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Microeconomics of Nitrogen Fertilization in Boreal Carbon Forestry

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Abstract: The nitrogen fertilization of boreal forests is investigated in terms of microeconomics as a tool for carbon sequestration. The effects of nitrogen fertilization's timing on the return rate on capital and the expected value of the timber stock are investigated within a set of semi-fertile, spruce-dominated boreal stands using an inventory-based growth model. Early fertilization tends to shorten rotations, reducing timber stock and carbon storage. The same applies to fertilization after the second thinning. Fertilization applied ten years before stand maturity is profitable and increases the timber stock, but the latter effect is small. The fertilization of mature stands, extending any rotation by ten years, effectively increases the carbon stock. Profitability varies but is increased by fertilization instead of merely extending the rotation.

Keywords: carbon sequestration; timber stock; rotation age; expected value; periodic boundary condition

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1. Introduction

Growing forests sequester atmospheric carbon dioxide, partially mitigating the ongoing change in the Earth's climate [1–3]. Enhancing the rate of forest growth advances the mitigation process. Various tools have been proposed for increasing the growth rate, such as plant improvement, ditch maintenance, thinning schedule optimization, and fertilization [4–6].

The forest growth rate, however, is not the only decisive factor contributing to climate change mitigation. The storage of carbon in solid biological materials reduces the amount of atmospheric carbon, thereby mitigating climate change [7,8]. Arithmetically, one cubic meter of roundwood stores the equivalent of one ton of carbon dioxide. However, carbon is also stored in roots, branches, leaves, litter, and soil. Altogether, the carbon storage of one cubic meter of commercial wood corresponds to about two tons of stored CO_2 [9,10]. Correspondingly, increasing the timber stock in forests reduces the amount of atmospheric carbon dioxide. Therefore, the mitigation effect not only depends on growth but also on harvesting, as well as natural decay processes.

Nitrogen fertilization appears to be most effective in increasing growth when combined with the addition of phosphorus [11]. Nitrogen fertilization is not very beneficial on the most fertile sites [12–14]. Nitrogen fertilization mostly applies to mineral soil [15,16]. The trees on the site must be both abundant and vital enough to utilize the fertilization effect [12,13]. Conifers respond well to fertilization, whereas birch (*Betula*) species are less responsive [16–19].

As the effect of boron fertilization may endure [20], nitrogen fertilization usually contributes for a period of, at most, 10 years [11,21]. Long-term nitrogen fertilization may reduce microbial activity in soil, possibly resulting in increased soil organic matter content [16,22].

A previous paper discussed the timing and intensity of fertilization in terms of a cash flow analysis [13]. This study adopts a financial perspective instead of the cash flow approach, and the carbon storage aspect is considered, in addition to business economics.

Using an inventory-based growth model on five example stands, four different timings of nitrogen fertilization within any rotation are examined, and their effect on the rate of return on capital on the one hand and on the expected value of the timber stock on the other are discussed. In other words, different fertilization timings and related harvesting schedules are investigated as climate change mitigation procedures, emphasizing the microeconomic perspective.

2. Materials and Methods

Within a cyclical system with periodic boundary conditions, the expected value of the profit rate is

$$\left\langle \frac{d\kappa}{dt} \right\rangle = \int_{b}^{b+\tau} \frac{d\kappa}{dt} p(t) dt \tag{1}$$

where τ is cycle duration, $p(t)$ is the probability density of time within the cycle, and $\frac{d\kappa}{dt}$ is any current profit rate. On the profit/loss–basis, the profit rate includes value growth, operative expenses, interests, and amortizations but neglects investments and withdrawals. On the other hand, the expected value of the capitalization is

$$\langle K \rangle = \int_{b}^{b+\tau} K p(t) dt \tag{2}$$

where the capitalization K, on a balance sheet basis, is directly affected by any investments and withdrawals. Then, the expected value of the rate of return on capital is

$$\langle r \rangle = \frac{\left\langle \frac{d\kappa}{dt} \right\rangle}{\langle K \rangle} \tag{3}$$

To apply Equation (3) in rotation forestry, it is necessary to include growth rate, prices, and expenses. It is also necessary to include some kind of initial stand conditions, which may consist of either establishment procedures of a stand of seedlings or saplings or measurement data of young, preferably not previously thinned stands [23,24]. Here, measurement data from five never-thinned Norway spruce (*Picea abies*) -dominated young stands are taken as the set of initial stand conditions. The stands (aged between 30 and 45 years) have been described in detail in earlier papers [23–28]. Each stand was represented by a circular spot with a ten meter radius, within which the breast-height diameter of each tree was recorded. The commercial volume of each trunk was determined on the basis of previously collected harvester data, as clarified in [28,29]. This study discusses nitrogen fertilization, and only mesic stands (medium fertility) are included; herb-rich stands wherein nitrogen fertilization does not apply well were excluded [12–14].

Prices and expenses were retained at the 2019 level to ensure comparability with earlier investigations [23–28]. Regeneration expenses are amortized first at the occurrence of final harvesting [30], whereas fertilization expenses are amortized at the occurrence of the first harvesting after fertilization.

Technically, a time evolution from any initial condition is established according to a growth model [31] with 30-month timesteps any field observation serving as the initial condition. The development of any stand from the time of establishment to the time of field observation was clarified in terms of exponential interpolation. In the absence of thinnings, this procedure results in an expected value of capital return rate for any rotation age τ, according to Equation (3), observable at the end of each time step. The rotation age giving the greatest expected value of the capital return rate appears the most feasible in the absence of thinnings. Then, one thinning is introduced, and within the computer program, one can experiment with its timing, severity, allocation to tree species, and diameter classes. If the thinning is successful in improving the maximal expected value of capital return rate, it is considered feasible. If thinning succeeds in improving the expected value of the capital return rate, another thinning is introduced, again experimenting with timing, severity, and allocation in terms of both introduced thinnings. Further thinnings are introduced this way, one by one, provided the previous one is successful in improving the expected value of the capital return rate. It is worth noting that, in principle, two or more thinnings could be financially feasible even if a single commercial thinning would not be profitable. However, the author is not aware of any such occurrence in boreal forestry, where the number of thinnings tends to be limited because of the requirements of operational efficiency.

The above procedure did not contain any fertilization treatments. Four different sets of boundary conditions for fertilizations were introduced as follows.

As the five example stands that were observed ranged in age from 30 to 45 years and had a stem count of 1655–2451/ha and a basal area of 29–49 m^2/ha, they were due for commercial thinning. The first fertilization treatment examined was implemented without delay after the thinning. Two of the five example stands were supposed to be thinned twice to maximize the expected value of the return rate on capital (Equation (3)). The other set of boundary conditions was to fertilize after the second thinning. While early fertilizations possibly shorten rotations, the third boundary condition was fertilization ten years before maturity, which supposedly does not shorten rotations. The fourth boundary condition was to fertilize at stand maturity, which would probably extend each rotation by ten years.

The effect of each nitrogen fertilization was technically implemented within the growth model [31] by increasing the site fertility index by five meters (dominant height at a breast-height age of 40 years) for a period of ten years. It was verified that the growth response obtained in this way corresponded with the results of experimental fertilization studies [11–13,16,19].

3. Results

The first fertilization treatment examined was implemented without delay after the first thinning. The results regarding the expected value of the operative rate of return on capital are shown in Figure 1. For comparison, Figure 1 also shows the corresponding results in the absence of fertilization. It was found that, in all five cases, fertilization increases the return rate on capital. On the other hand, fertilization reduces the rotation age corresponding to the rotation, resulting in the greatest return rate on capital. The shortening of the rotation was five years in four cases and ten years in one case.

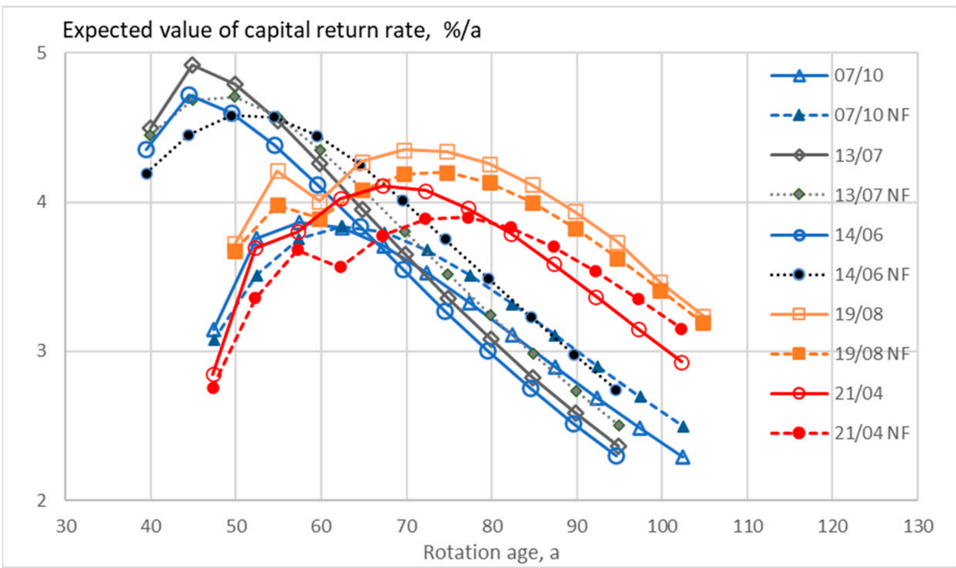

Figure 1. Expected value of capital return rate with fertilization applied after the first thinning and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

As the rotations are shortened, the expected value of the timber stock is reduced, as shown in Figure 2 (with one exception). The reduction in the timber stock is in the order of 5 to 10 m^3/ha.

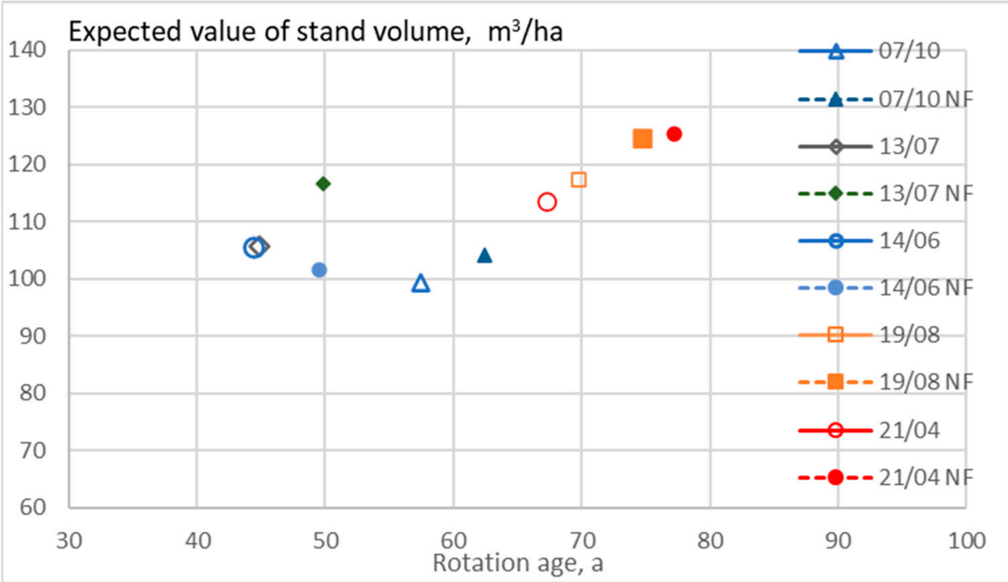

Figure 2. Expected value of stand volume with fertilization after the first thinning and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

It is worth noting that the expected value of the timber stock is already elevated at the leftmost data points appearing in Figure 1. These data points correspond to a time spot five years after the initial field observation. The observable difference in the expected value of the return rate on capital is affected by the fact that the suitable thinning intensity is not the same if the stand is supposed to be fertilized; the application of the fertilization favors a greater timber stock. Such a phenomenon is most pronounced in the case of stand 14/06, where the expected value of the timber stock increases (according to Figure 2).

In the presence of fertilization, the operative return rate on capital is maximized if the rotations are shortened (as shown in Figure 1). However, there is no obligation for shortening rotations. In four of the five cases, fertilization would be slightly profitable even if the rotations would not be shortened (Figure 1). The duration of the rotation could be contracted in a carbon sequestration agreement. However, in Figure 1, in the absence of fertilization, the maximum return rate on capital would be be obtained via final harvesting from 15 to 40 years after fertilization. It might be challenging to regulate rotation ages in such a long time frame.

Two of the five example stands appearing in Figure 1 are supposed to be thinned twice to maximize the expected value of the return rate on capital (Equation (3)). Then, a natural alternative for fertilization after the first thinning, shown in Figure 1, would be fertilization after the second thinning. The result in terms of the expected value of the return rate on capital is shown in Figure 3. In both cases, fertilization is profitable. However, not only the return rate on capital is increased, but the optimal rotation is shortened by ten years in both cases. In case the rotation would not be shortened, the fertilization would be non-profitable, as it would reduce the return rate on capital (Figure 3).

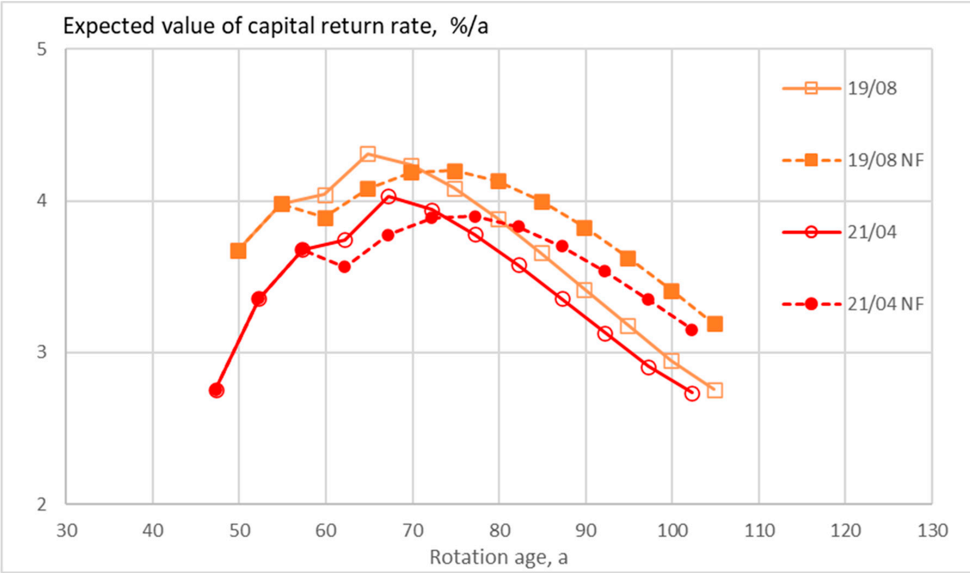

Figure 3. Expected value of capital return rate with fertilization applied after the second thinning and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

As the rotation age is shortened by a decade, the expected value of the timber stock is reduced, as shown in Figure 4. This occurs even though forthcoming fertilization induces an elevated timber stock to be retained after the second thinning.

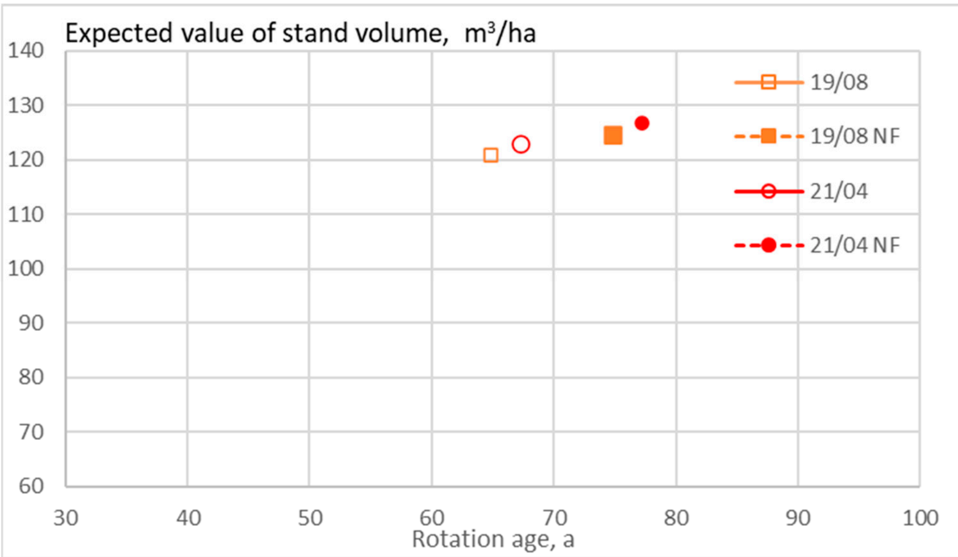

Figure 4. Expected value of stand volume with fertilization after the second thinning and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

Figures 1–4 indicate that early fertilization is not necessarily a functional tool of carbon sequestration, as it tends to shorten rotations and correspondingly reduce the expected value of the timber stock. An obvious solution for the problem involves delaying fertilization for ten years before stand maturity, in which case it should not shorten rotations. Figure 5 shows the results of such a procedure. In all five cases, fertilization is profitable, as it increases the expected value of the return rate on capital.

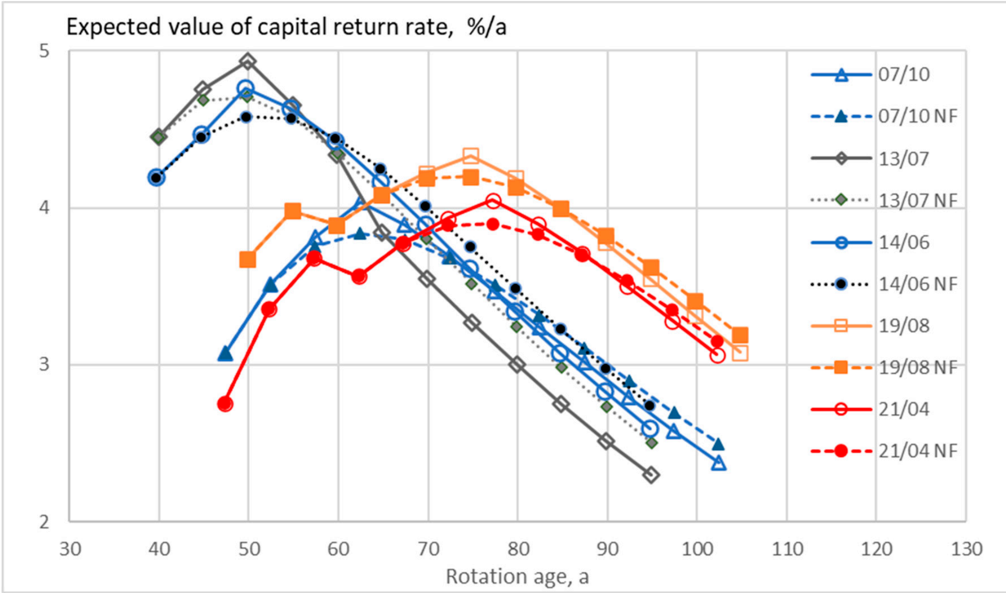

Figure 5. Expected value of capital return rate with fertilization applied ten years before stand maturity, not altering the rotation time, and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

Figure 6 shows the expected value of the timber stock with and without fertilization. In all cases, fertilization increases the expected value of the timber stock. However, in all cases, the effect is small (in the order of one to three percent). The small effect is understandable since the timber stock is slightly elevated for a small fraction of the rotation [23]. It is worth noting that, because the fertilizations in Figures 5 and 6 are not associated with any thinning, the thinning schedules have not been altered.

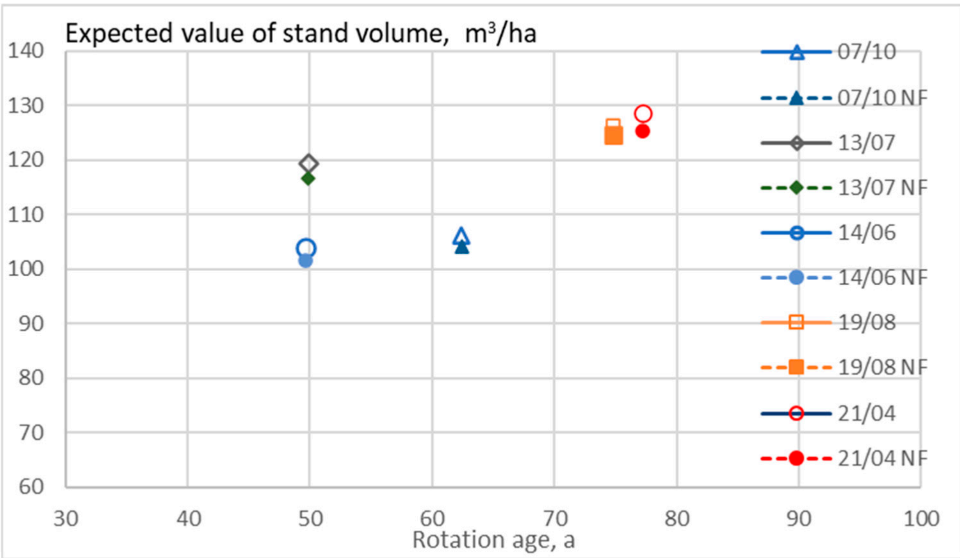

Figure 6. Expected value of stand volume with fertilization ten years before stand maturity, not altering the rotation time, and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

A larger increment of the expected value of the timber stock would be gained if the rotations are extended. Figure 7 shows the expected value of the return rate on capital when fertilization is applied at stand maturity and any rotation is extended by ten years. Profitability varies; in two of the five cases, the treatment is profitable, whereas in the remaining three cases, it is not. However, fertilization improves profitability in all cases compared to merely extending the rotation (Figure 7).

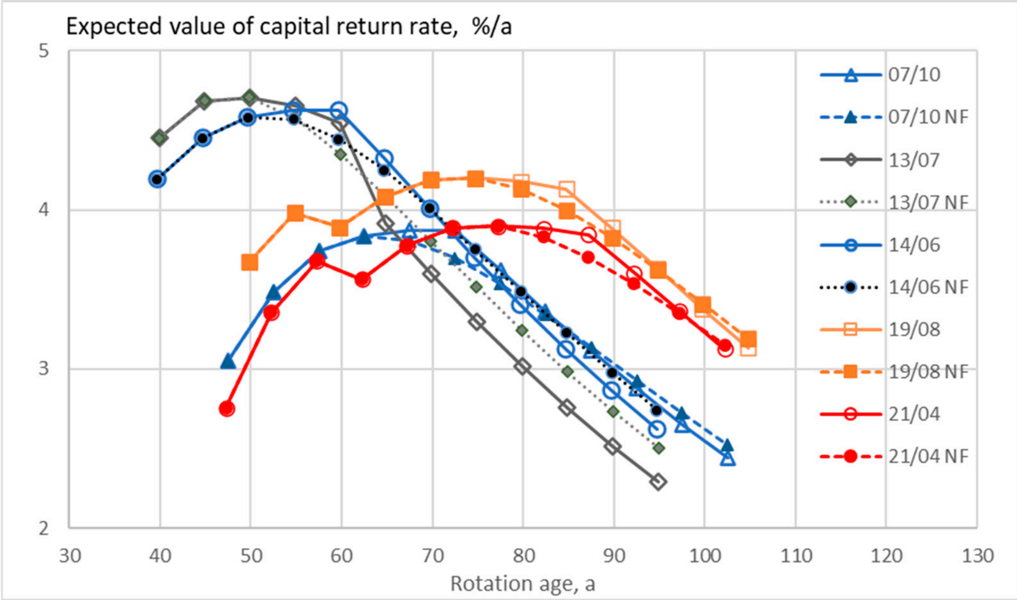

Figure 7. Expected value of capital return rate with fertilization applied at stand maturity, prolonging the rotation by at least 10 years, and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

Figure 8 shows that extending the rotation by ten years is an effective tool for increasing the timber stock. In the presence of fertilization, the expected value of the timber stock increases from 17.8% to 29.1% (the smallest increments gained by extending the longest rotations). In terms of cubic meters per hectare, these values correspond to 22–34 m^3/ha. In the absence of fertilization, the timber stock increment ranged from 16.6% to 26.9% (21–31 m^3/ha). Correspondingly, the fertilization effect on the timber stock increment is small. It can be seen from Figure 7 that the financial effect is probably more important.

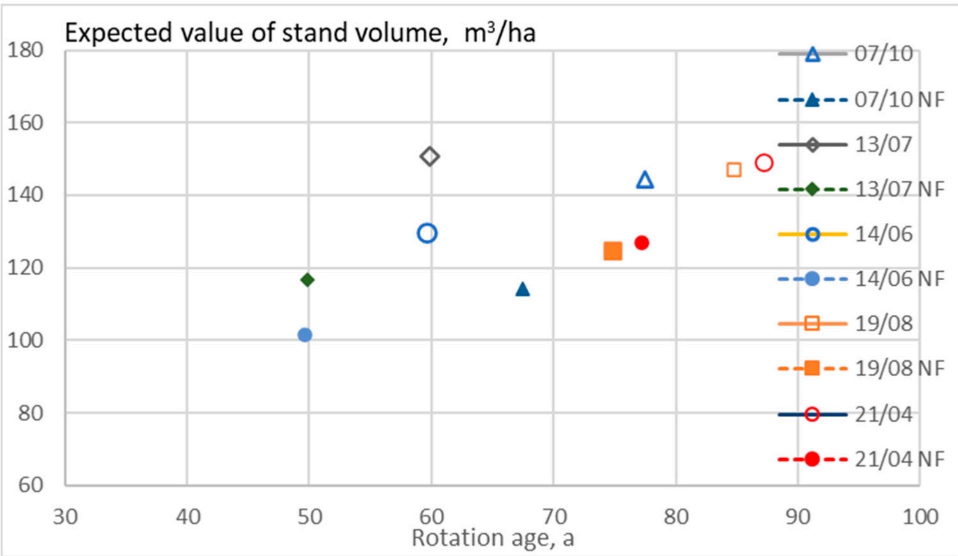

Figure 8. Expected value of stand volume with fertilization at stand maturity, extending rotation by ten years, and without fertilization (NF). The numbers in the legend refer to stand and plot identification.

Quantifying the financial effect of extending the rotation, as well as the effect of fertilization on it, appears possible. The financial expense of extending the rotation is

$$\langle E \rangle = -\Delta\langle r \rangle\,(\tau + \Delta\tau)(\langle C \rangle + \Delta\langle C \rangle) \tag{4}$$

where $\Delta\langle r \rangle$ refers to the change in the expected value of the rate of return on capital, $\Delta\tau$ refers to the change in the duration of the rotation, and $\Delta\langle C \rangle$ refers to the change in the expected value of capitalization.

The financial expense of enhanced timber stock per year and excess volume can subsequently be given as

$$\frac{\langle E \rangle}{\Delta\langle V \rangle\,(\tau + \Delta\tau)} \tag{5}$$

where $\Delta\langle V \rangle$ is the change in the expected value of commercial stand volume.

Figure 9 shows that the financial expense of extending the rotation by ten years, according to Equation (4), varies from 548 to 1628 Eur/ha without fertilization. Fertilization significantly reduces the financial expense, with the rotation extension becoming profitable in the case of two of the five example stands. It is still worth noting that the level of expenses is based on figures from 2019 [25,26,30].

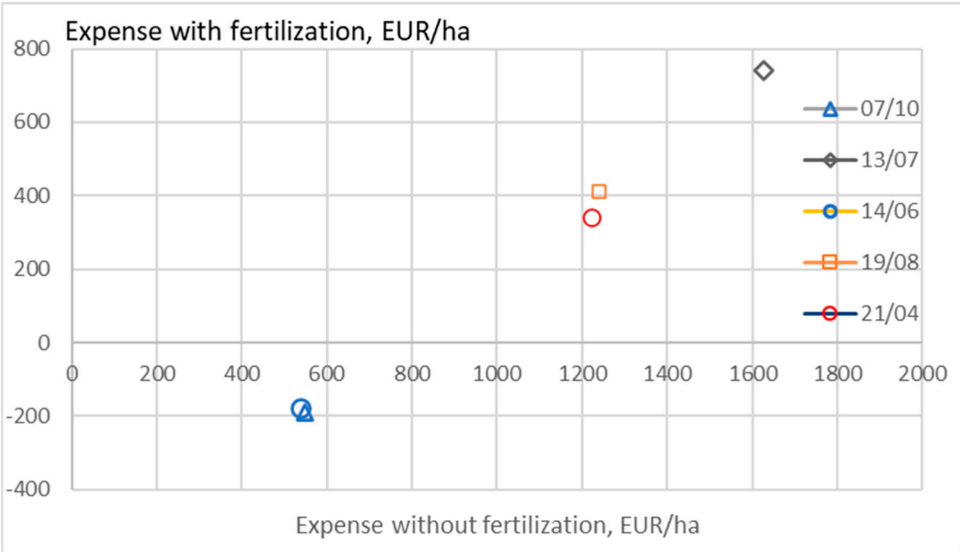

Figure 9. The financial expense of extending the rotation by ten years, according to Equation (4). Without fertilization (horizontal axis) and with fertilization (vertical axis). The numbers in the legend refer to stand and plot identification.

It is also possible to compute the financial expense of enhanced timber stock per year and excess volume according to Equation (5). Without fertilization, the financial expense is 0.32–0.80 Eur/(m^3*a), and with fertilization, the financial expense is -0.10–0.36 Eur/(m^3*a). According to Equation (5), the financial expenses allocated for the extension period onlyare achievable via scaling with $(\tau + \Delta\tau)/\Delta\tau$.

4. Discussion

The results indicate that early fertilization tends to shorten rotations, thereby reducing the expected value of the timber stock volume. Correspondingly, early fertilization cannot be used as a tool for carbon sequestration. There may be circumstances where this conclusion does not hold. In the case of a centrally planned economy instead of a market economy with microeconomic drivers, it might be possible to regulate the rotation ages. Even in a market economy, it might be possible to regulate the rotation ages in terms of voluntary carbon sequestration contracts. However, difficulties might appear in the realization of long-term contracts applicable to individual forest sites for several decades.

The results also indicate that, as fertilization implemented first ten years before stand maturity does not shorten rotations, it correspondingly does not reduce the carbon stock. Such an operation is often profitable (Figure 5), but the effect on carbon storage is small (Figure 6). This small contribution to carbon storage has previously been discussed in the literature [23].

Fertilization applied at stand maturity, thereby extending rotations, effectively increases carbon storage (Figure 8). However, as indicated in the text, the effect of fertilization on the increase in the expected value of timber stock is small, and the main contribution comes from the extension of the rotation. On the other hand, the effect of fertilization on finances is large, as indicated in Figure 9. According to Figure 9, fertilization significantly increases profitability; however, Figure 7 indicates that even if fertilization is applied, extending the rotation is mostly not profitable. Thus, microeconomics proposes that the extension of rotations requires some kind of external incentive, such as a carbon sequestration contract or something similar.

There are circumstances where the results of this paper do not apply. Firstly, nitrogen fertilization is not very beneficial on the most fertile sites [12–14]—such sites have been excluded from the present dataset. Secondly, nitrogen fertilization only applies to mineral soil [15,16]. Thirdly, the trees on the site must be both abundant and vital enough to exploit the fertilization effect [12,13].

The denominator of Equation (3) naturally includes bare land value. Bare forest land is not frequently traded, which makes it difficult to assess its market value. The value of bare land does contribute to the results; increased bare land value favors greater timber stocks and longer rotations. The effect of variable bare land value on fertilization was not investigated for this paper.

Instead of the financial formulation given in Equation (3), the present problematics could have been approached in terms of a cash flow analysis [13]. The author of the present paper recently attempted to use such an approach. Several problems appeared. Firstly, the overall results are very sensitive to discount rates. Secondly, the effect of the temporal displacement of activities is sensitive to discount rates. Thirdly, it is difficult to compare the current profitability of fertilizations implemented at different times. Fourthly, the profitability of fertilizations implemented at different times compared at any observation time (present time) depends on the selection of the observation time.

There may be other circumstances wherein the microeconomic approach applied in this paper is not functional. The present approach is based on the computation of an operative return rate of capital under periodic boundary conditions. The periodic boundary conditions, as such, are a simplification of reality; however, they are not necessarily unrealistic. More importantly, the periodic boundary condition can possibly be abandoned by divesting estates [32]. Hence, real estate proceeds may complement or exceed the income from forest operations. This might open new avenues for the utilization of early fertilization. However, a more detailed analysis of such economics is outside the scope of this study.

This paper has discussed the microeconomics of fertilization and the timing of harvesting, along with its consequences in carbon sequestration. The outcome, however, may depend on macroeconomic boundary conditions [6]. An extreme macroeconomic boundary condition might be a stiff (constant) demand for timber. Such a boundary condition would result in reduced harvesting elsewhere if harvesting is increased on one estate. If increased growth does not increase harvesting, increased growth is always beneficial for the accumulation of the carbon stock. However, the present study's author is not aware of any proof that suggests that such stiff demand-related boundary conditions would exist. Instead, one can reasonably assume that macroeconomics is a system producible by integrating microeconomies, even if interactions between microeconomies are difficult to predict [33–36].

It is worth noting that climate change mitigation was discussed in this paper in terms of boreal forest timber stock only. In reality, some substitution effects may also appear [37,38]. The carbon footprint of each fertilization operation was neglected due to the very small footprints of forest operations [39,40].

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