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# Impacts of Alternative Harvesting and Natural Disturbance Scenarios on Forest Biomass in the Superior National Forest, USA

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**Abstract:** The amount of biomass stored in forest ecosystems is a result of past natural disturbances, forest management activities, and current structure and composition such as age class distributions. Although natural disturbances are projected to increase in their frequency and severity on a global scale in the future, forest management and timber harvesting decisions continue to be made at local scales, e.g., the ownership or stand level. This study simulated potential changes in natural disturbance regimes and their interaction with timber harvest goals across the Superior National Forest (SNF) in northeastern Minnesota, USA. Forest biomass stocks and stock changes were simulated for 120 years under three natural disturbance and four harvest scenarios. A volume control approach was used to estimate biomass availability across the SNF and a smaller project area within the SNF (Jeanette Project Area; JPA). Results indicate that under current harvest rates and assuming disturbances were twice that of normal levels resulted in reductions of 2.62 to 10.38% of forest biomass across the four primary forest types in the SNF and JPA, respectively. Under this scenario, total biomass stocks remained consistent after 50 years at current and 50% disturbance rates, but biomass continued to decrease under a 200%-disturbance scenario through 120 years. In comparison, scenarios that assumed both harvest and disturbance were twice that of normal levels and resulted in reductions ranging from 14.18 to 29.85% of forest biomass. These results suggest that both natural disturbances and timber harvesting should be considered to understand their impacts to future forest structure and composition. The implications from simulations like these can provide managers with strategic approaches to determine the economic and ecological outcomes associated with timber harvesting and disturbances.

**Keywords:** forest management; natural disturbance; timber harvest; biomass; Minnesota

## 1. Introduction

Future global change scenarios predict increases in the frequency and severity of natural disturbances in forest ecosystems [1,2]. Quantifying the impact that natural disturbances have on forest productivity is essential to foster the continued interest in using forest-derived biomass for energy [3,4], understanding the contribution of salvage timber harvests to wood markets [5], and determining carbon source-sink dynamics associated with forest ecosystems [6]. Although forest productivity gains in response to future global change scenarios may be hypothesized, including projected natural disturbance rates in simulations of forest growth can negate any potential gains in productivity related to climate change [7]. These natural disturbances directly impact the age class distribution of trees of different species, which subsequently impacts forest biomass and carbon at landscape level.

In addition to natural disturbances, determining the role of anthropogenic disturbances such as timber harvesting and forest management lends insight into future forest growth patterns [8]. Consequently, models of forest growth should be flexible to account for changing forest dynamics such as biotic disturbance agents [9]. Understanding the simultaneous roles that both natural disturbance and timber harvesting have on forest biomass and carbon stocks is crucial [10]. The planning and implementation of timber harvesting to sustain or increase forest ecosystem carbon stocks must occur in the context of intensifying forest disturbances [10,11]. In the United States, 65 million hectares of unreserved, productive public timberlands are managed under laws that allow or mandate sustainable commercial timber harvests [12]. In the US state of Minnesota, 819,000 $m^3$ of wood was harvested on federal ownerships in 2012 [13], representing an important component of the state's timber supply. Common natural disturbances in this state include fires [14], windstorms [15], and insect outbreaks such as *Choristoneura fumiferana* (Clem.) [16]. These disturbances, each which vary in their intensity and severity, ultimately influence forest stand dynamics through increased tree mortality and changes in forest regeneration patterns. Strategic timber harvest goals across expansive publicly-managed timberlands in the US should incorporate varying natural disturbance scenarios to account for changes in forest biomass stocks and stock changes.

Forest management decisions on federally-owned timberlands in the US, e.g., lands managed by the US Department of Agriculture (USDA) Forest Service, are typically made at the forest or management unit level. While many natural disturbances will impact large geographic areas at the landscape level, forest management decisions such as annual harvest rates typically are made using forest inventory information such as the age class distribution of various tree species. In lieu of incorporating constant disturbance rates in long-term simulations of forest biomass stock changes, a model that incorporates the mortality of different forest types and stand ages would capture the way these factors affect stands in disparate ways. Further understanding the dynamics between natural disturbance and timber harvest and the subsequent implications to forest biomass stocks would allow strategic decision making by forest managers and planners on public timberlands.

The objective of this study is to investigate how potential changes in natural disturbance regimes alter timber harvesting goals across the Superior National Forest in northeastern Minnesota, USA. Specific objectives are to (1) quantify forest biomass stocks and stock changes over a 120-year time period associated with alternative forest management and natural disturbance scenarios, and (2) develop a probabilistic framework for determining annual timber harvest levels across varying natural disturbance regimes.

## 2. Materials and Methods

### *2.1. Study Area*

Approximately 508,000 ha of timberland are found across the Superior National Forest (SNF) in northeastern Minnesota, USA. Average annual temperature and precipitation in nearby Ely, MN is 3 °C and 69 cm, respectively. In addition to the entire SNF, managers were subsequently interested in determining alternative forest management strategies for a smaller project area, termed the Jeanette Project Area (JPA). The JPA occupies approximately 40,000 ha of timberland within the SNF (Figure 1) and borders the Boundary Waters Canoe Area Wilderness, a designated wilderness area of the SNF that was excluded in this analysis.

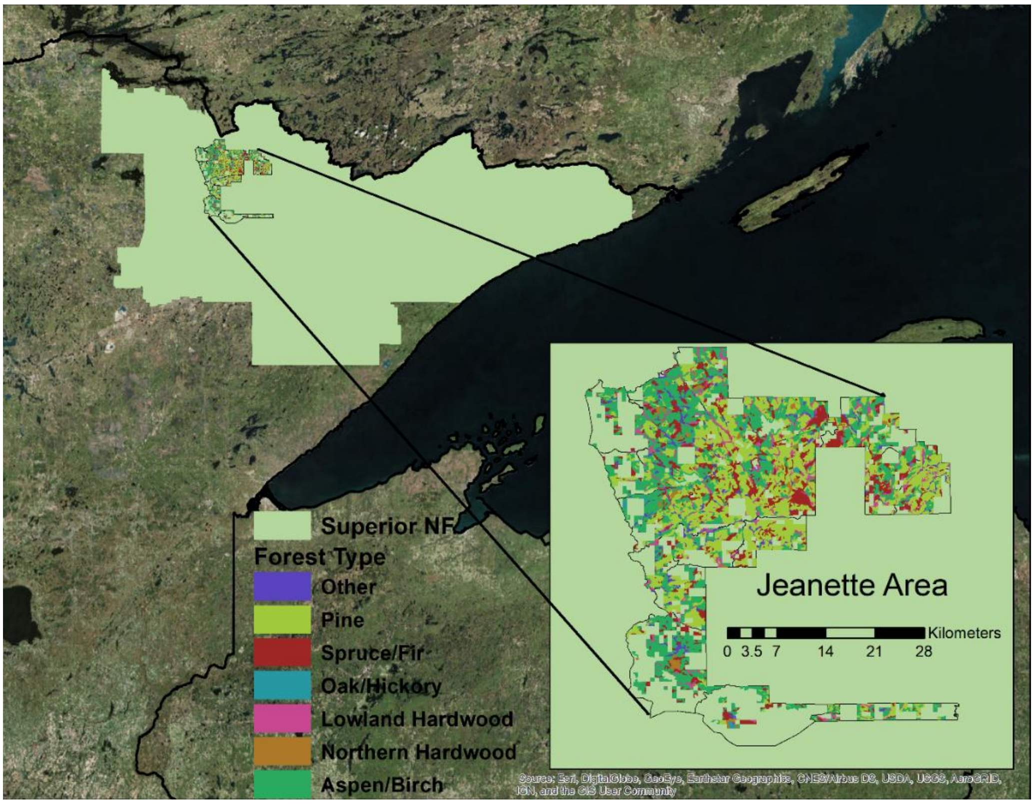


**Figure 1.** Location of Superior National Forest and Jeanette Project Area, with forest types, in northeastern Minnesota, USA.

The SNF is comprised of the Laurentian mixed-forest province and represents a transition between the Great Lakes-St. Lawrence and boreal forest regions [17]. The shade intolerant and pioneer species aspen (*Populus tremuloides* Michx.) and to a lesser extent birch (*Betula papyrifera* Marsh.) dominate much of the landscape [18]. Hardwoods such as elms (*Ulmus* spp.) and black ash (*Fraxinus nigra* Marsh.) occupy lowland areas. The primary conifer species include red (*Pinus resinosa* Aiton), white (*Pinus strobus* L.), and jack pine (*Pinus banksiana* Lamb.) in addition to the more shade tolerant spruce (*Picea* spp.) and balsam fir (*Abies balsamea* (L.) Mill.). The aspen/birch forest type dominates the SNF, but a higher proportion of the white/red/jack pine forest type is found within the JPA (Table 1).

**Table 1.** Summary of estimated timberland area and current biomass (including bole, tops, and branches) for the four primary forest types in the Superior National Forest (SNF) and Jeanette Project Area (JPA), northeastern Minnesota, USA. Timberland area for SNF and Jeanette based on 435 Forest Inventory and Analysis plots and stand type maps, respectively. Values in parentheses for SNF are biomass estimates obtained from Forest Inventory and Analysis plots using the EVALIDator tool [19].

| Forest Type | Timberland Area (ha) [1] | | Total Biomass (Tg) | | Biomass Density (Mg ha$^{-1}$) | |
|---|---|---|---|---|---|---|
| | SNF | JPA | SNF | JPA | SNF | JPA |
| Aspen/birch | 219,254 | 13,400 | 7.98 (8.24) | 0.48 | 36.4 (37.6) | 35.8 |
| White/red/jack pine | 63,529 | 14,680 | 3.00 (3.83) | 0.60 | 47.2 (60.3) | 40.9 |
| Spruce/fir | 161,307 | 5316 | 3.38 (5.67) | 0.12 | 21.0 (35.2) | 22.6 |
| Elm/ash/cottonwood | 19,607 | - | 0.88 (0.61) | - | 44.9 (31.1) | - |
| Total | 463,697 | 33,396 | 15.25 (18.35) | 1.20 | 32.9 (39.6) | 35.9 |

[1] These forest types occupy approximately 91% and 83% of the total timberland area across the SNF and JPA, respectively.

### 2.2. Forest Data

Data used to characterize the forest composition of the SNF were based on 435 measurement plots obtained from the USDA Forest Service's Forest Inventory and Analysis (FIA) database [20]. The FIA plots are measured using a nationally-consistent protocol with approximately one plot located every 2400 ha [21]. For the JPA, too few FIA plots were available ($n = 20$) to initialize model simulations. In lieu of this, detailed stand type maps that included total area of timberland by stand age classes and forest types in the JPA were used to initialize model simulations. Four forest types were included for the SNF simulations (aspen/birch, white/red/jack pine, aspen/birch, and elm/ash/cottonwood) but due to the minimal acreage in the elm/ash/cottonwood forest type in the JPA, it was excluded.

### 2.3. Simulation Model Initialization

The Forest Age Class Change Simulator (FACCS), a spreadsheet-based model, was used to control forest development by selecting appropriate amounts of biomass harvested annually [3,22]. The FACCS assigns an age class change matrix that is linked to timberland area estimates for individual forest types. Biomass estimates are produced from continuous yield curves in the FACCS model. Age classes and biomass stocks within each forest type are simulated as a function of time, harvest rate, and mortality. As an example, if a forest is harvested or disturbed, the proportion of the total area in that forest type is reset to zero and immediately begins growing again. As areas are harvested over time, this leads to a variety of age classes within an age class matrix [3,22].

To initialize the model, forest management is primarily represented in the forest type-specific rotation ages, obtained from the Minnesota Department of Natural Resources [23] and specified as 40 years for aspen/birch and 75 years for white/red/jack pine, spruce/fir, and elm/ash/cottonwood. The area of timberland in each forest type remains constant in the FACCS model throughout the simulation. The FACCS model simulations use a binary search approach to iteratively adjust the volume harvest goal up or down until the maximum sustainable harvest is found. Goals are based on theoretical long-term sustained yield (LTSY) calculated using area control techniques. Specifically, $\text{LTSY} = \text{Yield}_i \times (\text{TotalAcres}/\text{RotationAge})$, where $\text{Yield}_i$ is the per acre yield expectation for the forest type at rotation age, TotalAcres is the sum of acres in forest type $i$, and RotationAge is the typical age at which the cover type is harvested. Sustainability is assessed by examining the simulated harvests required to achieve a specific goal. When harvesting is pushed to age classes below rotation age, the goal is deemed unsustainable, resulting in a reduction of the goal for the next iteration. Despite the uncertainties of model simulations over long time-horizons (e.g., 100+ years), harvests are conducted iteratively by taking a small portion of the area from an age class until the annual harvest goal is reached. Harvesting continues until either the harvest goal is met or all age classes have been harvested [20]. Hence, resulting estimates of sustainable harvest levels are a conservative projection that may underestimate potential harvest targets. Simulations from FACCS have been used in previous studies to investigate forest biomass availability across Minnesota [24], assess carbon emissions associated with utilizing forest harvest residues [3,4], and determining the role of disturbance on forest carbon pools [10]. In this analysis, forest biomass stocks and stock changes were simulated for 120 years to capture at least one rotation for each forest type. Biomass estimates from FIA were obtained from the EVALIDator tool [19] and compared with the FACCS-generated estimates of current total biomass stocks (i.e., forest biomass at time 0) to ensure consistent starting values.

### 2.4. Simulating Timber Harvest and Natural Disturbance Scenarios

The FACCS model was customized with user-defined parameters forming different simulation scenarios. In this analysis, current FIA data from Minnesota were used to develop yield models for each forest type and age class within that forest type, an approach similar to those used in References [3,4].

Four timber harvest scenarios were specified in this analysis. The total timberland area by forest type (i.e., Table 1) was entered to initialize the model. A 10-year average harvest rate was calculated using previous timber harvest statistics compiled from the SNF. Across the SNF, this 10-year average was equivalent to approximately 102,000 $m^3$ of timber volume harvested on 1519 ha on an annual basis. Timber harvest statistics were not available specific to the JPA, hence, the proportion of total timberland area in JPA relative to the entire SNF was used to specify annual harvest rate. From these current rates (i.e., 100%), a 50% and 200% harvest rate were also simulated. In addition, the FACCS simulator tool was used to search for the optimal annual harvest rate based on specified parameters such as rotation age and timberland area in each stand age class, which created the fourth harvest scenario. Because of the limited data available for the JPA scenarios, we adjusted the ending width of the binary search interval to match the scale of available timber to the potential volume produced across the total area.

Three natural disturbance scenarios were specified in this analysis. Given the variety of forest types and stand age structures across the SNF, it would be unrealistic to assume a single natural disturbance rate to represent these diverse forest conditions. Instead, the EVALIDator tool [19], which queried FIA data across Minnesota, was used to determine a forest type- and age class-specific natural disturbance rate based on mortality of merchantable bole volume of trees at least 12.7 cm in diameter at breast height (Figure 2). This approach allowed us to simulate a specific age class within each forest type to be disturbed at a different rate compared to an older or younger age class.

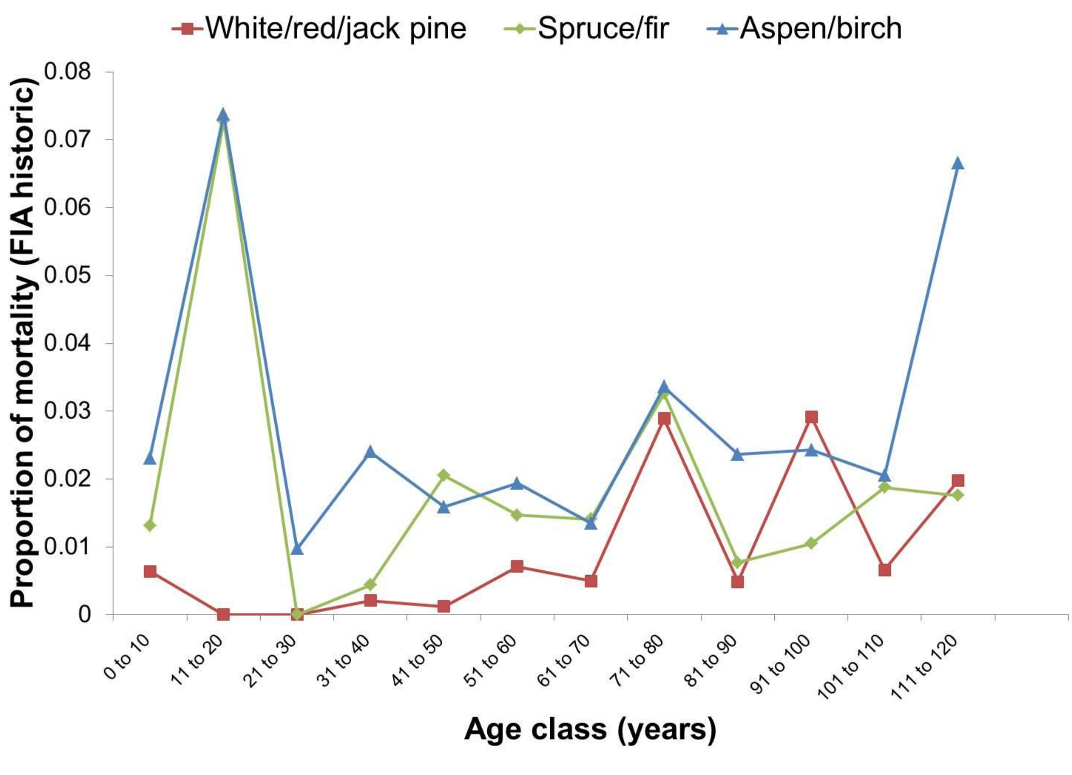


**Figure 2.** Current natural disturbance rates by age class for the three primary forest types used in the analysis, obtained from Forest Inventory and Analysis data from across Minnesota, USA.

## 3. Results

### *3.1. Timber Harvest and Natural Disturbance Effects on Forest Biomass Stocks*

Over 15.25 Tg of forest biomass in boles, tops, and limbs currently exist in the SNF, of which approximately 8% resides in the JPA. Current FIA estimates of total biomass and biomass density in the SNF were generally within ±20% of the inventory-based estimates used to inform the FACCS model (Table 1).

At the end of the 120-year simulation under the current timber harvest rate, the 200% disturbance scenario resulted in a 10.38% reduction in total forest biomass stocks in the SNF and a decrease of biomass by 2.62% in the JPA (Table 2). Under the 200% harvest rate, the 200% disturbance scenario resulted in reductions of 29.85% and 14.18% of total forest biomass in the SNF and JPA, respectively. In the SNF, the 50% harvest scenario resulted in slight decreases in forest biomass stocks (up to 9.60%) compared to current stocks, regardless of the amount of natural disturbance. In contrast, the JPA 50% harvest scenario resulted in minor changes from current stocks ranging from a decrease in 1.16% to an increase in 0.57% change in forest biomass stocks, regardless of the amount of natural disturbance. The 50% disturbance scenarios similarly resulted in slight decreases in forest biomass stocks at 50% and current harvest levels, however, when harvest rates were doubled, projected biomass stocks decreased by 22.08% and 8.58% in the SNF and JPA, respectively, compared to current biomass stocks.

**Table 2.** Percent forest biomass stock changes (%Δ) on the Superior National Forest (SNF) and Jeanette Project Area (JPA) under three natural disturbance and four harvest scenarios after 120-year simulations. Initial biomass stocks can be compared with those presented in Table 1.

| Forest Type | Natural Disturbance Rate [1] | Harvest Rate [2] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50% | Current | 200% | FACCS | 50% | Current | 200% | FACCS |
| | | %Δ | | | | | | | |
| | | SNF | | | | JPA | | | |
| Aspen/birch | 50% | −3.31 | −2.21 | −21.24 | −41.44 | 4.47 | 8.88 | −30.25 | −35.12 |
| | Current | −3.74 | −2.36 | −25.57 | −44.12 | 4.04 | 3.91 | −30.93 | −41.07 |
| | 200% | −5.31 | −4.96 | −32.69 | −43.19 | 0.79 | −5.69 | −36.92 | −37.76 |
| White/red/jack pine | 50% | −14.09 | −13.31 | −30.19 | −16.53 | −2.04 | 1.27 | 11.30 | −10.75 |
| | Current | −13.02 | −11.78 | −29.97 | −11.97 | −1.34 | 1.57 | 9.67 | −8.29 |
| | 200% | −12.18 | −11.80 | −33.14 | −17.01 | −0.88 | 2.69 | 7.38 | −8.56 |
| Spruce/fir | 50% | −7.84 | −9.05 | −11.02 | −29.45 | −2.13 | −8.85 | −20.01 | −27.04 |
| | Current | −9.08 | −10.23 | −12.71 | −27.40 | −4.42 | −13.92 | −23.07 | −33.65 |
| | 200% | −12.01 | −13.21 | −14.80 | −30.72 | −10.24 | −16.54 | −29.61 | −39.63 |
| Elm/ash/cottonwood | 50% | −12.42 | −29.70 | −44.56 | −40.57 | - | - | - | - |
| | Current | −17.67 | −32.73 | −46.75 | −43.85 | - | - | - | - |
| | 200% | −30.46 | −43.83 | −50.65 | −46.37 | - | - | - | - |
| Total | 50% | −6.97 | −7.50 | −22.08 | −33.82 | 0.57 | 3.31 | −8.58 | −22.20 |
| | Current | −7.56 | −7.72 | −24.81 | −34.06 | 0.51 | 0.95 | −9.97 | −24.04 |
| | 200% | −9.60 | −10.38 | −29.85 | −35.45 | −1.16 | −2.62 | −14.18 | −23.45 |

[1] Natural disturbance rates include current, 50%, and 200%. Rates vary by age class and forest type. [2] Harvest rates include current, 50%, 200%, and an optimized harvest rate indicated by the model (FACCS).

Several differences in forest biomass stock changes were evident after 120 years when investigating specific forest types. Although biomass in the white/red/jack pine forest type was projected to decrease under all scenarios in the SNF, biomass increased under current and 200% harvest scenarios within the JPA by as much as 11.30% under 50% natural disturbance and 200% harvest scenario. Forest biomass in the spruce/fir forest type was projected to decrease in all scenarios, with reductions as high as 14.80% and 29.61% under a 200% harvest−200% disturbance scenario in the SNF and JPA, respectively. Forest biomass dynamics in the aspen/birch forest type in the JPA, saw increases in biomass stocks in all scenarios except when the harvest rate was 200%. In all scenarios, the aspen/birch forest type biomass stocks decreased for the SNF.

### *3.2. Biomass Availability through Timber Harvest*

Under current harvest levels in the SNF, 121,977 Mg of total forest biomass is available annually (Table 3). Nearly 59% of these stocks could be derived from the aspen-birch forest type, 29% from the white/red/jack pine forest type, and an additional 6% from spruce/fir and elm/ash/cottonwood forest types. Under current harvest levels in the JPA, 8151 Mg of total forest biomass is available annually, comprised of aspen/birch (62%), white/red/jack pine (31%) and spruce/fir forest types (7%).

**Table 3.** Estimated annual biomass availability (Mg) by forest type on the Superior National Forest (SNF) and Jeanette Project Area (JPA) under current disturbance levels.

| Forest Type | Harvest Rate [1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% | Current | 200% | FACCS | 50% | Current | 200% | FACCS |
| | SNF | | | | JPA | | | |
| Aspen/birch | 35,992 | 71,444 | 142,520 | 195,194 | 2558 | 5085 | 10,151 | 11,223 |
| White/red/jack pine | 17,662 | 35,710 | 49,682 | 43,858 | 1264 | 2527 | 5031 | 10,777 |
| Spruce/fir | 3805 | 7575 | 15,118 | 46,292 | 270 | 539 | 941 | 1134 |
| Elm/ash/cottonwood | 3615 | 7247 | 12,320 | 10,705 | - | - | - | - |
| Total | 61,074 | 121,977 | 219,640 | 296,050 | 4091 | 8151 | 16,123 | 23,134 |

[1] Harvest rates include current, 50%, 200%, and an optimized harvest rate indicated by the model (FACCS).

Current levels of forest management and harvest were found to be approximately 41% and 35% of the optimized annual biomass available, as determined by the FACCS simulations for the SNF and JPA, respectively. Most notably in the SNF, FACCS simulation results indicated harvesting a lower proportion of total biomass from the white/red/jack pine forest type and a greater proportion from the spruce/fir forest type. Model results indicated the reverse for the white/red/jack pine forest type in the JPA, where FACCS indicated harvesting a greater proportion of total biomass (46% of total biomass), placing it roughly equal to the amount harvested in the JPA from the aspen/birch forest type (50%).

Using the optimized annual harvest rate determined by FACCS, simulations of total biomass stocks stabilized after 50 years for current and 50% disturbance rates but continue to decrease under a 200% disturbance scenario (Figure 3). Forest biomass stocks after 120 years were estimated as 9.84 and 1.03 Tg for the SNF and JPA, respectively, representing a decrease in forest biomass of 35.45% and 14.18% compared to current levels (Table 1).

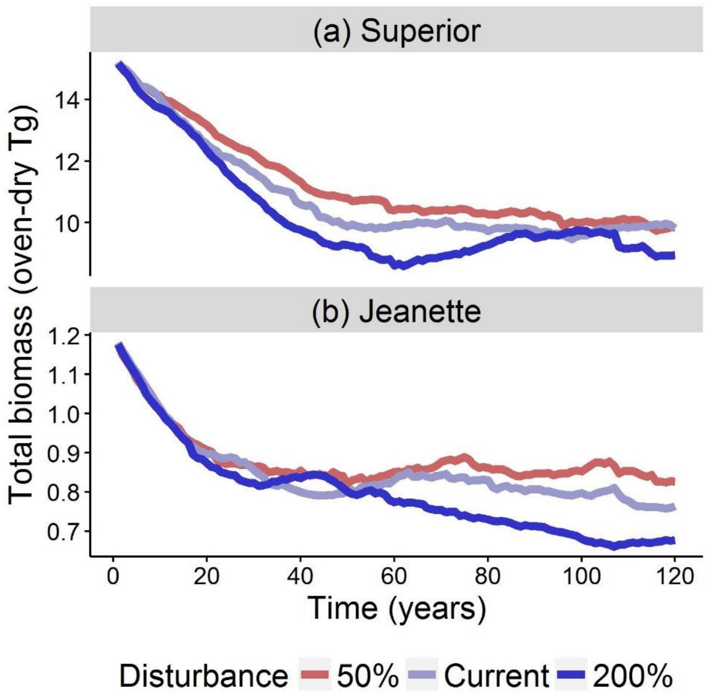


**Figure 3.** Simulation of total biomass stocks (including bole, tops, and branches) for the (**a**) Superior National Forest and (**b**) Jeanette Project Area using the optimized FACCS annual harvest rate and three natural disturbance scenarios. Note difference in scale in y-axis.

## 4. Discussion

Across the SNF, simulations at a 200% harvest rate under current natural disturbance scenarios indicated greater losses in forest biomass in 120 years compared to simulations at a 200% disturbance rate under current harvest rates. Ranging from decreases in current forest biomass stocks of 25.57% in aspen-birch to 46.75% in elm/ash/cottonwood forests, these results highlight the role that disturbances, both natural and human-caused, play in determining future forest composition. The primary mechanism behind the large decreases in forest biomass stocks likely arose because the forest type-specific rotation ages represent a minimum harvestable age [23]. Indeed, large areas of timberland were observed to exist at ages in excess of the forest-type specific rotation age when investigating current age class distributions across the SNF. Our estimate of 15.25 Tg of biomass in boles, tops, and branches within the SNF aligns with FIA EVALIDator estimates (18.35 Tg; Table 1) and was approximately 15% of the estimate that Domke et al. [4] provided (123.6 Tg) but for an area nearly seven times the size of the SNF that included similar forest types and stand conditions used in this analysis.

The smaller Jeanette Project Area showed similar trends compared to the SNF as a whole, with one notable difference being that forest biomass was projected to increase in the white/red/jack pine forest type for two of the harvest scenarios. This forest type likely behaved differently because current trends indicated a bimodal distribution in total area by age class, with peaks at 20 to 50 years old and 100 years and older for the white/red/jack pine forest type (Figure S1).

The finding that current harvest rates were 41% and 35% of the optimized annual harvest rate for the SNF and JPA, respectively, highlights potential additional biomass availability within these forest types, but only if current disturbance rates are considered (Table 3). For simulations at a 200% harvest rate, annual biomass availability would exceed that estimated by the FACCS model in the white/red/jack pine and elm/ash/cottonwood forest types across the SNF. Annual biomass availability for aspen/birch in the SNF and JPA under a 200% disturbance scenario was estimated to closely match the FACCS-optimized harvest rate, which reaffirms the relatively intensive management of this forest type across the US Lake States [18]. Additional forest types exist on the landscape in the SNF and JPA (i.e., maple/birch and oak/pine) but were not considered in this long-term simulation due to the small proportion of timberland in those types. Our estimate of 0.30 Tg yr$^{-1}$ of annual biomass available in boles, tops, and branches within the SNF was approximately 15% of the estimate that Domke et al. [4] provided (2.12 Tg yr$^{-1}$) but for the same forest types across an area nearly seven times as large. When compared to predicted annual roundwood and residue available across the entire state of Minnesota, the value observed in this analysis aligns with the approximate 3.55 Tg yr$^{-1}$ amount estimated by Kukrety et al. [3].

Under current and 50% disturbance rate scenarios, biomass stocks remained stable at the conclusion of simulations (e.g., through 120 years), a finding that indicates the optimized FACCS harvest rate may result in consistent long-term forest biomass stocks. Similar to Bradford et al. [10], this analysis indicated the strong role that natural disturbance plays in decreasing biomass stocks, even in combination with lower harvest rates. This was evident in the 200% disturbance scenario where biomass continued to decrease through 120 years (Figure 3). While this trend affirms the role of natural disturbance on biomass stocks and stock changes, it is important to note that natural disturbance rates will not influence all age classes within a forest type equally. In contrast to Bradford et al. [10], this analysis specified natural disturbances that were specific to both forest type and age class. These rates generally indicated a U-shaped pattern (e.g., Figure 2), with increased natural disturbance rates occurring at very young and very old age classes. These rates were likely higher at very young ages with small diameter trees due to competition-induced mortality. For older trees in larger diameter classes the rates are likely a reflection of tree senescence and disturbances. Future work may refine these natural disturbance rates by tailoring them to specific species of interest or using different sources of data to inform their values, such as information collected through aerial forest health surveys. As an example, the emerald ash borer (*Agrilus planipennis* Fairmaire) is a threat to ash species

(*Fraxinus* spp.) across Minnesota [25], yet disturbances specific to this insect were not considered in this analysis. Understanding the impact of timber harvesting on host susceptibility is needed to quantify the role of forest management in mitigating the impacts of disturbances such as insect outbreaks. Simulations that incorporate more catastrophic stand-replacing events such as windstorms and fire (e.g., Reference [15]) would also be worthy of considering in any analysis of forest biomass stock changes, but would likely require implementation of a probabilistic framework to specify return intervals associated with such events. In addition, past disturbances can influence current and future productivity rates in temperate forest ecosystems [26], which suggests the need to specify legacy effects of forest disturbance in future studies. While there is the potential for changing climate regimes to support increased productivity, natural disturbances may negate productivity gains related to climate change [7]. If future climate change scenarios are integrated into long-term simulations of forest biomass availability, accounting for adaptable forest management regimes and allowing forests to transition to different forest types are two examples that can integrate global change scenarios into this modeling approach. Despite the uncertainties with understanding the scale and impact of future natural disturbances, the use of national forest inventory data such as FIA is indispensable for determining natural disturbance parameters associated with different forest types and stand conditions. In performing these simulations, resource analysts can uncover trends at the forest and project area levels to inform strategic forest management approaches to maintain forest productivity.

## 5. Conclusions

Despite the uncertainty inherent in long-term projections of forest conditions, these results quantified the impacts of natural disturbance and harvesting on forest biomass stocks under current management strategies in northeastern Minnesota, USA. The inference that can be made from these forests is specific to current forest composition and age class distributions in the SNF and forest management activities that are typical of federally-managed ownerships. Actual forest biomass stocks will likely vary tremendously in the future based on changing natural disturbance regimes and the uncertainties inherent to them. These results can be compared across various management scenarios that have seen past forest disturbances typical of the US Lake States (e.g., Reference [27]). What this analysis provides is an assessment of the simultaneous impacts of harvesting and disturbance on long-term biomass availability, an approach that could similarly be applied to other forest ecosystems. Efforts to improve subsequent simulations of forest biomass can focus on species variability to a range of natural disturbances and refined estimates of potential mortality from specific pathogens, insects, and stand-replacing disturbance events. Additional examinations into the interactions between disturbance and timber harvesting, e.g., managers implementing alternative forest management regimes in anticipation or in response to a forest health threat, will require user-specified parameters if a desire is a long-term forecast of forest structure and composition.

Nevertheless, our results quantify the role that natural and human-caused disturbances play in shaping future forest composition. While the result that current harvest rates were 41% of the optimized annual harvest rate indicates additional biomass availability across the SNF, an appropriate level of natural disturbance needs to be considered by resource professionals as these findings are applied in forest management planning. Simulations of forest biomass stocks and stock changes are appropriate to conduct within project areas of national forests in the US, allowing managers to gauge the economic and ecological values associated with timber harvesting. This project suggests that a variety of natural disturbance and timber harvest scenarios be considered to understand the concomitant effects of forest management and natural disturbances on forest biomass stocks and stock changes.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/1999-4907/9/8/491/s1, Figure S1: Current age class distribution for the four primary forest types across the Superior National Forest, northeastern Minnesota, USA, acquired from the Forest Inventory and Analysis program.

**Author Contributions:** M.B.R., S.R.P., D.C.W., G.M.D. and K.L.F. conceived and designed the study; M.B.R., S.R.P., and D.C.W. performed the experiments and analyzed the data; All authors contributed to writing the paper.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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