGs it can emit. To exceed that amount it must obtain rights from another entity. Suppose that entity wishes to pursue a production pattern that will release GHGEs in excess of it's limit each year for the foreseeable future. Assume the entity announces it's intention to purchase GHGE rights and several opportunities present themselves. The opportunities involve offers from those who can undertake activities which: a) directly reduce emissions, b) sequester carbon in agricultural soils, and c) sequester carbon in forests. In this context the main question investigated herein becomes: How do the different saturation and volatility characteristics manifest themselves in the price that the entity would be willing to pay for a unit of carbon for each opportunity? The remainder of the paper focuses on quantifying the relative prices of the different mitigation options.

Evidence of Saturation

Because saturation is integral to this investigation, a quick review of the evidence regarding LBS saturation is in order. Two prominent forms of LBS are: (1) reductions in agricultural soil tillage intensity and (2) establishment of trees on currently unforested lands (afforestation). In terms of tillage, West et al summarize the observed carbon increments over time arising from about forty tillage change experiments. Their results are reproduced here in Figure 1. This figure shows that by year 20 the carbon increments us all the forty experiments have dropped essentially to zero – evidence of saturation. On the forestry side afforestation carbon is be sequestered in both soil and standing trees. Data from Birdsey(1996) shows forest carbon sequestration reaches a limit with soil carbon saturating and trees eventually growing at a declining rate (see Figure 2) although this takes a longer time than in agriculture. However forest cases become yet more complex when harvesting is introduced as significant fractions of the carbon are retained in harvested wood products. The wood product pool is not shown in

Figure 2 but is captured by the numerical analysis below.

An Analytical Approach for Comparing the Value of Offsets

GHGE offsets occur over time. Offsets could involve such enterprises as an emissions reducing fuel switching project which offsets emissions for many years. Similarly by beginning reduced tillage or establishing a forest one secures sequestration returns for some time into the future. Also if the reduced tillage or forest use is eventually discontinued there would be future releases. These dynamic considerations imply that a comparison involving sequestration should adjust for the time value of emissions offsets as argued in Richards(1997) and Fearnside et al (2000). Thus, we will use a net present value framework much like that used in Feng et al (2001) and we will solve for the constant real emissions price which equates the net present value of the GHGE offset by a strategy with the net present value of the costs for strategy implementation. From a mathematical standpoint, we solve for p in the following equation

$$\sum_{t=0}^{T}(1+r)^{-t}pE_t = \sum_{t=0}^{T}(1+r)^{-t}C_t$$

where r is the discount rate, T the number of years in the planning horizon, p the constant real price of emission offsets, E_t the emissions offset in year t, and C_t the cost of the emissions offset program in year t.

To proceed with the analysis we make several assumptions. First, to facilitate comparison across the offset options, we will assume equal incremental carbon generation potential offset rates and implementation costs for all -- 1 unit of carbon per period at a price of 1 unit. Second, we will evaluate the incremental costs and returns caused by use of each offset strategy over a time period of 100 years. Third, we will use a 4% real discount rate. Fourth, to keep the mathematics more straightforward, we will use linear approximations for the annual sequestration rates. For example, we will have a 1 unit offset for every year until the point of saturation and zero thereafter. Emissions from any CO_2 released after the saturation point (e.g., from harvest or reversion to conventional tillage) are also linearly approximated.

The Value of an Emission Offset

Suppose we first consider a direct GHGE offset. Such offsets would come about from fuel switching, less fertilizer use etc. We will assume that opportunity yields a one unit emission offset for one monetary unit per year. We also assume that program can be continued over the whole 100 year period. Application of our net present value framework shows the breakeven real carbon price (p) for this is 1.00.

The Relative Value of an Agricultural Soil Offset

Now suppose we consider an agricultural soil based offset coming about by changing tillage from an intensive system to a reduced tillage system. Based on West et al we assume that saturation occurs in year 20. We will also assume for comparability that the system sequesters one unit of carbon per year for the first 20 years and zero thereafter at a cost of one unit per year for as long as the payment is in place. We consider three different possibilities about the practice and program payments beyond year 20. Namely, farmers are paid to switch tillage for 20 years and then

I) at the end of the 20 years the payment ceases. In turn, farmers acting in their own best interests revert back to conventional tillage. Subsequently we assume that the sequestered carbon is released over three years in equal increments of 6.67 units.

II) the payment continues with farmers being paid for the full 100 years to continue the practice maintaining the sequestered carbon but carbon accumulation ceases at year 20.

III) at the end of the 20 years the payment ceases. However, farmers acting in their own best interest maintain the practice and thereby the carbon[2].

The carbon and cost profiles differ across the scenarios. The cumulative amount of additional carbon rises in linear fashion up to year 20 then either remains the same (cases II and III) or drops to zero over 3 years when the subsidy is discontinued (case III). Total program cost rises until year 20 then stays the same under cases I and III or continues to rise for the entire 100 years (Case II).

When we compute the real price (p) that equates the net present value of the sequestration offsets with GHGE reduction, we get 2.64 for case I where the carbon is released, 1.80 for case II where the farmer is paid well past the saturation point and 1.00 for case III where the practice continues without subsidy[3]. This shows relative to the one unit breakeven price for the emission offset that saturating agricultural soil carbon that requires a subsidy for the practice to be continued is only worth 38% to 56% as much. Thus while the emission reductions are

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[2]The argument behind case III is that farmers may require a learning process in order to master the superior practice of reduced tillage and/or time to obtain benefits from enhanced soil carbon. Under this scenario, once the reduced tillage practice is thoroughly learned and or the soil carbon benefits realized, the farmer will not revert. This can be bolstered by the observation that there are reduced tillage practices in use without carbon payments. On the other hand, it would be naive to assume this is the only case because farmers generally are highly profit motivated and factors corresponding with reduced tillage such as reduced yield, increased reliance on herbicides (which may not be sustainable), incompatibilities of reduced tillage with desired planting dates due to slower soil warming rates, and increased risk of may mean that such practices may not remain after subsidies are removed. In fact, the U.S. has seen a reduction in total reduced tillage with the expiration of some subsidy programs.

[3] It is worth mentioning that an extension of case III may exist in which subsidies might only be needed for, say, the first ten years to induce learning behavior or soil carbon induced benefits and then perhaps the farmer would continue the practice and society reap the benefits for the next 10 years. Such a practice which would trade at a premium relative to the emission case. However we will not analyze this case at length. We also note that such a case might exist with respect to emissions where the initial subsidy of emissions reducing practices might only be needed for some time and then industry would continue the practice forever.

valued at the amortized cost of generating them, the saturating nature of agricultural soil sequestration will result in a discount if either the carbon is released or the cost continues beyond the saturation point and the free lunch of case III does not occur. Under a 50% discount this implies that for a LBS agricultural soil activity to be competitive with a direct emissions reduction costing $100 a ton, it would have to cost $50 or less per ton.

Expanding to Consider Forestry Offsets

Now consider an forest based offset. In general, such offsets would come about from afforestation, lengthening harvest rotations, ceasing harvest altogether or improving management. For simplicity we only consider afforestation herein. Forestry carbon sequestration entails four types of carbon gains or emission offsets. First, forest soils hold more carbon than agricultural soils since: a) trees have larger root systems, b) forest soils are disturbed less frequently, and c) forests deposit and retain more surface matter litter. Second, standing trees hold carbon in their leaves, limbs and trunk. Third, harvested timber products are substantially made up of carbon and may be placed in long-term storage through their use in buildings, furniture, etc. Fourth, a sizeable portion of harvested forest carbon is used in ways that offset GHGE as they are used as an energy source replacing what otherwise would at least partially require fossil fuels and accompanying emissions. This occurs both through the trees used as fuel wood and the use of milling residues for co-generation.

Forestry offsets also exhibit saturation and volatility. Volatility occurs upon harvest where lands either revert to agriculture or have much of their above and below ground biomass removed in the harvesting process. Soils saturate and trees eventually becoming mature where net growth is matched by losses (Figure 2). We set up scenarios that evaluate various dimensions of the problem in Table 1, including:

1. Timing of forest harvest (if it occurs at all)
2. Whether reforestation occurs after harvest
3. The period of time over which payments occur

4. Use of harvest products for pulp or saw timber which influences residency time for harvested carbon as well as for biofuels.

The time to saturation and post harvest forest carbon profiles where set up based on the Birdsey 's (1996) data for southeastern U.S. pine plantations. Birdsey's data for onsite forest carbon from the FORCARB model (Birdsey and Heath 1995) is supplemented by data on the amount of carbon removed from the site at harvest, decay rates for the logging debris, and the carbon disposition by pool (product, landfill, energy use, and emissions) over time (Row and Phelps 1991).

Left alone, our model forest saturates after 80 years. Under the first group of scenarios we keep the forest at least until saturation (F-I, F-II). To be parallel with the agricultural cases we considered cases where:

A) payments cease upon saturation and the stand is harvested (Case F-I) and we get p=1.07 or a 93% value when fuel offsets are counted which falls to 91% without consideration of fuel.

B) payments continue until year 100 and the stand remains in its saturated state after year 80 (case F-II) where we find p = 1.02 or 98% of that for emissions offsets.

Next we turn our attention to a group of scenarios involving managed forests which are harvested for products and which volatilize part of their carbon upon harvest. First, we consider short rotation lands, primarily managed for pulpwood, which are harvested after 20 years. When such lands are harvested and revert back to agriculture we get a relative value of 65% with fuel offsets considered, 51% without(Case F-III). When the land is reforested that may mean landowners only need to be subsidized for the first rotation (analogous to the case III scenario in the agriculture results), then the "discount" factor with fuel considered actually rises above 1.0 to 1.254. This indicates that one would actually be willing to pay a premium for a 20-year sequestration project that produced this result, because it generates higher net discounted GHGE benefits than an emission reduction program alone.

When we consider longer rotations of 50 years, which is primarily a sawtimber (lumber and plywood) management regime (cases F-VI, F-VII and F-VIII), we find higher relative values because the carbon accumulates in the forest longer and because the products have longer shelf lives than those made with pulpwood (paper and paperboard).

Leasing

Some attention has been paid to leasing rather than buying GHGE offsets. In particular, Marland and Fruit; and Bennett and Mitchell independently argue the attractiveness of potential leasing where at the end of the lease period all bets are off and the lessor must find other carbon. A similar proposal has been advanced in the context of the Kyoto negotiations by Colombia. To investigate the implications of leasing, we examined 20 year lease where when the lease ends there are no more payments and no guarantee that the carbon stays sequestered. Thus we used the assumption that the carbon volatilized immediately upon completion of the lease. Under these circumstances we find that the leased carbon is worth 36 percent as much as an emission offset . Thus it appears that leased carbon does have value but would trade at a substantial discount.

Bridge to the Future

One argument regarding LBS is that it offers a relatively cheap mitigation option that can be exercised now allowing reductions and buying time until future GHGE rates are reduced by technological change. This raises the specter of non-constant emission offset prices. In such an arena several possibilities advance themselves. Future prices might

a) rise as regulations are tightened in an escalating attempt to develop an emissions cap theat will stabilize atmospheric GHG concentrations;

b) rise as increasing emissions increase atmospheric GHGs and the damages due to marginal GHG increments rise;

c) fall from current estimates as innovation is stimulated by GHG markets; or

d) initially rise but then fall as innovation occurs.

The bridge to the future argument is in line with the rising then falling price in case d.

We thought it desirable to examine the effect of such scenarios on the relative values of the offset possibilities. To do this we compared constant real price results with results under: (1) declining prices over time, (2) prices which peaked at some point in the next 100 years and (3) rising prices over time. We assumed the annual change in prices was 1% in this exercise. The subsequent results for the above cases including leasing but excluding the forest variants without biofuel credits. The results in table 2 show that the LBS and leasing opportunities are worth the most the closer the price peak is to today. This is more general than Feng et al's(2001) finding that sequestration should be undertaken as soon as possible. In our analysis, the relative value of LBS activities is greatest when the prices reach their peak. If that occurs in the future, this provides an incentive for delayed sequestration..

Sensitivity to Assumptions

The analytical framework used here embodies a number of assumptions. Several experiments were done to determine the sensitivity of the results to alternative assumptions. In particular we examined the effect of alternatives involving

Discount rates. We examined rates from 4-8 percent and found the value of the saturating assets increased the higher the discount rate. For example, in agricultural soil case I the saturating carbon was worth only 38% as much as an emission offset under a 4% discount rate but under an 8% rate this rose to 63% (as also shown in Feng, Zhao and Kling). The reason for this is that under saturation, most of the benefits accrue in the earlier years, which have a higher discounted value.

Nonlinear Approaches to Saturation. We found use of an exponential type approach increases the relative values of the saturating strategies relative to the linear pattern used above.

Conclusions: Squaring Up various Offset Categories

Sequestration and emission offsets are not worth the same amount. The agricultural soil offsets examined herein are only worth 38% as much as an emissions offset if the carbon saturates then volatizes at the end of the program. The value rises to 55% if the practice is maintained by continuing subsidies. Under most forest scenarios, sequestered carbon in forests is worth from 51-99% as much as an emissions reduction program, contingent on assumptions about the length of the harvest rotation, whether reforestation occurs, and whether credits for fuel offsets are applied.

Cases can be developed where a sequestration offset is worth just as much as, and potentially even more than, an emission offset. These arise when the initial payments subsidize the adoption of an agricultural or forest practice that will be continued after the subsidy ends. In this case, the payer of the offset receives a free ride from the adopters learning (and sustaining) the new technology. However, such effects could also occur through an emissions reduction program (e.g., a technical change subsidy) which would continue after program end thereby also generating mitigation benefits beyond the payment period.

The timing of sequestration as a mitigation strategy is critical. If carbon prices are falling, then sequestration has greatest relative advantage. This is particularly important in light of the fact that large scale GHGE reduction may require the adoption of entirely new technologies that are in various stages of development. In contrast, sequestration results from an existing technology endowed by nature and can thus be adopted immediately. However, if the carbon prices rise over time due, for instance, to worsening climate impacts, this reduces the advantage of sequestration as a mitigation strategy relative to emission reduction through technical change. Because we cannot know with certainty which future scenario will prevail, a mixed strategy of sequestration and emissions reduction might be the most prudent path to longrun cost-effective mitigation.

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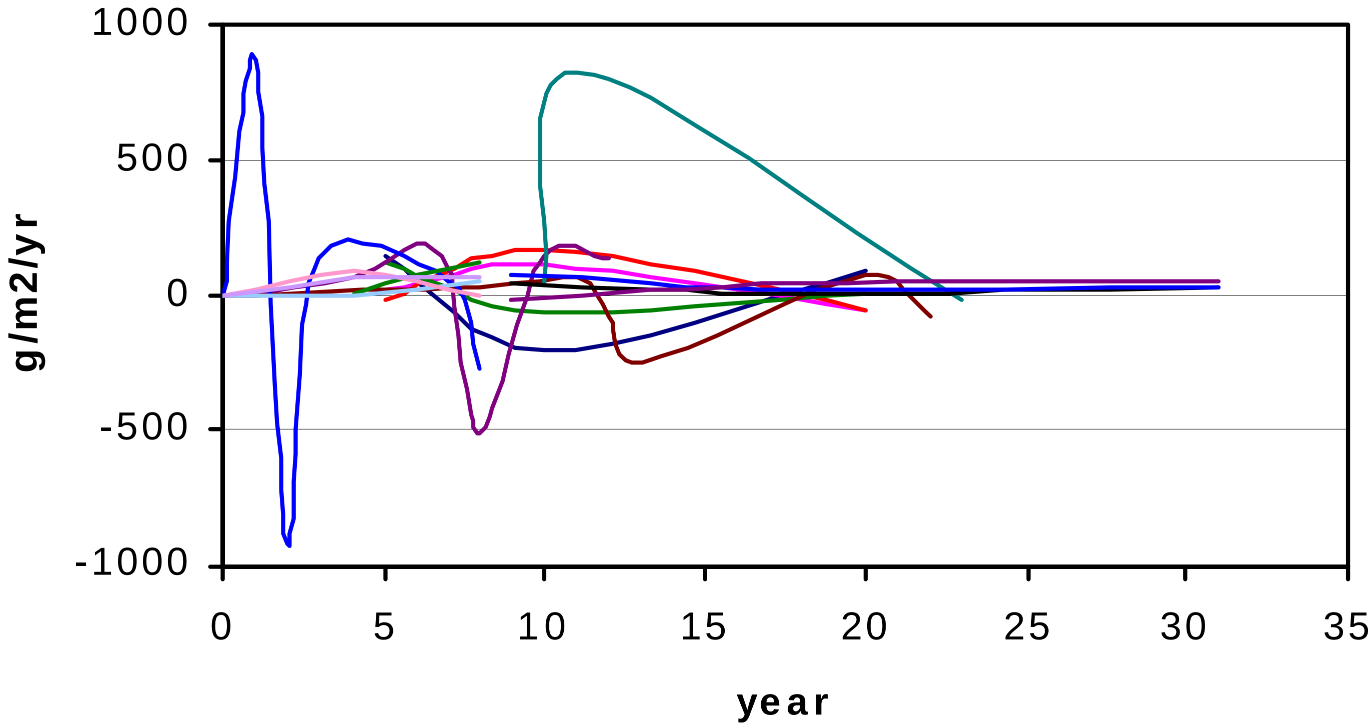
Figure 1: Results of Tillage Based Carbon Sequestration Experiments as Collected and Displayed by West et al

Results – C accumulation vs. time with change from conventional till to no-till



from Review of Task 2.1, National Carbon Sequestration Assessment,
Tris West, Mac Post, Jeff Amthor.

Figure 2. Cumulative Carbon sequestration in a Southeastern U.S. pine plantation
Source: Data Drawn form Birdsey (1996)

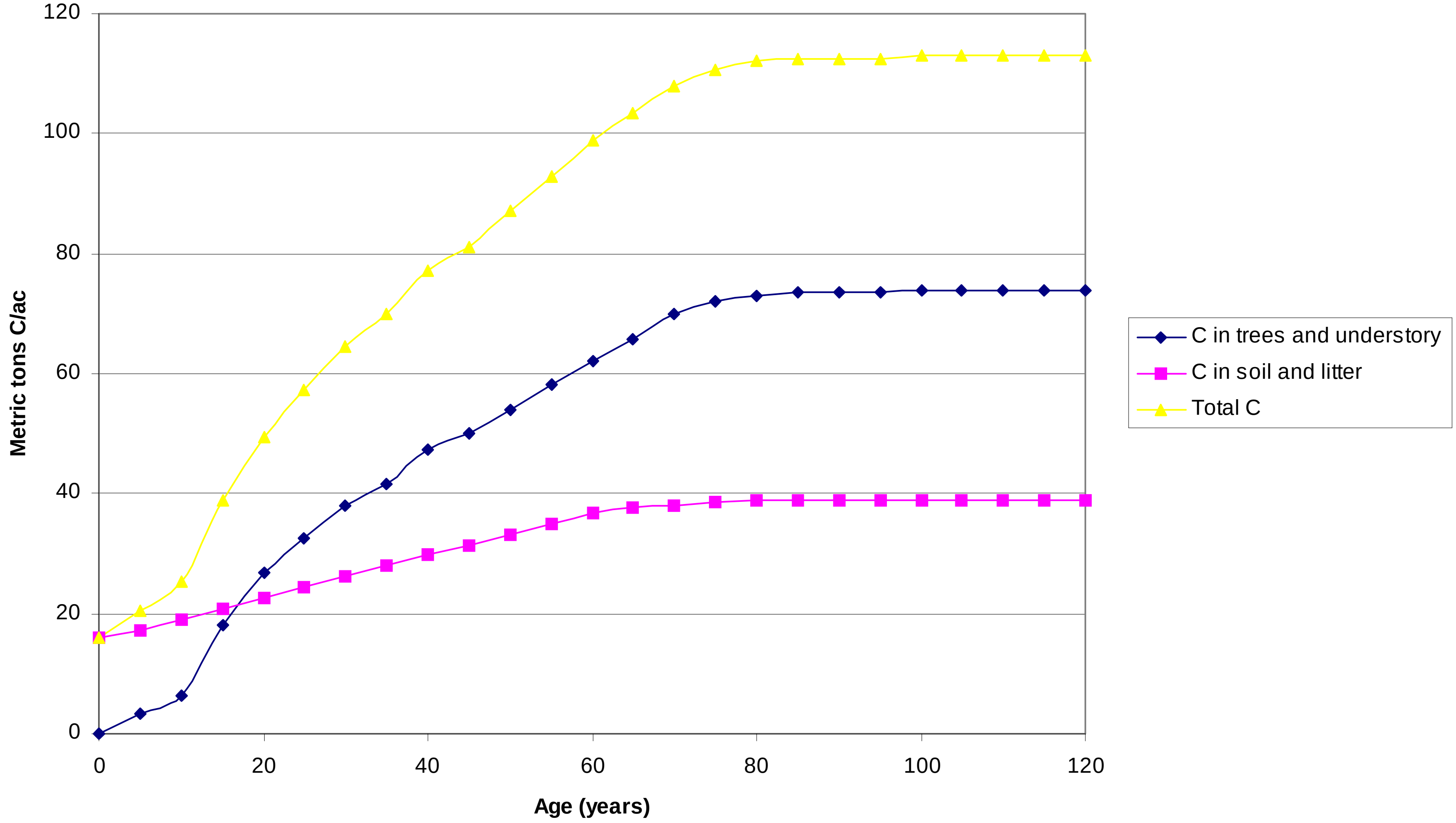


Table 1. Scenario Descriptions and Terms of Trade for Forest Carbon Offsets

Scenario Description		Defining Assumptions			Computed Results			
					With Consideration of Fuel Offset		Without Consideration of Fuel Offset	
Broad Scenario Class	Case	Harvest Age	Reforest After Harvest	Years of Payments	Equivalent price	Value Relative to Emission Offset	Equivalent price	Value Relative to Emission Offset
Forest kept to Saturation	F-I	80	No	80	1.07	93%	1.10	91%
	F-II	Never		100			1.02	98%
Shorter rotation forestry (primarily pulpwood)	F-III	20	No	20	1.54	65%	1.95	51%
	F-IV	20	Yes	100	1.44	69%	1.78	56%
	F-V	20	Yes	20	0.80	125%	0.99	101%
Longer rotation forestry (primarily sawtimber)	F-VI	50	No	50	1.18	85%	1.26	79%
	F-VII	50	Yes	100	1.15	87%	1.22	82%
	F-VIII	50	Yes	50	1.01	99%	1.07	93%

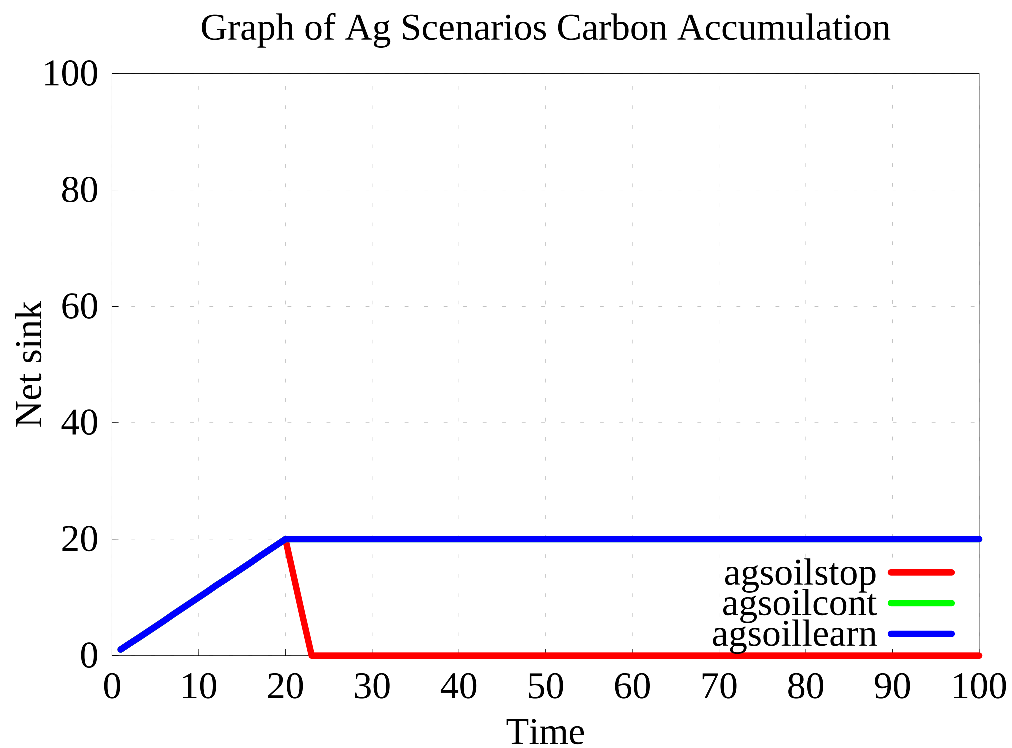
Table 2 Effect of Non Constant Price Patterns

	Time of Price Peak								
Scenario	NoPeak	Year0	Year10	Year20	Year30	Year40	Year60	Year80	Year100
Emission	100%	100%	100%	100%	100%	100%	100%	100%	100%
Ag Soil-I	38%	52%	47%	34%	29%	27%	26%	25%	25%
Ag Soil-II	55%	63%	62%	58%	54%	51%	48%	47%	47%
Ag Soil-III	100%	114%	111%	105%	97%	93%	87%	85%	84%
F-I	98%	99%	99%	99%	98%	98%	97%	96%	95%
F-II	94%	98%	98%	97%	97%	96%	93%	89%	86%
F-III	66%	82%	79%	69%	59%	55%	52%	50%	50%
F-IV	66%	71%	70%	67%	65%	63%	61%	60%	60%
F-V	119%	129%	127%	121%	117%	114%	111%	109%	109%
F-VI	86%	95%	94%	93%	90%	86%	76%	73%	73%
F-VII	87%	91%	91%	90%	88%	86%	82%	82%	82%
F-VIII	99%	104%	103%	102%	101%	98%	93%	93%	93%
Lease	35%	49%	44%	30%	27%	25%	24%	23%	23%

Rest is Just here for seminars

Figure 3: Soil Carbon Cases

Panel a Carbon Quantity over Time



Panel b Cumulative Program Cost over Time

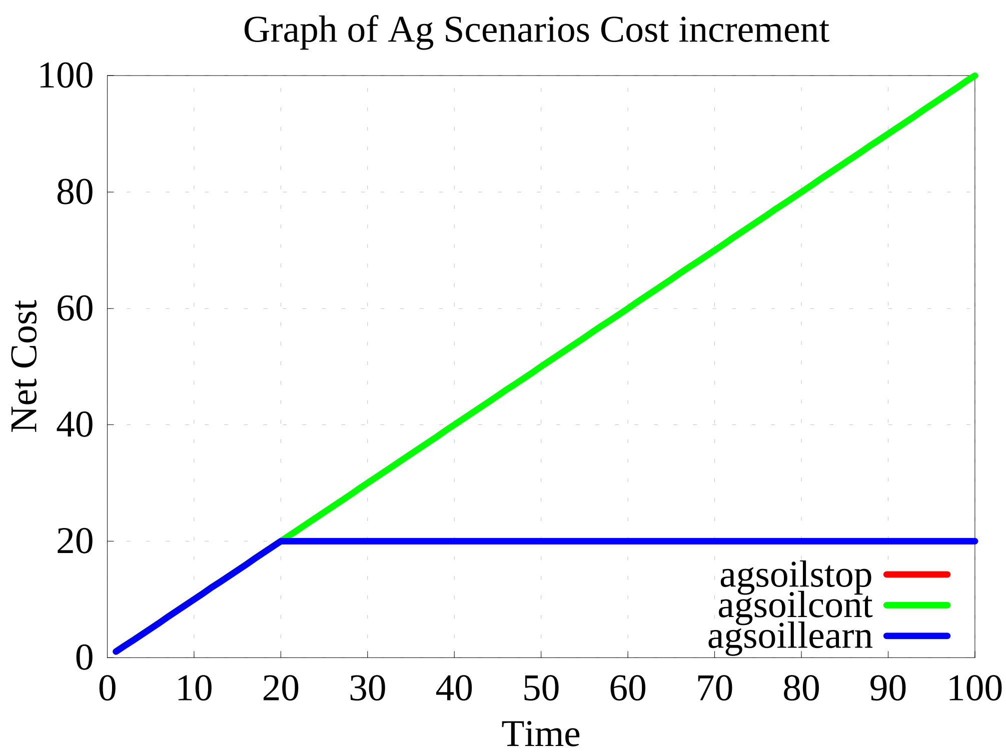
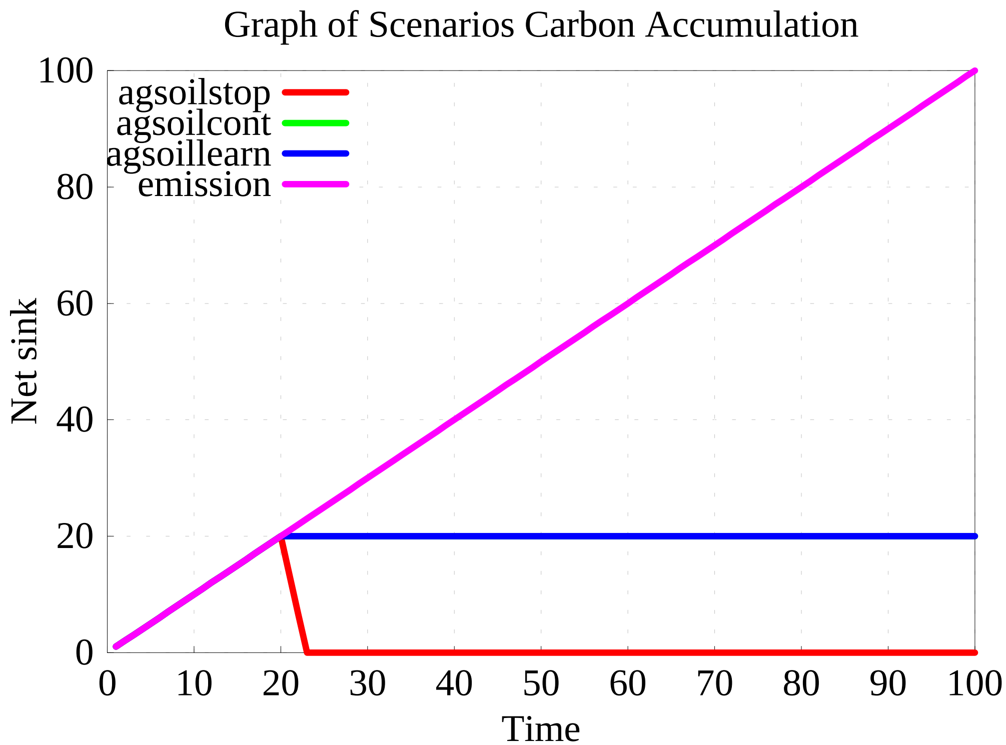


Figure 4: Adding an emissions offset to Soil Carbon Cases

Panel a Carbon Quantity over Time



Panel b Cumulative Program Cost over Time

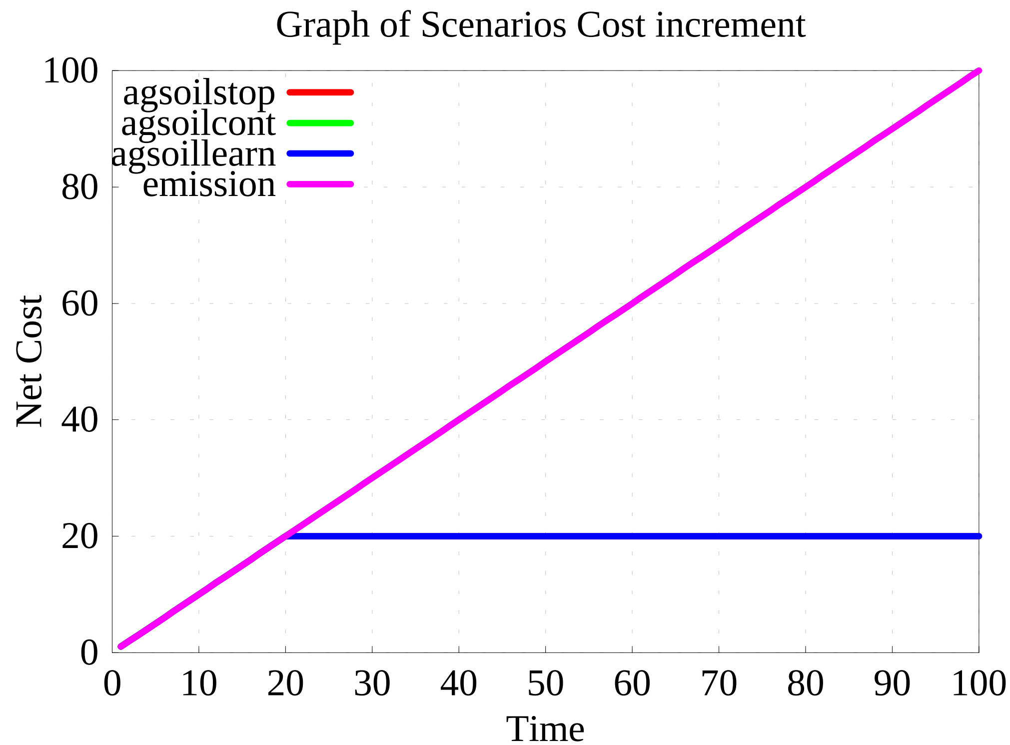

Graph of Scenarios Cost increment
agsoilstop
agsoilcont
agsoillearn
emission
Net Cost
Time
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80
90
100

Figure 4: Adding an forestry case -- Carbon Quantity over Time

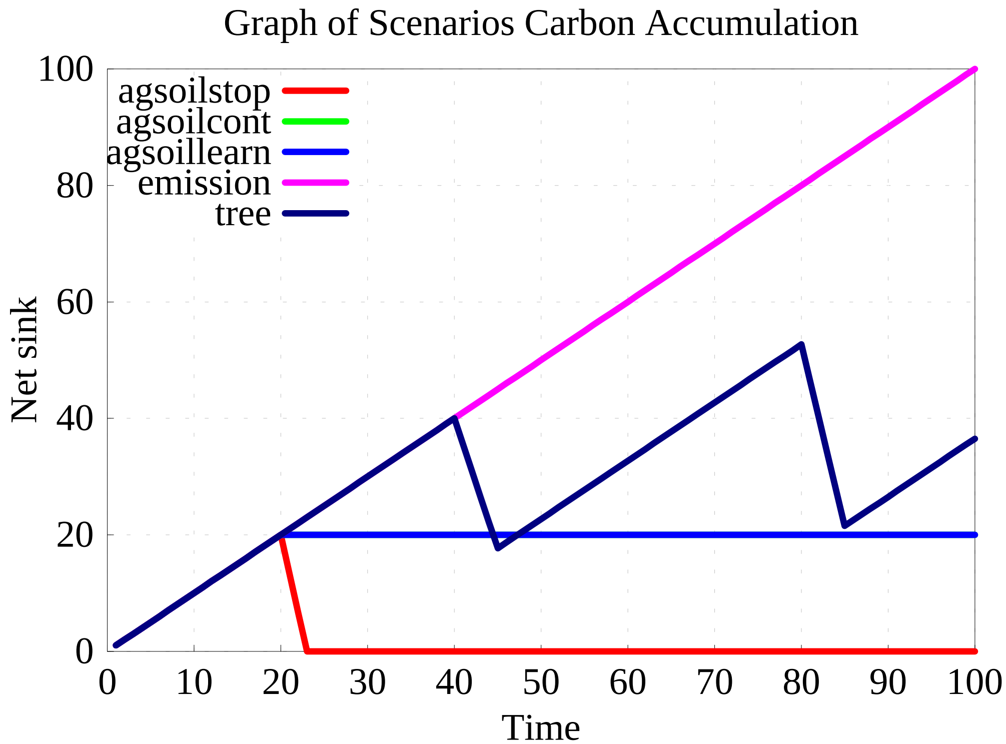


Table 1 Effect on Relative Value of Carbon under Strategy of Using Alternative Discount rates

	4%	5%	6%	7%	8%
agsoilstop– case I	0.379	0.452	0.518	0.575	0.625
agsoilcont– case II	0.556	0.629	0.694	0.746	0.787
agsoillearn– case III	1.000	1.000	1.000	1.000	1.000
emission	1.000	1.000	1.000	1.000	1.000
tree	0.741	0.800	0.855	0.893	0.917

Table 2 Effect on Relative Value of Carbon under Strategy of Using Alternative Price Patterns

	Year Price Peaks						
	No Peak	0	10	20	30	40	100
agsoilstop–case I	0.379	0.517	0.467	0.338	0.286	0.273	0.248
agsoilcont–case II	0.556	0.631	0.613	0.582	0.539	0.515	0.467
agsoillearn–case III	1.000	1.139	1.104	1.043	0.967	0.924	0.837
emission	1.000	1.000	1.000	1.000	1.000	1.000	1.000
tree	0.741	0.804	0.791	0.774	0.742	0.702	0.653

$$\sum_{t=0}^{T}(1+r)^{-t}\, pE_t = \sum_{t=0}^{T}(1+r)^{-t} C_t$$

r is the discount rate
T the number of years in the planning horizon
p the constant real price of emission offsets
E_t the emissions offset in year t
C_t the cost of the emissions offset program in year t.