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Quantifying carbon additionality for uneven-aged forests

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ABSTRACT

Forests can be managed to sequester atmospheric carbon in addition to producing timber. Forest carbon represents a nature-based solution to climate change and global warming. To internalize the positive externality (social benefit) of forest carbon, additionality must be defined and quantified. In this study, the discounted cash flow approach is applied to an uneven-aged sugar maple forest at a steady state to measure carbon additionality. Carbon credits are generated from the marginal forest growth, while a carbon release penalty is incurred by a harvest. The business-as-usual scenario is defined by a shorter harvest cycle, while an alternative carbon scenario is defined by a longer one. Then, additionality is defined by the difference in the net present value of carbon sequestration on a perpetual basis between the two scenarios. Compared with previous analysis on even-aged southern pine plantations, there is some evidence that the uneven-aged sugar maple forest is less economically effective in carbon offset as indicated by the benefit-cost ratio.

INTRODUCTION

Forests can be managed to provide wood fiber and ecosystem services simultaneously. Among the many ecosystem services, forest carbon has been a primary one, especially during the era of global warming induced by greenhouse gas emissions (Ecosystem Marketplace 2022). To internalize the positive externality of carbon sequestration by managed forests, the social benefit and the opportunity cost of forest carbon need to be better understood by landowners, carbon credit buyers and traders, policy makers, as well as the general public. To quantify the benefit of forest carbon, a key step is to measure the additionality, or additional carbon sequestered by a managed forest beyond its business-as-usual practice.

While carbon additionality is theoretically sound, how to gauge it in practice remains a challenge (e.g., Mason and Plantinga 2013; Tahvonen and Rautiainen 2017). Recently, Mei (2023a) demonstrates how to quantify carbon additionality by examining the carbon related cash flows on a perpetual basis for an even-aged southern pine plantation. However, how to quantify carbon additionality for an uneven-aged forest is still worth some investigation. Unlike even-aged forest, trees of different ages coexist in an uneven-aged forest. There are no clear cuts but rather selective harvests. In other words, stands have no beginning or end. From the management standpoint, trees come from natural regeneration which saves replanting cost, but a selection harvest usually incurs more cost than a clear cut.

An uneven-aged forest with trees of all ages is rare (Buongiorno and Gilless 2003). Typically, trees are grouped in patches of similar age but these patches are too small to be considered as even-aged. For example, an uneven-aged forest can be categorized into three size classes according to the size distribution. Once the initial condition (e.g., number of trees in each size class) is identified, a stand can be converted to a desired steady state, in which harvest equals regeneration for each harvest cycle.

In this study, the discounted cash flow method is used to examine carbon additionality of an uneven-aged sugar maple forest in the northeast region of the United States. A carbon credit is derived from the marginal growth of forest over a harvest cycle, while a carbon release penalty is incurred by a harvest based on biomass removal. The business-as-usual is defined by a shorter harvest cycle, in which the profit from perpetual timber production is maximized, whereas an alternative carbon scenario is defined by a longer harvest cycle. Then, additionality is defined by the difference in the net present values of carbon sequestered between the two scenarios on a perpetual basis. In addition, several key factors are qualitatively analyzed to investigate their impact on carbon additionality. Results from this study can shed some light on the economics of forest carbon from uneven-aged forests.

MATERIAL AND METHODS

With a *n*-year harvest cycle and assuming the first harvest takes place in *n* years, the present value of an infinite series of harvests or the forest value (*FV*) is

$$FV = \frac{H}{(1+r)^n - 1} \tag{1}$$

where *H* is the harvest profit every *n* years and *r* is the discount rate. Here, a real discount rate of 5% is used based on past literature (Buongiorno and Zhou 2020; Li 2018; Mei 2023b). If the value of current inventory is *S*, then the land expectation value (*LEV*) of an uneven-aged forest can be calculated as

$$LEV = FV - S \tag{2}$$

Uneven-aged forest management can be modelled as a linear programing problem and multiple objectives can also be factored into the model. The analysis here is based on a sugar maple forest in the northeastern United States as described in Buongiorno and Gilless (2003). Suppose that a sugar maple forest has three size (or age) classes. Size class 1 has the smallest trees while size class 3 has the largest trees (Table 1).

Table 1. Key parameters for the uneven-aged sugar maple forest.

Diameter class	Diameter range (cm)	Number of trees (/ha)	Average diameter (cm)	Basal area of average tree (m^2)	Value per tree ($)
1	10-19.9	840	15	0.02	0.30
2	20-34.9	234	27	0.06	8.00
3	35+	14	40	0.13	20.00

Note: Value per tree is real. Data source: Buongiorno and Gilless (2003).

The growth of the forest every five years can be modeled as

$$\begin{aligned} y_{1,t+1} &= 0.92y_{1,t} - 0.29y_{2,t} - 0.96y_{3,t} + 109 \\ y_{2,t+1} &= 0.04y_{1,t} + 0.9y_{2,t} \\ y_{3,t+1} &= \qquad\qquad 0.02y_{2,t} + 0.9y_{3,t} \end{aligned} \tag{3}$$

where y_1, y_2 and y_3 are the number of trees in each size class, and *t* indicates time measured over a 5-year period. The first term in the first equation means that 92% of size 1 trees will remain in the same size class and the remaining terms describe a natural forest regeneration process. The second equation means that 4% of size 1 trees will migrate into size class 2 and 90% of size 2 trees will remain in the same size class. The third equation means that 2% size 2 trees will migrate into size class 3 and 90% of size 3 trees will remain in the same size class. Given an initial state and a long enough time period (e.g., 100 years) without any disturbance, the forest itself may achieve a steady state, in which the number of trees in each size class does not change over time.

Next, periodic harvests are introduced to the forest management. The goal is to find the optimal harvest rule every *n* years so that the forest sustains a steady state and *LEV* is maximized. As shown in Table 1, the respective initial number of trees for each size class is 840, 234, and 14 per hectare, and the respective economic value per tree for each size class is \$0.30, \$8.00, and \$20.00 (Buongiorno and Gilless 2003). With the harvest decision h_1, h_2 and h_3 for each size class, the optimization problem can be stated under a linear programing framework as

$$\begin{aligned} &\underset{h_1,h_2,h_3}{Max}\, LEV = FV - S \\ &s.t. \quad FV = \frac{H}{(1+r)^n - 1} \\ &\qquad H = 0.3h_{1,t} + 8h_{2,t} + 20h_{3,t} \\ &\qquad S = 0.3y_{1,t} + 8y_{2,t} + 20y_{3,t} \\ &\qquad y_{1,t+1} = 0.92(y_{1,t} - h_1) - 0.29(y_{2,t} - h_2) - 0.96(y_{3,t} - h_3) + 106 \\ &\qquad y_{2,t+1} = 0.04(y_{1,t} - h_1) + 0.9(y_{2,t} - h_2) \\ &\qquad y_{3,t+1} = \qquad\qquad 0.02(y_{2,t} - h_2) + 0.9(y_{3,t} - h_3) \\ &\qquad y_{i,t+1} = y_{i,t}, \text{ for } i = 1, 2, \text{or } 3. \end{aligned} \tag{4}$$

where $y_{i,t} - h_{i,t}$ replaces $y_{i,t}$ in the forest growth function and the standing inventory value *S* is calculated at the steady state. With a computer software (e.g., Excel Solver), the optimal solution can be solved.

Similar to (Mei 2023a), a carbon credit is accounted on an annual basis and a carbon release penalty is triggered at a harvest so that the net future value (*NFV*) of carbon is calculated as

$$NFV = \sum_{t=1}^{n} C_t (1+r)^{(n-t)} - H_n \quad (5)$$

where n is the harvest cycle, C_t is the carbon credit at year t, H_n is the carbon release penalty from a harvest at year n, and r is the discount rate. Carbon release is assumed to be 85% of total carbon stored in the forest biomass removed at the time of a harvest (Creedy and Wurzbacher 2001; Smith et al. 2006). Then, the perpetual carbon value (*PCV*) is calculated as

$$PCV(n) = \frac{NFV}{(1+r)^n - 1} \quad (6)$$

In other words, *PCV* reflects the monetized social benefit from forest carbon, and the change in *PCV* between the baseline timber management and the alternative carbon management measures additionality.

Carbon credits are converted from marginal forest growth. Given that the forest is at a steady state, growth approximately equals harvest within a harvest cycle. To convert aboveground forest biomass to dry masses, the following allometric equation for a sugar maple tree is used (Fatemi et al. 2011),

$$\log(Y) = 2.180 + 2.416 \log(X) \quad (7)$$

where Y is the weight of dry masses in grams and X is the diameter at breast height in centimeters. Carbon is assumed to be 50% of dry mass (Lamlom and Savidge 2006; Smith et al. 2006) and is assumed to accumulate in trees linearly over time within a harvest cycle. Then, a carbon price of \$20 per metric ton (\$5.45 per ton of CO_2 equivalent) based on recent transaction prices in the voluntary carbon market (Donofrio et al. 2021) is used in combination with carbon weight to calculate annual carbon credits. That is, an equal annual carbon credit is used within a harvest cycle in the calculation of *PCV*.

RESULTS AND DISCUSSION

Without any disturbance, the uneven-aged maple forest converges to a steady state in about 75 years (Figure 1), reflecting its biological carrying capacity without any management in which the growth just offsets the mortality and the stand structure per hectare varies little through time.

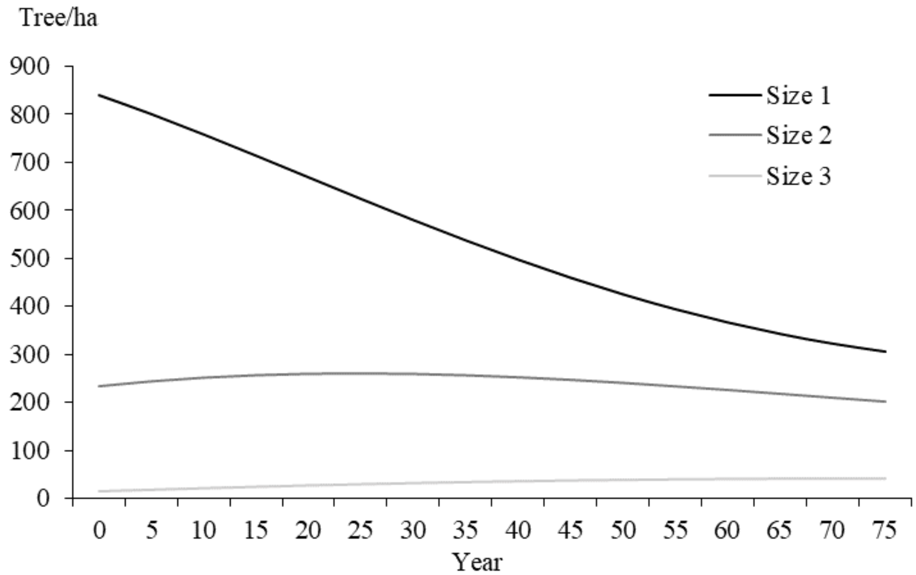

Figure 1. The evolvement of an uneven-aged sugar maple forest to a steady state without any disturbance.

Despite an enhanced diversity in the number of trees in each size class at the steady state, there are no proceeds from timber harvest. When the uneven-aged forest is managed with a chosen harvest cycle instead, a different steady status would be reached and an economic gain from selling timber periodically can be realized.

Provided the same initial condition, the optimal solution for the baseline scenario of a 5-year harvest cycle is solved as h_1=0, h_2=55, h_3=0, y_1=1363, y_2=55, y_3=0, and LEV is maximized at \$733.35 per hectare. Considering carbon additionality, an alternative 10-year carbon harvest cycle is implemented so that carbon is stored in the forest for five additional years and carbon release at the time of harvest is delayed for five years. The optimal solution is h_1=0, h_2=97, h_3=1, y_1=1267, y_2=97, y_3=1, and LEV is maximized at \$87.86 per hectare. Therefore, the opportunity cost for the landowner to store 5-year additional forest carbon is 733.35 – 87.86 = \$645.49 per hectare.

With a 5-year harvest cycle, forest growth equals 55 trees per hectare in the second size class. According to Equation 7, the average weight of dry masses of a size 2 class tree is $10^{2.180 + 2.416\log(27)}$ = 434,685.2 grams or 0.4346852 metric tons. Carbon is one half of the dry mass, and with a carbon price of $20 per metric ton, the annual carbon credit is 0.4346852 × 0.5 × 20 × 55 ÷ 5 = $47.82 per hectare. At the time of harvest, the carbon release penalty is 0.4346852 × 0.5 × 20 × 55 × 0.85 = $203.22 per hectare. The corresponding NFV and PCV are $60.99 and $220.77 per hectare, respectively.

With the 10-year harvest cycle, forest growth equals 97 trees in the second size class and one tree in the third size class per hectare. Following the same procedure, the corresponding NFV and PCV are calculated to be $176.52 and $280.69 per hectare. Therefore, the benefit from 5-year additional forest carbon is 280.69 – 220.77 = $59.92 per hectare. The benefit cost ratio is 59.92 / 645.49 = 0.093.

Next, the impact of some key factors on the benefit-cost analysis of carbon sequestration from an uneven-aged forest is discussed qualitatively. First, a higher carbon price would result in a higher benefit of forest carbon and, thus, a higher benefit-cost ratio. Second, higher timber prices make the opportunity cost of forest carbon higher, hence reducing the benefit-cost ratio. Third, a change in the discount rate has an ambiguous impact on the benefit-cost ratio as it affects both the numerator and the denominator. The ultimate impact depends on the relative change of the benefit verses the cost.

Fourth, the initial condition of the uneven-aged forest matters as it determines the steady state and the optimal harvest, which in turn determines the opportunity cost of forest carbon. The initial condition also determines the time to convert an uneven-aged forest to a steady state and the associated timber profit and carbon accounting during this transition period. More future work is needed along this line. Lastly, forest growth follows a sigmoid curve and is nonlinear in nature. Given that most growth in this analysis comes from the smaller size class, the marginal growth is likely higher in the early years during a harvest cycle, and so are the corresponding carbon credits. Therefore, the estimate of carbon benefit in this study tends to be conservative.

CONCLUSIONS

Forest carbon is a crucial tool to mitigate global warming. To internalize its externality, carbon additionality needs to be quantified. While there have been many endeavors to analyze forest carbon from even-aged plantations, research on forest carbon from uneven-aged forests has been sporadic, partly because uneven-aged systems are more complex than even-aged ones. In this study, the discounted cash flow approach is applied to an uneven-aged sugar maple forest at a steady state to measure carbon additionality. Compared with the even-aged southern pine plantation (Mei 2023a), there is some evidence that the uneven-aged sugar maple forest is less economically effective in carbon offset as indicated by the benefit-cost ratio. Should we aim for total carbon sequestration instead, the ranking might change. However, we need to keep in mind that uneven-aged forest management is very attractive for multiple uses, especially when timber production is not the primary objective. When it comes to carbon, the proposed method here helps understand the tradeoff between the timber profit to forgo by the landowners and the carbon benefit to achieve by the whole society.

CONFLICT OF INTERESTS

The author declares no conflict of interest.

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