Anonymous Referee #1

REFEREE #1:
General comments
The manuscript deals with the legacy effects of disturbances (both natural and anthropogenic), and of future climate change, on the C balance of the forest. It is a relevant topic and provides new input to the field. The manuscript is well-written and the work has been done thoroughly.

AUTHORS:
We thank the referee for his/her overall positive evaluation of our study.

REFEREE #1:
The first part of the study is an analysis of possible interactions between two past disturbance events. Although I can appreciate the work that has gone into digging out the old archives, my impression is that the analysis was more exploratory in nature, while writing it up, one reference (Schurman et al. 2018) was used as a quick excuse for a hypothesis and the discussion is more focussed to find references on temporal autocorrelations at different time scales. Perhaps part of the material in the discussion should be transferred to the introduction to provide a more solid hypothesis (like the references in line 442/443), or no hypothesis should be given at all and the patterns found should be discussed against other findings in literature. A weak point here is that there were only two events, and no autocorrelation analysis could be done at different time scales. Furthermore, I'm not always convinced by the arguments the authors bring up in comparing their results to other studies. For example, they state that they find a low probability for the same area to be affected by the two episodes (line 443), which is in contrast to a study that does find correlations between episodes but at very different timescales. I think there is only a contrast if both studies were at the same timescale, and if not, they cannot be compared. Similarly, they state that other studies did find correlations at the plot and stand scale (line 450), but the authors attribute their different finding to the fact that they work at the landscape scale. I do not see why this would yield so different results. If you check a sufficient number of stands and find correlations, I would expect the same would hold true for the landscape. If not, you would expect low correlations at the stand scale as well. Also, lines 457-466 pose some possible reasons why the two events were different. I think they should have enough material to check some of these alternative explanations, or should be able to obtain them with little effort (for example wind direction of both events). Overall, I suggest the authors re-think their hypothesis and discussion for this part of the analysis.

AUTHORS:
The referee makes an important point with regard to revising the hypotheses and the part of the discussion pertaining to the first part of our analysis. Given the lack of explicit data on past disturbance episodes, comparisons as the one undertaken here are rare, which makes embedding it in the literature challenging. Furthermore, as some important characteristics of the first disturbance episode remain unknown (e.g., exact wind speed, wind direction) some uncertainties about the causes of the difference between the two episodes will necessarily remain. Furthermore, we'd like to point out that an analysis of individual drivers of the Central European disturbance regime is beyond the scope of the current contribution, in fact the causes of natural

disturbances have been investigated in detail already in prior studies (Marini et al., 2012; Overbeck and Schmidt, 2012; Pasztor et al., 2014, 2015; Thom et al., 2013).
Nonetheless, we agree with Reviewer #1 that the correlation between the two disturbance events warrants further attention. Congruent with the suggestions of referee #1 and referee #2, we have added another analysis to investigate the contribution of past land use to the second disturbance episode (l. 364 – 372 in the manuscript version with track changes). Based on our factorial simulation design, we have now analyzed the effect of four different combinations of previous natural disturbances and management on the second disturbance episode in 320 simulations (those including the second disturbance episode). This analysis has revealed a high uncertainty about the relationship between both disturbance episodes, while past land use clearly increased disturbances on the landscape (l. 479 – 483). Following the referee's advice we have also reformulate our hypothesis and substantiated it with some of the material provided in the discussion section. Based on the results of the new analysis, we also have reformulated and extended the discussion in section 4.1.

REFEREE #1:
The second part of the study deals with an analysis of the future effect of human and natural disturbances, and future climate change. I think this part of the study is well described and the conclusions are valid. The authors give great care to initialise their model in 1905 using an innovative method, and to simulate the conditions until now, and then project their model into the future. They conclude that the past trajectory is very important to understand the future carbon dynamics. Usually, models would be initialised according to the current state of the forest, and carbon dynamics projected into the future. The current state of the forest would in most cases represent past events, and legacy effects are thus already present. I'm wondering if the 100-year simulation of the past really influences the results, and that this would be a recommended procedure for all models, or that the correct representation of current state and current management is sufficient to include these legacy effects. I could imagine the authors use their new initialisation procedure to represent the current state and compare future projections with and without the 100-year historic run. Perhaps this is too much to add to the current paper, but I would encourage the authors to give some indications on this issue. Are the current initialisation procedures sufficient to take care of past legacies or are longer historic runs needed?

AUTHORS:
We thank the referee for the positive evaluation of the second part of our study. The Reviewer is in fact correct in stating that usually legacy information is captured via the initialization of a model. This is not different in iLand, the model applied here. However, our point here is a slightly different one, namely: How different would the state of the forest (and hence the initialization of a simulation model) be if it would have had a different disturbance history? We thus quantify the structural effects of different past activities onto the state of the forest in 2013, and investigate how long these differences persist into the future, given everything else is equal. So the Reviewer is correct in assuming that if the initial conditions are known the legacies are adequately captured for modeling. However, in many cases the initial conditions of a forest landscape are incompletely known. This is for instance the case for the state of our landscape in 1905, for which we have information about species composition and growing stock, but not for

other important variables (e.g., soil C pools, the spatial composition and configuration of stands). The legacy spin-up approach presented here was designed to address this very issue.
In the revision we have added some more explanation in section 2.4 in order to clearly distinguish between the different steps of our modeling approach, and to make explicitly clear what our contribution with the legacy spin-up is. In this regard, also the new arrangement of the supplement into sections helps to distinguish the legacy spin-up from subsequent simulations (see next comment).

REFEREE #1:
The ordering and numbering of the supplement is a bit strange. S2 and S3 are figures connected to text S1, S4 is text, while S5 and onwards are again figures. While reading the main text, the first reference is S4 while earlier supplementary material is referred to later. Perhaps the supplement could be ordered according to the appearance in the text, and a difference could be made between text and figures.

AUTHORS:
We agree that the enumeration of the supplement can be improved. This has also been suggested by referee #2.
In our revision, we have restructured the supplement into three sections and have provided all figure with a consecutive number. Sections and figures were numbered continuously throughout the text.

REFEREE #1:
Specific comments

In Figure 1 it would be helpful to add a small map to show where the study area is located within Austria.

AUTHORS:
We have complemented the figure with another panel showing a map of Austria and the location of the landscape.

REFEREE #1:
Line 152: does the model allow for build-up of beetle populations over the years?

AUTHORS:
Yes indeed, the process-based bark beetle module implemented in iLand is able to simulate the build-up of bark beetle populations over multiple years. Weather conditions affect the bark beetle population directly (e.g., the number of generations and sister broods per year, as well as winter survival rate). Furthermore, the vitality of trees and thus their defense capacity (simulated via the available non-structural carbohydrates) as well as the amount of windthrown trees (easily colonizable breeding material) influence beetle populations in the model. Seidl and Rammer

(2017) found that iLand was well able to reproduce the 2nd bark beetle disturbance episode contained in our analysis here.
We have added this information in l. 188-196 in the revised version of the manuscript.

REFEREE #1:
Line 285: I assume the weather data was adapted to the elevation gradient in the study area somehow? If yes, could you add one sentence about it?

AUTHORS:
Indeed, elevation gradients are captured in the climate data used. The climate data from 1950 – 2099 were all statistically downscaled to a resolution of 100 x 100 m by means of quantile mapping. For the years 1905 – 1949, we had only temperature and precipitation from a nearby weather station. We thus drew a climate from the period 1950 – 2099 for each missing year by matching its temperature and precipitation data to that of the weather station record for 1905 – 1949.
We have extended the information about the downscaling approach of the climate data in l. 325-327.

REFEREE #1:
Line 356: Simulated species shares were compared against “independent” data for the year 1905. I think 1905 data were used to make the spin-ups for the model. If it is the same data, they are not independent. Or is it really another source? If so, please specify here.

AUTHORS:
We agree with the referee that the comparison of the simulation with the observed data is not entirely independent, as the observed data was used to guide the spin-up procedure.
We have changed the text accordingly in the revised version of the manuscript (l. 429-430).

REFEREE #1:
Line 410: Is “stock” perhaps better than “storage” here?

AUTHORS:
We have changed to “stock” in the revision.

REFEREE #1:
Line 487: You mention here that you only studied wind and bark beetles, while other agents may become more important in future. I think wildfire was included in your simulations as well. Moreover, you conclude that management was far more important than disturbances, i tihnk this needs to be highlighted here as well.

AUTHORS:

Our simulations included disturbances by wind and bark beetles only, as stated in l. 179-181 "As wind and bark beetles are of paramount importance for the past and future disturbance regimes of Central Europe's forests (Seidl et al., 2014a; Thom et al., 2013), we employed only these two process-based disturbance submodules in our simulations". Although it is correct that iLand is able to simulate disturbance from wildfire, we did not include wildfires here as they are not an important component of the disturbance regime in our study system.
With regard to management we agree on its importance, and have highlighted this more explicitly in the revision. Throughout the text we are now distinguishing between natural disturbances and land use, and, in particular, in l. 579-591 of the discussion we are pointing out the superior role of past land use as a driver of NEE.

References

Marini, L., Ayres, M. P., Battisti, A. and Faccoli, M.: Climate affects severity and altitudinal distribution of outbreaks in an eruptive bark beetle, Clim. Change, 115(2), 327–341, doi:10.1007/s10584-012-0463-z, 2012.

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Pasztor, F., Matulla, C., Rammer, W. and Lexer, M. J.: Drivers of the bark beetle disturbance regime in Alpine forests in Austria, For. Ecol. Manage., 318, 349–358, doi:10.1016/j.foreco.2014.01.044, 2014.

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Thom, D., Seidl, R., Steyrer, G., Krehan, H. and Formayer, H.: Slow and fast drivers of the natural disturbance regime in Central European forest ecosystems, For. Ecol. Manage., 307, 293–302, doi:10.1016/j.foreco.2013.07.017, 2013.

Anonymous Referee #2

REFEREE #2:
This study depicts the past and future of a forest landscape in Austria. It aims at evaluating the respective weights of past natural disturbances, past human management, and future climate change on the forest capacity to sequester carbon. For this, the authors reconstructed the landscape history of the federal forest under study using historical data sources. This history is marked by a windstorm in 1905 followed by a bark beetle outbreak, technological evolution of management practices until 1997 when management is ceased, and a second wind and bark beetle event in 2007. The historical reconstruction results show that there is no correlation between the locations impacted by the first and the second natural disturbance events. In a second time, the authors designed a factorial simulations experiment in which the forest landscape under study undergoes all combinations of conditions : 1917 windstorm and bark beetle event or no, evolution of management practices between 1924 and 1997 or no management after 1924, 1997 windstorm and bark beetle event or no, four climate scenarios from 2013 to 2099. The simulations show that the net ecosystem exchange is dominated by past management found to explain 97.7%. The recovery from past management causes an increase in the future carbon storage. The authors find that by 2100 the effect of human and natural disturbances overcome the effect of climate change.
The object of this study is interesting and timely as the issue of the response of forests to climate change becomes more pressing. The case study is interesting due to its particular history including two large natural disturbance events and a ceasing of human management that allow the analysis of the legacy of management practices on a forest landscape. The simulation experiment is well designed and the model used (iLand) is appropriate to address the questions raised and introduced in a satisfactory way. However, the results and discussion section are somewhat superficial and do miss some important points. Also, the way the study is presented is often confusing or misleading and impairs the comprehension and interpretation of the results. The display items as well as the presentation of the results should be reconsidered to enhance the impact of the work presented.

AUTHORS:
We thank the referee for his/her interest in our study and the very thoughtful review with valuable comments to help us improve our manuscript.
In the revision, we have particularly focused on dissolving the confusing interpretation of results that were highlighted by the reviewer. See our responses below on how we achieved this.

REFEREE #2:
Detailed comments
Terminology : " disturbance " My main concern is about the use of the word disturbance all along the article, from the title on. The use of this term disturbance is misleading. Usually disturbance refers to natural disturbance (Overpeck et al., 1990; Seidl et al. 2014, 2011). In the present manuscript, it is sometimes used to refer to natural disturbances only (p4 L73 or L395) and sometimes to refer to natural + anthropogenic. It seems that the authors are aware of the confusion this creates, because most times they explicit that disturbances is natural+anthropogenic (ex : p5L86). Aggregating two very different processes such as

management and natural disturbances, on top of being very confusing for the reader, impedes the discussion of one very important result which is the extreme dominance of the effects of management compared to natural disturbances on carbon sequestration of forests. To this regard even the title of the article is misleading or even incorrect since it is not the legacy of the natural disturbance events (explaining only 2,8%) but of past management that has a stronger legacy effect than climate change. The manuscript should be revised to account explicitly for this distinction in the processes analyzed which is obvious in the results.

AUTHORS:
We thank the Reviewer for pointing this out. Our idea in the initial submission was to first combine natural and human disturbances to quantify the overall disturbance effect on carbon storage, and subsequently disentangle the partial effects of natural and human disturbances. As two of the three referees (referee #2 and referee #3) found the combination of natural and human disturbances into the overall disturbance effect confusing and problematic, we concede that this idea had to be revised.
In the revision we now clearly distinguish between land use and natural disturbance throughout our study. We have also rephrased the title of the study into "Legacies of past land use have a stronger effect on forest carbon exchange than future climate change in a temperate forest landscape".

REFEREE #2:
Methods
In the description of the simulation experiment it is noted that each scenario is replicated 20 times (p15 L 347) ? The rationale for this should be explained. What changes between the replicates ? Is there a stochastic component in the model ?

AUTHORS:
iLand is a process-based model including fully-dynamic submodules for natural disturbances and forest management, and each of these components contain stochasticity (e.g., the spread of an individual bark beetle cohort from an infested tree is determined by drawing from a distribution of empirically determined dispersal distances, with spread direction drawn randomly between 0° and 360°). To account for this stochasticity, we have replicated every simulation 20 times. This particular number has been proven to be a good middle ground between determining robust results and keeping simulation times reasonable in previous applications of the model (e.g., Seidl et al., 2018; Thom et al., 2017).
We have now provided the rationale of the replicates more explicitly in l. 417-420 (see manuscript version with track changes).

REFEREE #2:
L212: the sentence describing the 1905 age distribution seems a bit far-reaching from fig S8 as the bimodal distribution is not obvious, and the statement is very qualitative.

AUTHORS:
We agree with the referee and have changed the text accordingly (l. 253-255).

REFEREE #2:

Results and discussion

The manuscript seems very unbalanced with 13,5 pages of intro and methods (both well written and with relevant content) and only 5,5 pages of results and discussion (2,5 and 3 respectively). As reflected by these numbers, the results and discussion sections are sometimes shallow compared to the information presented and the very large number of display items included both in the main text and the supplementary materials (8 and 12 respectively).

AUTHORS:

We only partly agree with the referee on this point. We feel that it is important to include an extensive methods section in highly complex and computational extensive studies in order to ensure the highest possible degree of reproducibility (see also Scheller et al., 2011; Schwaab et al., 2015; Temperli et al., 2013). As 5 of the 8 figures as well as both tables are anchored in the results section, the manuscript is overall less imbalanced as it may seem based on text pages only. Moreover, besides the 5.5 pages for results and discussion, there is another page of text making up the conclusion section, which should be considered as well. With regard to the supplement we feel that the extensive additional material presented here helps the reader to understand our study and provides additional context on the validation and applicability of the methods used in our study (while not further clogging the main text).

Nonetheless, we have further strengthened the results and discussion sections in the revised version of the manuscript through an additional analysis of the impacts of management and the first disturbance episode on the second disturbance episode (see our response below). Additionally, we have improved the clarity of information provided in the results and discussion sections based on reviewer comments. However, we refrained from omitting parts of the methods (which the referee agrees are relevant to understand the study) or prolong the results and discussion sections extensively (as our manuscript is already fairly long).

REFEREE #2:

Some missing information : - 3.1 Performance of the reconstruction of past events:L377 " a good match" with reference to three supplementary figures, L379 " well able " with reference to one supplementary figure, L381 "small overestimation", L382 "corresponded well" with reference to one supplementary figure etc. all results from section 3.1 are qualitative and based on supplementary figures. An effort should be made to quantify the quality of the reconstruction and to present it in a concise manner in one display item, that, if judged crucial for the validity of the results should be presented in the main text.

AUTHORS:

We understand the desire of Referee #2 for a single, concise evaluation result. However, we here follow a patter-oriented modeling approach (Grimm et al., 2005), which means that a variety of very different indicators are considered in order to evaluate the model’s ability to reproduce the empirically derived historic data (i.e., tree species composition in 1905 and 1999, management, natural disturbances). In our opinion these cannot be combined into a single number/ figure, as such a combination may hide important information regarding model performance (e.g., the

model could be doing very well wrt one indicator while performing poorly wrt a second one, which would give on average moderate performance; if the poorly captured indicator is, however, of particular importance for the study, this information would be lost in such an aggregate evaluation). After careful consideration of the Referees comment we thus have decided to retain the multidimensional nature of our evaluation.
In the revision we have explained this in more detail and provided our rationale for this approach for the reader in l. 350-355.

REFEREE #2:
- 3.2 Temporal interaction of disturbance events: the autocorrelation between natural disturbance events is described and found very low. No link is analyzed between disturbance events and management: is there a correlation between stands affected by natural disturbance and species? And age? And density?

AUTHORS:
We thank the Referee for bringing up the issue of management in this context. In fact the possibility of a connection between management and the second disturbance episode has also been pointed out by referee #1, and we agree that this is an important issue here. We thus have now added an additional analysis in this regard to our manuscript.
Following the advice of referees #1 and #2, we have investigated the contribution of land use on the second disturbance episode in our revision. In particular, we have analyzed the effect of all 4 potential combinations of past natural disturbance and land use on the second disturbance episode in 320 simulations (i.e., those including the second disturbance episode). This additional analysis has helped us to investigate legacy effects of past land use and natural disturbance on subsequent disturbances. In particular, we found only a moderate non-significant effect of the first disturbance episode on the second disturbance episode, while past land use had a strong and significant impact on the second disturbance episode. These new results are presented in l. 479-483, and are further discussed in l. 557-567.

REFEREE #2:
- 4.1 The discussion of the lack of autocorrelation between both natural disturbance events and the link to previously published literature is not always clear. For example, the authors state that their hypothesis was that older stands are more prone to wind and bark beetle damages (L442) and link this statement to the low probability of a same area to be affected twice. The fact that a stand is affected by a disturbance does not make it older hence more susceptible to a second disturbance. Several hypotheses are formulated to explain the lack of autocorrelation between both episodes as found in other studies, but none is backed by data so that the discussion is not convincing. One hypothesis is that the longer and larger temporal and spatial scales analyzed here weaken the link found in smaller scale studies. I do not see why stands being more prone would not show up at the landscape scale. Similarly, the hypothesis of a dampening effect of a previous disturbance due to the resulting heterogeneity should be backed by minimal tests on the age and species structures of the affected and non affected stands. As well, the suggestion as to the difference in wind directions of both events needs to be investigated. In summary, an analysis

of the characteristics of the stands affected by both natural disturbance events would enlighten this part.

AUTHORS:
As highlighted by referees #1 and #2 we agree that this part of the discussion needed to be revised. We have tried to find other studies investigating the spatial autocorrelation of two consecutive major disturbance episode, but spatio-temporal autocorrelation of disturbances has been usually either described over very limited time frames (e.g., Pasztor et al., 2014) or the spatial resolution for the comparison of disturbances over longer time frames has been very coarse (e.g., Senf and Seidl, 2018). In this regard, our analysis constitutes a novel contribution, improving our understanding of disturbance dynamics over extended temporal scales. Although we have spatially explicit disturbance data for both events, we cannot conduct a process-based analysis at the level of individual drivers. The reason is that we do not know all the characteristics of the wind event of the 1917-1923 disturbance episode (e.g., wind direction and wind speeds) as these have not been faithfully documented. Moreover, we feel that the analysis of disturbance drivers is beyond the scope of the current contribution, as this has been investigated in more detail in other studies in Central European ecosystems (e.g., Marini et al., 2012; Overbeck and Schmidt, 2012; Pasztor et al., 2014, 2015; Thom et al., 2013). Nonetheless, we have improved the analysis of how past legacies have affected recent disturbances in the revised version of the manuscript. As mentioned above we have added a new analysis investigating the contribution of the first disturbance episode and forest management on the second disturbance episode. This analysis has served to substantiate our finding of a weak contribution of one disturbance episode on the other, and provides more insights into the effect of forest management on the Central European disturbance regime. Based on these results we have also improved the discussion in section 4.1 of the revised manuscript. Moreover, following the Reviewer’s advice, we omitted the comparison of our results with other studies investigating autocorrelation between natural disturbance events at different temporal and spatial scales.

REFEREE #2:
-4.2 disturbance legacies on future C uptake The authors argue that other studies of effect of climate change on carbon sink do not explicitly consider the legacy of past events. It is a bit surprising as past events’ legacy in embedded in the initial conditions. The legacy spinup method derived here is interesting and relevant but should be placed in the context of alternative methods to describe forest initial conditions, see for example (Crookston et al., 2010; Garcia-Gonzalo et al., 2007; Hurtt et al., 2002; Karjalainen et al., 2002; Peng et al., 2009). The novelty of this study does not seem to be the inclusion of the disturbances’ legacy but their quantification so this section should be rephrased. Several sentences are not backed by any reference and should be justified and developed. For example on L484, the sentence stating that these results may not hold for longer time frames, on L499 the sentence interepreting the simulation results as a change in forest types.

AUTHORS:
We agree with the Reviewer that the legacy effects are indeed embedded in the initial conditions, if the initialization is based on a comprehensive set of empirical data. It is also correct that the

quantification of the legacy effect is the actual novel contribution of our study (see also our response to a similar comment of Referee #1).

We have rephrased this section to indicate that only few studies have quantified the legacy of past natural disturbances and forests management to date. However, we feel that further discussion about the legacy spin-up would decrease the focus of this section, as the legacy spin-up refers to the landscape history before 1905, while this section addresses the legacies of the disturbance episodes in 1917-1923 and 2007-2013 as well as land use between 1905-1997 on future trajectories. Instead, we have extended the supplement with a discussion of empirical initialization approaches (l. 110-122 in the version with track changes), followed by a comparison of traditional spin-up approaches with the legacy spin-up developed for this study (l. 123-151).

REFEREE #2:

- effect of climate change It is not explained in many details what response of forest growth to climate change is simulated by iLand (with respect to species or altitude for example). The results shown here on the comparison of climate change and management are highly related to the processes included in the modeling exercise as correctly stated in L501-507 and would deserve a more in-depth explanation. A discussion section on the simulated response of forest growth to climate change only would help put the results in perspective.

AUTHORS:

We agree that this is important information for readers in order to understand the results presented here. iLand considers both direct and indirect vegetation responses to climate change. For instance, temperature increases directly affect processes such as leaf phenology and the length of vegetation period, the efficiency of photosynthesis (modeled using a state acclimation approach following Mäkelä et al. 2008), and the availability of water in the soil (via altered evapotranspiration rates). Similarly, rising CO_2 levels directly affect net primary production via CO_2 fertilization. Thus, climate change might affect growth of one species differently than that of another species (direct effect), leading to a change in forest competition and structure (indirect effect).

We have provided more details of the climate change effects on forest vegetation in iLand in l. 167-174. We are also explicitly referring the reader to the more technical iLand papers describing this issue in detail (Seidl et al., 2012b, 2012a; Thom et al., 2017).

REFEREE #2:

Display items

Some display items do not help the understanding of the text, are redundant, or at the contrary lack information, and so should be rethought as material that supports the claim made in the text. Fig2 aims at summarizing the events included in the historical reconstruction of the forest landscape. Its design is more appropriate for a slideshow than a written article. Fig3 illustrates how the events shown in fig2 are included in the simulation experiments. Its design is confusing, especially with the ‘n’ that is cumulated from left to right (it takes some time to understand this) and that attempts at expliciting the factorial combination of the events simulated. These 2 figures

could be condensed into a single display item where only the information relevant to the study would be presented. For example a table structured as below:
Period / Scenarios' options / details
1905-1924 / disturbed / storm+bark beetle+
...
/ undisturbed /
1924-1997 / managed / Technological improvements
/ unmanaged / Forest left to grow
1997-2013 / disturbed /
/ undisturbed /
2013-2099 / Climate scenario 1 /
/ Climate scenario 2 /
/ Climate scenario 3 /
/ Climate scenario 4 /

AUTHORS:
We have evaluated different options to combine both figures, but haven't found a satisfying solution. As mentioned by the Referee, Figures 2 and 3 are highlighting two different aspects of the study: Figure 2 represents the history of events on the landscape while Figure 3 shows the simulation design.
In order to provide the reader with a visual impression of the historic events relevant for this study, we decided to retain Fig. 2 instead of converting it into a table. Following the reviewer's advice, we have omitted Fig. 3 to avoid confusion and redundancy, and instead elucidated the simulation design in more detail in the text (l. 414-417).

REFEREE #2:
Other problematic display items are Fig5, Fig6 and FigS14. These three figures are redundant and should be combined into a single figure that shows the time evolution of NEE attributed to climate, event1, event2, and management. Please explain 'cumulative NEE'. From fig5, since the climate driven cumulative NEE decreases it means that the forest becomes a source of carbon between 2035 and 2050? This pattern should be discussed (see comment on 'effect of climate change').

AUTHORS:
The referee is right that there is some redundancy between these figures, as the endpoints in Fig. 5 and Fig. S14 reflect the effect size in Fig. 6. However, the interpretation of NEE by the Referee is not correct here. As NEE = -NEP a decrease in NEE means an increase of carbon in terrestrial ecosystems, i.e., between 2035 and 2050 there is an uptake of carbon by forests under climate change. We have provided a definition of NEE in l. 363f.: "NEE denotes the net C flux from the ecosystem to the atmosphere, with negative values indicating ecosystem C gain (Chapin et al., 2006)". The effect of climate change on NEE between 2035 and 2050 can be explained by more favorable conditions for tree growth (longer vegetation periods in the higher elevation parts of our mountainous study area) in combination with a CO2 fertilization effect, relative to baseline climate conditions.

We have combined Fig. 5, Fig. 6 and Fig. S14 as suggested by the referee in the revised version of the manuscript. We have also improved the text in l. 116-119 and in the figure caption with regard to the interpretation of NEE in order to avoid confusing interpretations by future readers.

REFEREE #2:
Supplementary materials
The supplementary figures are excessive. Some could be merged into a single figure such as Fig. S11 and S12 that show the same variable (growing stock per species). Some are not even cited in the text such as Fig S13. Fig.S5 is not clear, why showing two sites in the fictitious landscape map with only on stand development below. Letters A to D are shown but not used in the explanation but the outcome of the spinup (letter D I guess?) is not highlighted.

AUTHORS:
Figures S11 and S12 show the same variable, but provide different aspects of the simulation. While Fig. S11 compares the simulated with the observed species composition and growing stock in year 1999, Fig. S12 presents the temporal trajectory from 1905 to 2013 of the simulation only. The temporal trajectory cannot be provided for the observed data as there are no records available at annual resolution. Hence, by omitting Fig. S12 we would omit crucial complementary information. Fig. S13 (now Fig. S11) was cited in the text in l. 462. “At the same time total ecosystem carbon increased by 40.9% (Fig. S11).” Letters A to D have been explained in the supplement in l. 162 – 173 “For instance, the initial planting could plant trees according to the target species shares (A in Fig. S5). During the simulation the defined management steps are executed (e.g., thinnings, B, final cut C). Periodically, the state of the forest is evaluated against the available reference data. A basic evaluation compares, for instance, the growing stock and species shares emerging from the simulation with the respective reference state, and calculates a similarity score (e.g., Bray-Curtis index). When the deviation between the emerging state space from the simulations and the reference state are not satisfactorily, the STP for the next rotation can be altered. In the example in Fig. S5, the simulated share of spruce was lower than the spruce share in the reference state, indicating that spruce was likely favored by past management, either by planting spruce (C) or by favoring spruce via selective thinnings. This information is incorporated in the spin-up run, which henceforth uses a modified STP for the given stand and the next rotation (D).”
In our opinion, the supplement figures all provide unique and complementary information, and are important to understand our approach and evaluate model behavior. As these figures will only appear in the online supplement and not the main paper, we do not see a reason for reducing them, and thus withholding the details of our model evaluation efforts from interested readers. Regarding Fig. S5 we agree with Referee #2 and have extended the figure caption to facilitate its interpretability.

REFEREE #2:
Technical details
P3 L49 ‘Keenan and others’ instead of ‘et al’ the numeration of the supplementary materials is confusing with only one line of numbering for text sections and figures. There should be section S1, section S2, section S3, figure S1, figure S2, figure S3, figure S4

AUTHORS:
We agree with the referees #1 and #2 that the structure of the supplement needed to be improved. We also thank the referee for his/her close view on the text, pointing out a mistake in the citation style.
We have followed the referee’s suggestion to differentiate between sections and figures, and corrected the citation style where necessary.

REFEREE #2:
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Please also note the supplement to this comment:
https://www.biogeosciences-discuss.net/bg-2018-145/bg-2018-145-RC2-supplement.pdf

AUTHORS:
Thanks for providing the references and the pdf which has been more convenient to work with than the online version of the text.

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Anonymous Referee #3

REFEREE #3:
General comments : The research article named ’Disturbance legacies have a stronger effect on future carbon exchange than climate in a temperate forest landscape,’ try to explore the effect of disturbance legacies and climate change in the projection of the forest carbon sequestration. In order to do that, they reconstruct a well documented historical scenario of an Austrian forest landscape with two disturbance events and one forest management shift. At the end of the paper, they encourage the scientific community to take into account the forest history when initializing the forest state before running projections of the forest dynamic. This is a nice attempt to promote the integration of disturbances and abrupt mortality in model development. I really appreciate the quality of the work done by the simulation experiment and the past reconstruction forest state with the new method of spin-up. I am convinced that this paper can be published without deep changes in the structure and the content.

AUTHORS:
We are grateful for the positive evaluation of our study.

REFEREE #3:
However, five points need to be clarified:
1) The results of the simulation experiment show that past forest management (absence or presence) is the main factor to explain the divergence between simulations. But this finding is not central to the paper! Instead of that, the authors define forest management as a human disturbance (that is perfectly true) and merged natural and human disturbances in one general disturbance term. This merging leads to a misinterpretation of the title and the conclusion because, for most of the ecologist and the forest manager, disturbance legacies always refer to an extreme event legacy like storms, beetles outbreaks, fires or droughts. My advice is to explicitly divide interpretation of the result into the natural and the human disturbance. For example, the title will become: "Human disturbance/forest management/human activity legacies have a stronger effect on future carbon exchange than climate in a temperate forest landscape."

AUTHORS:
We thank the reviewer for this important comment, and for the recommendations on how to improve our work further. This comment is congruent with one of the comments provided by Referee #2. As mentioned already in the response to Referee #2, our attempt was to combine natural and human disturbances first in order to quantify the overall disturbance effect on carbon storage, and subsequently to disentangle the partial effects of natural and human disturbances. However, we understand the potential confusion this has been causing.
In the revision we now clearly distinguish between effects of land use and natural disturbances throughout the study. We have also rephrased the title of the study to “Legacies of past land use have a stronger effect on forest carbon exchange than future climate change in a temperate forest landscape”.

REFEREE #3:
2) the authors need to be careful with the last statement of the title: "than climate in a temperate forest landscape" because the authors only realized simulations with a medium climate change scenario (A1B). The strongest climate change scenario like the RCP 8.5 is most likely to happen, and it will have a stronger impact. In addition, the authors forget to take into account the indirect effect of CC on forest growth via the increase of the frequencies and the intensities of the extreme events. This partly due to the setup of the simulation experiment where disturbances are forced and disconnected to the mortality module of iland. But this interaction can be simulated in iland because the authors already developed abrupt mortality module into this model.

AUTHORS:
We agree with the referee that a more severe climate change scenario will likely alter the effect of climate change in our study. The exclusion of high intensity disturbance events after 2013 was necessary to exclude confounding effects from disturbance interactions with past disturbance events (i.e., spatio-temporal autocorrelation) in order to disentangle the partial effects of past disturbance and future climate change. Also, it is congruent with the cessasion of forest management, and was thus a prerequisite for comparing effects of past natural disturbances and past land use in a meaningful way.
In the revision, we have added this aspect explicitly to the discussion, highlighting possible impacts of a more severe climate change scenario on NEE (see l. 592-596 in the manuscript version with track changes). We now also explicitly mention tour rationale for excluding high intensity disturbances in the methods section (l. 400-402).

REFEREE #3:
3) The way the authors display the results of the simulation experiment is very confusing. The figure 5 for example which display the difference between reference NEE and alternative NEE, starts to diverge from 2013 and not from 1905. The simulations without management should not be far from other simulation in 2013?

AUTHORS:
In order to derive the effect of management and natural disturbance legacies on the future trajectories of NEE we have defined the starting point of the analysis after the second disturbance episode, i.e. in 2013. The figure thus presents the cumulative differences in carbon uptake or release resulting from legacy effects of past land use and natural disturbance (comparing, for instance, managed and unmanaged scenarios) as well as climate change (comparing climate change and baseline climate) on the future NEE. To complement these results, the differences in total ecosystem carbon storage starting from year 1905 are presented in Table 1.
Based also on the comments of referee #2, we have omitted Fig. 6 and combined Fig. 5 and Fig. S14. To avoid confusion, we have extended the figure caption, explaining more specifically how to interpret the newly added figure.

REFEREE #3:

4) In table 1, we can see a difference of about 40 tC ha between managed and unmanaged simulations. The strangest thing here is that in 2099 this difference disappears (compensation process?). This is interesting but the authors don't mention that in the discussion. Why? and why the figure 5 doesn't display that?

AUTHORS:
As the referee points out correctly, Table 1 indicates that the differences in total ecosystem carbon storage between formerly disturbed and undisturbed scenarios become negligible by the year 2099. In other words, this shows that the legacy effect of past disturbances does not influence carbon storage beyond 2099. Fig. 5 corresponds to the output presented in Table 1 by showing that the cumulative carbon uptake levels off over time. Consequently, the differences in cumulative NEE in Fig. 5 at year 2099 correspond approximately to the differences in total ecosystem carbon storage in year 2013 between disturbed and undisturbed scenarios in Table 1 (~40 tC ha^{-1}). The underlying reason for this compensatory effect is an increased growth (increased carbon uptake) of forests after disturbance.
We have amended the discussion regarding the duration of the legacy effect of past land use and natural disturbances as well as the cause of the compensatory effect on NEE in lines 599-606.

REFEREE #3:
5) Did the two imposed disturbances have a different impact on the forest across simulations? If not, it means that the authors can't observe the legacy effect of one disturbance to another future one. It is maybe the reason why they don't observe a strong effect of natural disturbances. Due to this lake of interaction, the interesting questions like: - Can this forest have the capacity to absorb extreme events well enough to keep the same level of NEE if the intensity and the frequencies of natural disturbances will increase? Or - Are the forest management made between 1905 and 1997 is able to change disturbance impact on NEE in the future? cannot be tackled. It is a pity because it will strengthen the purpose of this paper.

AUTHORS:
While we could not use the dynamic disturbance modules to mimic the first disturbance episode as we did not know its characteristics reasonably well to represent it in our process-based disturbance module (e.g., wind speed, wind direction), the second disturbance episode was in fact simulated dynamically, i.e., the simulation model produced different disturbance impacts on forests and carbon storage depending on the inclusion or exclusion of the first disturbance episode and forest management. The simulation design is explained to the reader in detail in l. 395 – 398: "From 1905 to 1923 management and natural disturbances were implemented in the simulation as recorded in the stand-level archival sources. After 1923, natural disturbances were simulated dynamically using the respective iLand disturbance modules." However, the aim of our study has not been to assess the effects of past natural and human disturbance on future disturbances. Instead, we excluded high mortality disturbance events in order to not confound the investigation of the legacy effects from past disturbances on NEE.
Also in response to comments of other referees, we have added a new analysis to investigate the contribution of the first disturbance episode and forest management on the second disturbance episode (l. 364 – 372). This analysis has revealed a high uncertainty about the relationship

between both disturbance episodes, while past land use clearly increased disturbances on the landscape (l. 479 – 483) We further discuss these new results in l. 557 – 567.

~~Disturbance legacies have a stronger effect on future carbon exchange than climate in a temperate forest landscape~~

Legacies of past land use have a stronger effect on forest carbon exchange than future climate change in a temperate forest landscape

Running head: "~~Disturbance~~ Land use legacies determine C exchange"

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Abstract

Forest ecosystems play an important role in the global climate system, and are thus intensively discussed in the context of climate change mitigation. Over the past decades temperate forests were a carbon (C) sink to the atmosphere. However, it remains unclear to which degree this C uptake is driven by a recovery from past land use and natural disturbances ~~vs.~~or ongoing climate ~~warming~~change, inducing high uncertainty regarding the future temperate forest C sink. Here our objectives were (i) to investigate legacies within the natural disturbance regime by empirically analyzing two disturbance episodes affecting the same landscape 90 years apart, and (ii) to unravel the effects of past land use and natural disturbances ~~and~~ as well as future climate on 21st century forest C uptake by means of simulation modelling. We collected historical data from archives to reconstruct the vegetation and disturbance history of a forest landscape in the Austrian Alps from 1905 to 2013. The effects of ~~past~~ legacies and ~~future~~ climate were~~as~~ ~~determined~~ disentangled by individually controlling for past land use, natural disturbances, and future scenarios of climate change in a factorial simulation study~~simulating 32 different combinations of past disturbances (including natural disturbances and management) and future climate scenarios~~. We found only moderate spatial overlap between two episodes of wind and bark beetle disturbance affecting the landscape in the early 20th and 21st century, respectively. Our simulations revealed a high uncertainty about the relationship between the two disturbance episodes, whereas past land use clearly increased the impact of the second disturbance episode on the landscape. ~~-~~The future forest C sink was strongly driven by ~~past disturbances~~the cessation of historic land use, while climate change reduced forest C uptake. Compared to land use change t~~T~~he two past episodes of natural disturbance had only marginal effects on the future carbon cycle. ~~Historic management (and its cessation) had a considerably stronger influence on the future C balance than the natural disturbance episodes~~

~~of the past.~~ We conclude that neglecting ~~disturbance~~ legacies can substantially bias assessments of future forest dynamics.

Key words: bark beetles, climate change, forest history, forest management, Kalkalpen National Park, legacy effects, net ecosystem exchange, wind

Copyright statement

1. Introduction

Carbon dioxide (CO_2) is responsible for 76% of the global greenhouse gas emissions, and is thus the single most important driver of anthropogenic climate change (IPCC 2014). Forest ecosystems take up large quantities of CO_2 from the atmosphere, and play a key role in mitigating climate change (IPCC 2007). During the period 1990 – 2007, established and regrowing forests were estimated to have taken up 60% of the cumulative fossil carbon emissions (Pan et al., 2011). This carbon (C) sink strength of forests has further increased in recent years (Keenan ~~and others~~et al., 2016), resulting from multiple drivers~~. Yet, it is likely that a combination of factors play a role in the increasing carbon sequestration of forest ecosystems:~~. On the one hand, possible factors contributing to an increasing sink strength of the biosphere are CO_2 (Drake et al., 2011) and nitrogen (Perring et al., 2008) fertilization, in combination with extended vegetation periods resulting from climate warming (Keenan et al., 2014). On the other hand, the accelerated carbon uptake ~~by~~ of forests might be a transient recovery effect of past carbon losses from land ~~-~~use and natural disturbances (Erb, 2004; Loudermilk et al., 2013).

For the future, dynamic Global Vegetation Models (DGVMs) frequently suggest a persistent forest carbon sink (Keenan et al., 2016; Sitch et al., 2008). However, while DGVMs are suitable for tracking the direct effects of global change, they frequently neglect the effects of ~~disturbances and their~~ long-term legacies of the past~~y~~. Both natural disturbances (e.g., wind storms and bark beetle outbreaks) and ~~anthropogenic disturbances~~ land use have decreased the amount of carbon currently stored in forest ecosystems (Erb et al., 2018; Goetz et al., 2012; Harmon et al., 1990; Seidl et al., 2014a). The legacy effects of past disturbances and land use have the potential to significantly influence forest dynamics and alter the trajectories of carbon uptake in forest ecosystems over time frames of decades and centuries (Gough et al., 2007; Landry et al., 2016; Seidl et al., 2014b). This is of particular importance for the forests of Central Europe, which have been markedly affected by ~~anthropogenic (i.e.,~~ forest management~~)~~ and natural ~~(e.g., wind storms and bark beetles)~~ disturbances over the past centuries (Naudts et al., 2016; Svoboda et al., 2012). The importance of an improved understanding of past disturbance dynamics and its impacts on the future carbon cycle is further underlined by the expectation that climate change will amplify natural disturbance regimes in the future (Seidl et al., 2017). In this context the role of temporal autocorrelation within disturbance regimes is of particular relevance, i.e., the influence that past disturbances and land use have on future disturbances at a given site. Are past disturbances and land use increasing or decreasing the propensity and severity for future disturbances? And are such temporal autocorrelations influencing the future potential of forests to take up carbon? The propensity and effect of ~~disturbance interactions~~ such interactions between disturbances and land use across decades remain understudied to date, largely ~~because of~~due to a lack of long-term data on past disturbances and land use~~natural and human disturbances~~.

Here we investigate the effect of long-term disturbance and land use legacies on forest ecosystem dynamics, in order to better understand the drivers of future forest carbon uptake, and thus aid the development of effective climate change mitigation strategies. In particular, our first objective was to ~~empirically~~ investigate the temporal interaction of two major episodes of natural disturbance affecting the same Central European forest landscape 90 years apart (i.e., 1917 – 1923 and 2007 – 2013). We hypothesized a temporal autocorrelation of the two major disturbance episodes, and specifically an amplifying effect from the earlier disturbance episode on the later disturbance episode~~, based on recent observations of centennial disturbance waves in Europe's forests~~ (see e.g., Schurman et al., 2018). Our hypothesis was based on the importance of landscape topography for wind and bark beetle disturbances (Senf and Seidl, 2018; Thom et al., 2013), and the fact that susceptibility to these agents generally increases with stand age, and is usually high after 90 years of stand development (Overbeck and Schmidt, 2012; Valinger and Fridman, 2011). In addition, we tested the effect of land use on the more recent natural disturbance episode, following the hypothesis that land use increased natural disturbance risk in Central Europe by promoting homogeneous structures and single-species plantations (Seidl et al., 2011; Silva Pedro et al., 2015). Our second goal was to quantify the contribution of past natural disturbance~~s~~ ~~(both natural and anthropogenic)~~and land use on the future C uptake of the landscape under a number of climate change scenarios using simulation modelling. We were particularly interested in the relative effects of past disturbance~~s~~, land use, and future climate ~~scenarios~~ on the future forest C sink strength. To that end we reconstructed the vegetation ~~and disturbance~~ history of the landscape from 1905 to 2013 using historical sources and remote sensing. We subsequently determined the effect of past disturbance~~s~~ and land use on 21st century C dynamics by simulating forests from the early 20th century to the end of the 21st century, experimentally altering past disturbance and land use regimes in a factorial simulation experiment. These analyses were run under multiple climate scenarios for the 21st century, and focused on Net Ecosystem Exchange (NEE) (i.e., the net C exchange of the ecosystem with the atmosphere, which is the inverse of Net Ecosystem Productivity, NEP) as the response variable. We hypothesized that the legacies~~y~~ of past disturbance~~s~~ and land use ~~(management + natural causes) is~~ are of paramount importance for the future carbon sink (Gough et al., 2007; Thom et al., 2017a), expecting a saturation of carbon uptake as the landscape recovers from past disturbance~~s~~ and land use (i.e., a negative but decreasing NEE through the 21st century). Moreover, we hypothesized a negative impact of future climate change on carbon uptake as a result of less favorable conditions for carbon-rich spruce dominated forests (Kruhlov et al., 2018; Thom et al., 2017a).

2. Materials and Methods

2.1 Study area

We selected a 7,609 ha forest landscape located in the northern front range of the Alps as our study area (Fig. 1). Focusing on the landscape scale allowed us to mechanistically capture changes in forest structure and C stocks by jointly considering large scale processes ~~at the large scale~~ such as disturbances as well as fine scale processes such as competition between individual trees. The focal landscape is particularly suited to address our research questions as it (i) was affected by two major episodes of natural disturbance (driven by wind and bark beetles) in the past century, and (ii) has a varied ~~management~~ land use history, with intensive management up until 1997, and then becoming a part of Kalkalpen National Park (KANP), the largest contiguous protected forest area in Austria. The steep elevational gradient of the study landscape, ranging from 414 m to 1637 m a.s.l., results in ~~large~~ considerable variation in environmental conditions. For instance, temperatures range from 4.3 – 9.0°C and mean annual precipitation sums vary between 1179 – 1648 mm ~~on~~ across the landscape. Shallow Lithic and Renzic Leptosols as well as Chromic Cambisols over calcareous bedrock are the prevailing soil types (Kobler 2004). The most prominent natural forest types on the landscape are European beech (*Fagus sylvatica* [L.]) ~~dominated~~ forests at low elevations, mixed~~tures~~ forests of Norway spruce (*Picea abies* [K.]), silver fir (*Abies alba* [Mill.]) and European beech at mid-elevations, and Norway spruce ~~dominated~~ forests at high elevations. These forest types are among the most common ones in Europe, and are highly valuable to society also from a socio-economic perspective (Hanewinkel et al., 2012).

2.2 Simulation model

We employed the individual-based forest landscape and disturbance model (iLand) to simulate past and future forest dynamics at our study landscape. iLand is a high-resolution process-based forest model, designed to simulate the dynamic feedbacks between vegetation, climate, management and disturbance regimes (Seidl et al., 2012a, 2012b). It simulates processes in a hierarchical multi-scale framework, i.e., considering processes at the individual tree (e.g., growth, mortality as well as competition for light, water, and nutrients), stand (e.g., water and nutrient availability), and landscape (e.g., seed dispersal, disturbances) scale as well as their cross-scale interactions. Competition for resources among individual trees is based on ecological field theory (Wu et al., 1985). Resource utilization is modelled employing a light use efficiency approach (Landsberg and Waring, 1997), incorporating the effects of temperature, solar radiation, vapor pressure deficit~~,~~ as well as soil water and nutrient availability on a daily basis. Resource use efficiency is further modified by variation in the atmospheric CO_2 concentration. Seeds are dispersed via species-specific dispersal kernels (20 × 20 m horizontal resolution) around individual mature trees. The establishment success of ~~the~~ tree regeneration is constrained by environmental filters (e.g., temperature and light availability). Mortality of trees is driven by stress-induced carbon starvation and also considers a stochastic probability of tree death depending on life-history traits.

Climate change affects tree growth and competition in iLand in several ways (Seidl et al., 2012a, 2012b). For instance, an increase in temperature modifies leaf phenology and the length of the vegetation period, but also reduces soil water availability due to increased evapotranspiration. Net primary production is further influenced by climate change-induced alterations in precipitation, atmospheric CO_2 levels, and solar radiation. Trees respond differently to changes in climate in iLand based on their species-specific traits. Climate change thus not only alters biogeochemical processes in the model but also modifies the competitive strength of tree species, and consequently forest composition and structure (Thom et al. 2017a).

~~Mortality of trees is driven by stress-induced carbon starvation and also considers a stochastic probability of tree death depending on life-history traits.~~ ~~Additionally,~~ iLand currently includes three submodules to simulate natural disturbances, ~~including~~ i.e., wind (Seidl et al., 2014c), bark beetles (Seidl and Rammer 2017), and wildfire (Seidl et al., 2014b). As wind and bark beetles are of paramount importance for the past and future disturbance regimes of Central Europe’s forests (Seidl et al., 2014a; Thom et al., 2013), we employed only these two process-based disturbance submodules in our simulations. The impact of wind disturbance in iLand depends on species- and size-specific susceptibility (e.g., critical wind speeds of uprooting and stem breakage), vertical forest structure (e.g., gaps), and storm characteristics (e.g., maximum wind speeds). The bark beetle module simulates the impact of *Ips typographus* (L.) on Norway spruce, and thus addresses the effects of the most important bark beetle species in Europe with respect to area affected and timber volume disturbed (Kautz et al., 2017; Seidl et al., 2009). The model *inter alia* accounts for insect abundance, phenology and development, as well as emergence and dispersal. It computes the number of beetle generations and sister broods developed per year as well as winter survival rates based on the prevailing climate and weather conditions, and considers individual tree defense capacity and susceptibility (simulated via the non-structural carbohydrates pool of individual trees). Thus the model accounts for inter-annual variation in the interactions between trees and bark beetles. Interactions between wind and bark beetle disturbances arise from a high infestation probability and low defense capacity of freshly downed trees after wind disturbance, while newly formed gaps (e.g., by bark beetles) increase the exposure of surrounding forests to storm events. Seidl and Rammer (2017) found that iLand is well able to reproduce these interactions for Kalkalpen National Park.

In addition to the submodules of natural disturbance we used the agent-based forest management module (ABE) in iLand (Rammer and Seidl, 2015) to simulate past forest ~~disturbances by~~ management. ABE enables the dynamic application of generalized stand treatment programs, including planting, tending, thinning, and harvesting activities. The dynamically simulated management agent observes constraints at the stand and landscape scales, such as maximum clearing sizes and sustainable harvest levels. Besides silvicultural treatments, we used ABE to emulate the past management practice of salvage logging after bark beetle outbreaks. ~~A detailed description of the implementation of historic management activities in the simulations can be found in the Supplementary Material (S4).~~

iLand simulates a closed carbon cycle, tracking C in both aboveground (stem, branch, foliage, tree regeneration) and belowground live tree compartments (coarse and fine roots). Decomposition rates of detrital pools are modified by temperature and humidity to allow for the simulation of C dynamics under changing climatic conditions. Detrital pools include litter (i.e., dead material from both leaf and fine root turnover) and soil organic matter (Kätterer and Andrén, 2001) as well as snags and downed coarse woody debris.

iLand has been extensively evaluated against independent data from forest ecosystems of the northern front range of the Alps using a pattern-oriented modeling approach (Grimm et al., 2005). The patterns for which simulations were compared against independent observations include tree productivity gradients and natural vegetation dynamics (Thom et al., 2017b), wind and bark beetle disturbance levels and distribution~~s~~ (Seidl and Rammer 2017), as well as management trajectories (Albrich et al., 2018). A comprehensive documentation of iLand can be found online at http://iLand.boku.ac.at, where also the model executable and source code are freely available under a GNU GPL open source license.

2.3 Reconstructing forest ~~management and~~ disturbance and land use history

The study area has a long history of intensive timber harvesting for charcoal production, mainly driven by a local pre-industrial iron-producing syndicate. This syndicate was active until 1889, when the land was purchased by the k.k. ("kaiserlich und königlich") Ministry for Agriculture. During the 20th century, the majority of the landscape was managed by the Austrian Federal Forests, and only limited areas within the landscape were still under the ownership of industrial private companies (Weichenberger, 1994, 1995; Weinfurter, 2005). Forest management in the late 19th and early 20th century was strongly influenced by the emerging industrialization. The substitution of wood by mineral coal for heating, but especially for industrial energy supply, changed the focus of forest management from fuel wood to timber production. At the same time, an increase in agricultural productivity (also triggered by an input of fossil resources ~~as well as~~and artificial fertilizer) allowed for the abandonment of less productive agricultural plots, often followed by afforestation or natural regrowth of forest vegetation. Consequently, growing stocks increased in many parts of Europe throughout the 20th century as the result of increases in both forest extent and density (Bebi et al., 2017). In our study system, the shifting focus from fuel wood to timber production around 1900 was accompanied by the introduction of systematic stand delineation for spatial management planning (Fig. S1~~2~~) ~~and~~ as well as decadal inventories and forest plan revisions. These documents are preserved in the archives of the Austrian Federal Forests, and were used here to reconstruct past forest vegetation as well as management and disturbance history (see Section S1, Fig. S1~~2~~ and S2~~3~~ in the Supplementary Material for details).

The oldest historic vegetation data available for the landscape were from an inventory conducted between the years 1898 and 1911 and comprised growing stock and age classes for 11 tree species at the level of stand compartments for the entire landscape; we subsequently used the year 1905 (representing the area-weighted mean year of this initial inventory) as the temporal starting point for our analyses (Fig. 2). A major challenge for managers was to extract resources from remote and inaccessible parts of the topographically highly complex landscape. The most important means of timber transportation in the early 20th century was drifting (i.e., flushing logs down creeks and streams after artificially damming them). However, this transportation technique was not feasible for heavy hardwood timber such as beech (Grabner et al., 2004). Consequently, managers harvested trees selectively, and mainly focused on accessible areas (i.e., stands close to streams).~~,~~ ~~leading to a bimodal age distribution on the landscape in 1905 with many young and several old stands~~This resulted in some parts of the landscape holding young, recently cut forests, while others containing stands of >160 years of age (Fig. S3~~8~~).

In addition to deriving the state of the forest in 1905, we reconstructed management activities (thinnings, final harvests, artificial regeneration) and natural disturbances (wind and bark beetle outbreaks) until 2013. From 1905 to 1917 timber extraction was fairly low. Between 1917 and 1923, however, a major disturbance episode by wind and bark beetles hit the region. Resulting from a lack of labor force (military draft, malnutrition) in the last year of World War I a major windthrow in 1917 could not be cleared, and the resulting bark beetle outbreak affected large parts of the landscape. Overall, wind and bark beetles disturbed approximately one million cubic meters of timber in ~~our study area~~ the region between 1917 and 1923 (based on ~~calculation from~~ archival sources; Soyka, 1936; Weichenberger, 1994). Consequently, a railroad was installed to access and salvage the disturbed timber. After the containment of the ~~disturbance~~ bark beetle outbreak in 1923 forest management resumed at low intensity and no major natural disturbances were recorded. Following World War II, a network of forest roads was built in order to gradually replace timber transportation by railroads. The introduction of motorized chain saws (Fig. 2) further contributed to an intensification of harvests. By 1971, forest railroads were completely replaced by motorized transportation on forest roads, resulting in a further increase in the timber extracted from the landscape ~~(Fig. S9)~~. Timber removals from management as well as natural disturbances ~~from~~ by wind and bark beetles between 1905 and 1997 were reconstructed from ~~yearly~~ annual management reviews available from archival sources. With the landscape becoming part of KANP forest management ceased in 1997. A second major natural disturbance episode ~~of natural disturbances~~ affected the landscape from 2007-2013, when a large bark beetle outbreak followed three storm events in 2007 and 2008. This second disturbance episode was reconstructed from disturbance records of KANP in combination with remote sensing data (Seidl and Rammer, 2016; Thom et al., 2017b).

2.4 Landscape initialization and drivers

The vegetation data for the year 1905 were derived from historical records for 2079 stands with a median stand ~~area~~ size of 1.7 ha. On average over the landscape, the growing stock was 212.3 m^3 ha^{-1} in 1905. The most common species were Norway spruce (with a growing stock of on average 116.3 m^3 ha^{-1}), European beech (68.0 m^3 ha^{-1}), and European larch (*Larix decidua*

[Mill.], 21.5 m^3 ha^{-1}). With an average growing stock of 4.2 m^3 ha^{-1} silver fir was considerably underrepresented on the landscape relative to its role in the potential natural vegetation composition, resulting from historic clear-cut management and high browsing pressure from deer (see also Kučeravá ~~and others~~et al., 2012). Despite these detailed ~~data ~~records on past vegetation not all information for initializing iLand were available from archival sources, e.g., diameters at breast height (dbh) and height of individual trees, as well as tree positions, regeneration and belowground carbon-pools had to be reconstructed by other means. To that end we developed a new method for initializing vegetation and carbon pools in iLand, combining spin-up simulations with empirical reference data on vegetation state, henceforth referred to as "legacy spin-up".

Commonly, spin-ups run models for a certain amount of time or until specified stopping criteria are reached (e.g., steady-state conditions). The actual model-based analysis is then started from the thus spun-up vegetation condition (Thornton and Rosenbloom, 2005). This has the advantage that the model-internal dynamics (e.g., the relationships between the different C and N pools in an ecosystem) are consistent when the focal analysis starts. However, the thus derived initial vegetation condition ~~does ~~frequently~~ not correspond well with~~ diverges from the vegetation state observed at a given point in time (e.g., due to not all processes being represented in the applied model), and does not account for the legacies of past management and disturbance. The legacy spin-up approach developed here aims to reconstruct an (incompletely~~partially~~) known reference state of the vegetation (e.g., the species composition, age, and growing stock reconstructed from archival sources for the current analysis) from simulations (Fig. S4~~5~~). To this end, iLand simulates long-term forest development for each stand under~~, employing an approximation of the~~ past management and disturbance regimes. During the simulations, the emerging forest trajectory is periodically compared to the respective reference values, and the assumed past management is adapted iteratively in order to decrease the difference between simulated vegetation states and observed reference values. This procedure is executed in parallel for all stands on the landscape over a long period of time (here: 1000 years).~~,~~ ~~and t~~The simulated vegetation state~~s~~ best corresponding to the reference values ~~are~~ is stored individually for each stand (including individual tree properties, regeneration, and carbon pools), and later used ~~as initial values for~~to initialize model-based scenario analyses. A detailed description of the legacy spin-up approach is given in the Supplementary Material Section S2~~4~~.

In simulating 20th century forest dynamics we accounted for the abandonment of cattle grazing and litter raking in forests (Glatzel, 1991) as well as an increasing atmospheric deposition of nitrogen ~~from the atmosphere~~ (Dirnböck et al., 2014; Roth et al., 2015). Specifically, we dynamically modified the annual plant available nitrogen in our simulations based on data of nitrogen deposition in Austria between 1880 and 2010, with nitrogen input ~~culminating~~ peaking in the mid 1980s, followed by a decrease and a stabilization after 2000 (Dirnböck et al., 2017). Besides edaphic factors also an increase in temperature has led to more favorable conditions of tree growth (Pretzsch et al., 2014). Detailed observations of climate for our study region reach back to 1950. Climate data were statistically downscaled to a resolution of 100 × 100 m by means of quantile mapping, accounting for topographic differences in climate conditions (Thom et al., 2017b).~~ However, t~~The lack of detailed climate information before 1950 required~~ing~~ an extension of the climate time series ~~to~~ for the years 1905 to 1949. To that end, ~~W~~we extracted data from the nearest weather station covering the period from 1905 to present (i.e., Admont, located approximately 20 km south of our study area), and used its temperature and precipitation record to sample years with corresponding conditions from the observational record for our study landscape.

After using the legacy spin-up to generate tree vegetation and carbon pools in 1905, ~~S~~simulations were run from 1905 until 2099, considering four different climate scenarios for the period 2013 – 2099. Climate change was represented by three combinations of global circulation models (GCM) and regional climate models (RCM) under A1B forcing, including CNRM-RM4.5 (Radu et al., 2008) driven by the GCM ARPEGE, and MPI-REMO (Jacob, 2001)~~,~~ as well as ICTP-RegCM3 (Pal et al., 2007), both driven by the GCM ECHAM5. The A1B scenario family assumes rapid economic growth with ~~a~~ global population peaking ~~in~~ mid-century and declining thereafter, and a balanced mix of energy sources being used (IPCC 2000). With average temperature increases of between +3.1°C and +3.3°C and changing annual precipitation sums of -87.0 mm to +135.6 mm by the end of the 21st century, the scenarios studied here are comparable to the changes expected under the representative concentration pathways RCP4.5 and RCP6.0 for our study region (Thom et al., 2017c). In addition to the three scenarios of climate change a historic baseline climate scenario was simulated. The years 1950 – 2010 were used to represent this climatic baseline, and were randomly resampled to derive a stationary climate time series until 2099.

2.5 Analyses

First, we evaluated the ability of iLand to reproduce the empirical data gathered for the studied landscape. Following a pattern-oriented modeling approach (Grimm et al., 2005) we evaluated a suit of different processes such as tree growth and competition, natural disturbances and forest management. Specifically, we compared model outputs for different aspects of landscape development (e.g., species composition, harvested and disturbed growing stock) at various points in time against empirically derived historical data.

To address our first objective, i.e. ~~and~~ investigating~~e~~ the spatio-temporal interactions of natural disturbances, we used the empirically derived stand-level records of the two historic disturbance episodes (1917 – 1923 and 2007 – 2013).~~ First, w~~We discretized the information (disturbed/

undisturbed) and rasterized the stand polygon data to a grid of 10 × 10 m. Subsequently, we used this grid to calculate an odds ratio for the probability that the two disturbance events affected the same locations on the landscape (i.e., the odds that areas disturbed in the first episode were disturbed again in the second episode). We calculated the 95% confidence interval of the odds ratio using the vcd package in R (Meyer et al., 2016).

To gain further insights into the drivers of the second disturbance period we ran simulations under a combination of different land use and disturbance histories. Specifically, we investigated the effect of two factors on the growing stock disturbed during the second disturbance episode by controlling for their effects individually and in combination, resulting in four simulated scenarios. The two factors considered were (i) the first episode of natural disturbance (1917-1923), and (ii) forest management between 1923 (the end of the first disturbance episode) and 1997 (the foundation of Kalkalpen National Park) (Fig. 2). Differences among scenarios were compared by means of permutation-based independence tests using the coin package (Hothorn et al., 2017).

To address our second objective, i.e., ~~and~~ evaluating~~e~~ the impact of past land use and natural disturbance~~s and~~as well as future climate on the 21st century carbon sink strength, we extended our factorial simulation design to also account for the second disturbance episode and different~~ran simulations under a combination of different disturbance histories and climate~~ future~~s~~ climate scenarios. ~~Specifically, we experimentally permutated disturbances between 1905 and 2013, and analyzed the effect of these permutations by continuing the simulations until the end of the 21st century. At three points in time a bifurcation of the disturbance history was considered in the simulation, resulting in eight different pathways of past landscape dynamics. The~~ Hence, a third~~three bifurcations to~~factor considered in the simulated landscape history was ~~were (i) the inclusion or omission of the first episode of natural disturbance (1917-1923), (ii) a continuation of management until the founding of the national park 1997 or a~~

~~cessation of forest management after 1923, and (iii)~~ the ~~inclusion or omission of the~~ second natural disturbance episode (2007-2013) (Fig. 2~~3~~). ~~This~~ The factorial ~~permutationof~~combination of elements representing ~~of~~ the actual ~~disturbance~~ history of our study landscape ~~of the landscape~~ was chosen as a reference for~~to~~ assessing the effects of past disturbance and land use ~~both past and recent episodes of natural disturbance~~ on future C uptake. ~~, as well as to quantify the role of past management, while accounting for the dynamic interactions between these factors in the simulation (e.g., between first and second episode of natural disturbance).~~ After 2013 four different climate scenarios were simulated for all alternative disturbance histories, to assess the impacts of climate change on the future NEE of the landscape.

All simulations were started from the landscape conditions in 1905, determined by means of the legacy spin-up procedure described above. From 1905 to 1923 management and natural disturbances were implemented in the simulation as recorded in the stand-level archival sources. After 1923, natural disturbances were simulated dynamically using the respective iLand disturbance modules. For the second disturbance episode (2007 – 2013) the observed peak wind speeds for the storms Kyrill (2007), Emma (2008) and Paula (2008) were used in the simulation (see Seidl and Rammer 2017 for details). Beyond 2013, natural disturbances were dynamically simulated with iLand, however, we excluded high intensity wind disturbance events to control for confounding effects with past disturbance events. Specifically, ~~W~~we randomly sampled annual peak wind speeds from the distribution of years ~~1924 –~~ before 2006, and simulated the wind and bark beetle dynamics emerging on the landscape (see also Thom et al., 2017a).

Management interventions from 1924~~3~~ to 1997 were simulated using ABE. The individual silvicultural decisions w~~h~~ere thus implemented dynamically by the management agent in the model, based on generic stand treatment programs of past management in Austria’s federal forests and the emerging state of the forest. The advantage of this approach was that management was realistically adapted to different forest states in the simulations, e.g., with harvesting patterns differing in the runs in which the disturbance episode 1917 – 1923 was omitted. Moreover, in line with the technical revolutions of the 20th century (Fig. 2) the simulated management agent was set to account for an intensification of forest management over time (e.g., a higher number of thinnings and shorter rotation periods). In summary, our simulation design consisted of 32 combinations of different land use and disturbance histories and climate futures (first disturbance episode (yes/no) × management (yes/no) × second disturbance episode (yes/no) × 4 climate scenarios).~~, which were~~ In order to account for the stochasticity of iLand (e.g., with regard to bark beetle dispersal distance and direction, uprooting and breakage probability during storm events etc.) we replicated each scenario combination 20 times (i.e., in total 640 simulation runs) for the years 1905 – 2099 (195 years).

We evaluated the ability of iLand to reproduce past ~~human and~~ natural disturbance~~s~~ and land use as well as the resultant forest vegetation dynamics on the landscape by comparing simulations of the baseline scenario (i.e., including historic climate, as well as reconstructed natural disturbance~~s~~ and ~~forest management~~land use) with independent empirical data for different time periods: The simulated amount of timber extracted was compared to historical records for three time periods ~~divided by~~ signifying major technical ~~revolutions~~ system changes during the 20th century (Fig. 2). Simulated impacts of the second disturbance episode (2007 – 2013) on growing stock were compared against empirical records from KANP. ~~Simulated~~ Model outputs for species shares and total growing stock were compared against ~~independent the~~ historical ~~data~~ records for the year 1905, testing the ability of the legacy spin-up to recreate the initial vegetation state. Furthermore, simulated species shares and growing stocks were ~~also~~ related to observations for 1999, i.e., testing the capacity of iLand to faithfully reproduce forest conditions after 95 years of vegetation dynamics. The results of all these tests can be found in the Supplement Sections S2 and S3 ~~of this study~~.

We used simulation outputs to investigate the changes in NEE over time ~~and to compare the~~and across different scenarios. NEE denotes the net C flux from the ecosystem to the atmosphere, with negative values indicating ecosystem C gain (Chapin et al., 2006). To determine the impact of past disturbance~~s~~ and land use as well as future climate on the 21st century carbon balance of the landscape, we first computed the cumulative NEE over the period 2014 – 2099 for each simulation. Next, the effects of past disturbance~~s~~ and land use as well as future climate were ~~calculated~~ determined from mean differences between the different factor combinations ~~of~~ in the simulation experiment with regard to their cumulative NEE in 2099. P-values were computed by means of ~~permutation-based~~ independence tests ~~using the coin package~~ (Hothorn ~~and others~~et al., 2017)~~, and subsequently transformed into confidence intervals for visualization (Altman 2011)~~. All analyses were performed using the R language and environment for statistical computing (R Development Core Team 2017).

3. Results

3.1 Reconstructing historic landscape dynamics

Using iLand, we were able to successfully reproduce historic vegetation ~~and disturbance~~ dynamics on the landscape. The results from the legacy spin-up revealed a good match with the species composition and growing stock expected from the historic records for the year 1905 (see Section S2~~4,~~ including Fig. S5~~6~~, Fig. S6~~7~~). Furthermore, the iLand management module ABE was well able to reproduce the intensification of forest management over the 20th century (Fig. S7~~9~~). Only the first evaluation period (1924 – 1952) resulted in a small overestimation of simulated harvests. Further, the simulated wind and bark beetle disturbances between 2007 and 2013 corresponded well to the expected values derived from KANP inventories (Fig. S8~~10~~). Our dynamic simulation approach adequately reproduced the tree species composition and growing stock at the landscape scale after 95 years of simulation (Fig. S9~~11~~). Despite an intensification of harvests until 1997 and the occurrence of a major disturbance event in 1917 – 1923, the average growing stock on the landscape doubled between 1905 and 2013 (Fig. S10~~2~~). At the same time total ecosystem carbon increased by 40.9% (Fig. S11~~3~~). European beech dominance increased over the 20th century, in particular at lower elevations (Fig. S10~~2~~, Fig. 1e and 1f). Further details on historic landscape development can be found in the Supplement in Sections S2~~4~~ and S3 (~~ and ~~Fig. S4~~5~~-S11)~~3~~.

3.2 Long-term ~~temporal interactions~~drivers of natural disturbances

We used the empirically derived spatial footprint of two episodes of natural disturbance 90 years apart to investigate the long-term temporal interactions between disturbances. Both disturbance episodes were found to have a similar impact on growing stock (117,441 m^3 and 93,084 m^3 of growing stock disturbed~~ at the landscape~~, respectively), whereas the first episode affected an area more than twice the ~~area ~~size of the second episode (2334 ha and 1116 ha, respectively). Only 9.2% of the area disturbed during the first episode was also affected by the second episode (Fig. ~~4~~3). Whereas the first disturbance episode mainly affected the central and southern reaches of the study area, the effects of the second disturbance episode were most pronounced in the northern parts of the landscape. The odds ratio of 0.49 ($p<0.001$) revealed a lower probability that the same location of the first disturbance episode is affected by the second disturbance episode on the landscape compared to the odds that a previously undisturbed area is disturbed by the second disturbance episode. Based on our simulations we found only a moderate positive effect of the first disturbance episode on the volume disturbed during the second episode (+8,181 m^3, p=0.401). In contrast, land use had a considerable impact on the second disturbance episode. On average, land use increased the volume disturbed by +28.927 m^3 ($p<0.001$).

3.3 The effect of past disturbance and land use as well as ~~and~~ future climate on 21st century carbon sequestration

Our simulations revealed a considerable impact of past ~~disturbances~~ land use on the current state of total ecosystem carbon (Table 1). On average over all ~~Simulations~~scenarios, ~~without~~ the cessation of ~~disturbances~~ land use resulted in an increase in carbon ~~storage~~ stocks of +39.7 tC ha^{-1} (+9.2%) in 2013. ~~compared to the baseline scenario (i.e., including natural and human disturbance). The effect of disturbances was strongly dominated by forest management (97.7%), with only a small influence of t~~The two episodes of natural disturbance had a ~~very~~ limited effect on current carbon stocks. The omission of both natural disturbance episodes increased carbon stocks in 2013 by only +4.2 tC ha^{-1} (+0.9%). ~~Past disturbances also resulted in a considerable carbon uptake beyond 2013 (Table 1, Fig. 5, Fig. 6), *inter alia*, as a result of a persistent recovery of growing stock (Table 2). Further~~Conversely, ~~P~~past ~~forest management~~land use ~~had a~~initiated a strong and continuous positive legacy effect on the future cumulative carbon uptake of the landscape beyond 2013 (Table 1, Fig. 4), resulting from a persistent recovery of growing stocks (Table 2). ~~(~~Notably, past land use caused a cumulative decrease in future NEE ~~until 2099~~ of -41.8 tC ha^{-1}~~,~~ ($p<0.001$) until 2099 on average over all scenarios~~(Table 1, Fig. 5, Fig. 6), *inter alia*, as a result of a persistent recovery of growing stock (Table 2)~~. ~~-~~ T~~T~~he second disturbance episode ~~caused~~ resulted in an initial release of carbon (positive NEE) ~~over the first years of future simulations~~lasting for several years after the event, followed by a reversal of the trend towards a negative NEE effect (Fig. 4~~S14~~). Its overall impact on cumulative NEE at the end of the simulation period was -3.1 tC ha^{-1} (p=0.191), i.e. over the 21st century the recent disturbance period had an overall positive effect on forest C sequestration. The first disturbance episode (1917-1923) had almost no effect on the ~~future forest~~ carbon dynamics in the 21st century (NEE effect of -0.6 tC ha^{-1}, p=0.792). ~~Simulations of the total legacy effect of past disturbances (both natural and human) resulted in a cumulative NEE of on average -43.8 tC ha^{-1} (p<0.001) until 2099, indicating that a substantial future C uptake results from the recovery of forest ecosystems from past disturbance (Fig. 6).~~

Climate change weakened the carbon sink strength on the landscape, mainly as a result of a climate-mediated ~~differences in~~alteration of successional trajectories ~~of forest ecosystems~~ (Table 2). ~~However~~Also, climate change effects on NEE were more variable compared to disturbance legacy effects, with increasing uncertainty over time as a result of differences in climate scenarios (Fig. ~~5~~4). On average, climate change increased the cumulative NEE until 2099 by +22.9 tC ha^{-1} (p<0.001), and thus reduced the carbon uptake of the landscape relative to a continuation of historic climate (Fig. 4~~6~~).

4. Discussion

4.1 ~~Natural and h~~Human and natural ~~D~~disturbance interactions ~~in time~~

~~Consistent with~~Based on previous studies assessing the spatial and temporal autocorrelation of disturbances in Europe (Marini et al., 2012; Schurman et al., 2018; Stadelmann et al., 2013; Thom et al., 2013)~~,~~ we hypothesized that ~~the~~ a disturbance episode in the early 20th century influenced disturbances in the early 21st century. ~~Our hypothesis was based on the importance of landscape topography for wind and bark beetle disturbances (Senf and Seidl, 2018; Thom et al., 2013), and the fact that susceptibility to these agents generally increases with stand age, and~~

~~is usually high after 90 years of stand development (Overbeck and Schmidt, 2012; Valinger and Fridman, 2011).~~ However, our analysis revealed a low probability for the same area to be affected by ~~the~~ two consecutive disturbance episodes of the same disturbance agents (Fig. ~~4~~3). ~~This finding is in contrast to previous studies, which, however, investigated interactions between disturbance events in the mountain forests of the Alps over only a few years (e.g., Pasztor and others 2014), while we here analyzed temporal autocorrelation across multiple decades. Furthermore, also our focus on an entire landscape (and its large heterogeneity in topographic settings and stand conditions) is different from previous assessments of long-term disturbance feedbacks (but see Hanewinkel et al., 2008), which have largely focused on plot to stand-level analyses using dendroecology (e.g., Schurman et al., 2018).~~ Moreover, our simulations only indicate a weak correlation between the two consecutive disturbance episodes on the landscape. Hence, our data do not support the hypothesis of amplified disturbance interactions and long-term cyclic disturbance in Central European forests. Our initial assumption was based on the expectation of ~~We here tested for an amplifying feedback of natural disturbances in time, expecting high susceptibility for large parts of the landscape recovering uniformly~~uniform recovery after the first disturbance episode, ~~and~~ with large parts of the landscape reaching high susceptibility to wind and bark beetles simultaneously. However, disturbances can also have negative, dampening effects on future disturbance occurrence, e.g., when they lead to increased heterogeneity (Seidl et al., 2016) and trigger autonomous adaptation of forests to ~~new~~ novel environmental conditions (Thom et al., 2017c). The low overlap between the two disturbance episodes reported here could thus be an indication for such a dampening feedback between disturbances in parts of the landscape, yet further tests are needed to substantiate this hypothesis for Central European forest ecosystems. An alternative explanation for the diverging spatial patterns of the two disturbance episodes might be a different wind direction in the storm events initiating the two respective episodes, affecting different parts of the highly complex mountain forest landscapes. Also the legacy effects from past ~~forest management~~land use were different for each episode. The more open structure within stands resulting from heavy exploitation before 1900 may, for instance, have increased wind susceptibility in the central and southern reaches of the landscape ~~regions~~.

In contrast to our finding regarding interactions between natural disturbances, our simulations supported our expectation of an amplifying effect of past land use on recent disturbance activity. This finding is congruent with other analyses suggesting past forest management as a driver of current natural disturbance regimes (Hanewinkel et al., 2014; Schelhaas, 2008; Seidl et al., 2011). Past forest management in Central Europe has, for instance, strongly promoted Norway spruce, which is one of the most vulnerable species to natural disturbances in the region (Hanewinkel et al., 2008; Pasztor et al., 2014). Pure stands of Norway spruce are particularly conducive to large-scale eruptions of bark beetles, and even-aged management creates edges that are highly susceptible to strong winds (Hanewinkel et al., 2014; Thom et al., 2013). Our analysis thus suggests that as disturbances increase under climate change (Seidl et al., 2017; Thom et al., 2017a), forests that have been homogenized by past land use are at particular risk.

4.2 The role of ~~disturbance~~ legacies on future C uptake

Past studies investigating drivers of the forest carbon balance have largely focused either on historic factors (Keenan et al., 2014; Naudts et al., 2016) or future changes in the environment (Manusch et al., 2014; Reichstein et al., 2013). Only few studies to date have explicitly ~~considered~~ quantified the effect of legacies from natural disturbance and land use ~~legacies~~ when assessing climate change impacts on the future carbon uptake of forest ecosystems. However, disregarding legacy effects could lead to a misattribution of future forest C changes. Here we harnessed an extensive long-term documentation of ~~disturbance~~vegetation history to study impacts of past natural disturbance and land use ~~and~~as well as future climate on the future NEE of a forest landscape. We found long-lasting legacy effects of both past natural disturbance land use and on the forest carbon cycle (see also Gough et al., 2007; Kashian et al., 2013; Landry et al., 2016; Nunery and Keeton, 2010), supporting our hypothesis regarding the ~~paramount~~ importance of ~~disturbance~~ legacies for future C dynamics.~~-~~ While the legacy effect of past land use was strong, the impact of natural disturbances on the future NEE was an order of magnitude lower (Fig. 4). Here it is important to note that our results are strongly contingent on the intense and century-long land use history in Central Europe. A~~In line with a~~ dynamic landscape simulation study for western North America, for instance, emphasized the dominant role of natural disturbances to determine future NEE (Loudermilk et al., 2013). In our study system, however, ~~our results revealed that disturbance~~ land use legacies may have a stronger effect on future NEE than past natural disturbances and future changes in climatic conditions ~~i~~ (~~on average 1.87 times higher cumulative effect over the 21st centurythan two major episodes of natural disturbance and climate change – see~~ Fig. 4~~6~~). Disregarding legacy effects may thus cause a substantial bias when studying the future carbon dynamics of forest ecosystems. It has to be noted, however, that our study ~~was limited to three~~only considered three relatively moderate climate change scenarios. Hence we might underestimated the effect of climate change on NEE, if future climate change will follow a more severe trajectory (see e.g., Kruhlov et al, 2018). Furthermore, it is likely that over longer future time frames as the one studied here the effects of climate change will become more important relative to past legacy effects (Temperli et al., 2013).

While we here focused on the strength of ~~the disturbance~~ legacy effects, our results also provide insights into their duration. Land-use related differences in C stocks persisted throughout the simulation period, with trajectories converging only towards the end of the 21st century. Hence, our data indicate that land use legacies affect the forest C cycle for at least one century in our study system. Despite the considerably lower impacts of natural disturbances, the legacy effect of the second disturbance episode also lasted for several decades (Fig. 4). ~~f~~Future efforts ~~could~~ should aim at determining the duration of past legacies more precisely, considering a variety of different forest conditions (e.g., Temperli et al., 2013). Moreover, while ~~our analyses~~we here focus on~~ addressed~~ the effects of wind and bark beetle disturbances – currently the two most important natural disturbance agents in Central Europe (Thom et al., 2013) – as well as their interactions, future climate change may increase the importance of other disturbance agents not investigated here (see e.g., Wingfield et al., 2017).

The specific disturbance history of our study area, characterized by an intensive ~~natural and human~~ disturbance~~s~~ and land use history~~ in the past~~ and major socio-ecological transitions throughout the 20th century, is key for interpreting our findings. In particular, the cessation of forest management in 1997 had a very strong impact on the future carbon balance of the landscape (an on average 52.8 and 13.4 times higher effect than the first and second episodes of natural disturbances, respectively – see Fig. 4~~6~~). In addition to disturbance legacy effects, also climate change significantly affected the future NEE. In contrast to the general notion that temperate forests will serve as a strong carbon sink under climate change (Bonan, 2008), our dynamic simulations suggest that climate change will decrease the ability of the landscape to sequester carbon in the future, mainly by forcing a transition to forest types with a lower carbon storage potential (see also Kruhlov et al., 2018; Thom et al., 2017a). However, considerable uncertainties of climate change impacts on the carbon balance of forest ecosystems remain (e.g., Manusch et al., 2014). These uncertainties may arise from a wide range of potential future climate trajectories, but also from a limited understanding of processes such as the CO$_2$ fertilization effect on forest C uptake (Kroner and Way, 2016; Reyer et al., 2014). In addition to the direct impacts of climate change (e.g., via temperature and precipitation changes) on forest ecosystems, climate change will also alter future natural disturbance regimes (Seidl et al., 2017). The potential for such large pulses of C release from forests is ~~making~~ rendering the role of forests in climate mitigation strategies highly uncertain (Kurz et al., 2008; Seidl et al., 2014a).

5. Conclusions

Past natural disturbance regimes ~~(both human and natural)~~ and land use have a long-lasting influence on forest dynamics. In order to project the future of forest ecosystems we thus need to better understand their past. We here showed how a combination of historical sources and simulation modeling – applied by an interdisciplinary team of scientists – can be used to improve our understanding of the long-term trajectories of forest ecosystems (Bürgi et al., 2017; Collins et al., 2017; Deng and Li, 2016). Two conclusions can be drawn from the strong historical determination of future forest dynamics: First, as temperate forests have been managed intensively in many parts of the world (Deng and Li, 2016; Foster et al., 1998; Naudts et al., 2016), their contribution to climate change mitigation over the coming decades is likely determined already to a large degree by their past (see also Schwaab et al., 2015). This means that for the time frame within which a transformation of human society needs to be achieved in order to retain the earth system within its planetary boundaries (Steffen et al., 2011), the potential for influencing the role of forests might be lower than frequently assumed. Efforts to change forest management now to mitigate climate change through *in situ* C storage~~,~~ have high potential (Canadell and Raupach, 2008), but will likely unfold their effects too late to make a major contribution to ~~the transition of~~climate mitigation in the coming decades. Second, any ~~changes in the disturbance regime of forests – whether~~ intentional (~~when altering~~by forest management) or unintentional ~~in the case of changing~~(~~-~~by natural disturbances) changes~~—~~ in forest structure and composition may have profound consequences for the future development of forest ecosystems. This underlines that a long-term perspective integrating past and future ecosystem dynamics is important when studying forests, and that decadal to centennial foresight is needed in ecosystem management.

Author contribution

RS, DT and WR designed the study, RG collected historical data from archives, DT and WR performed simulations, DT analyzed the outputs, all authors contributed to writing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Tables

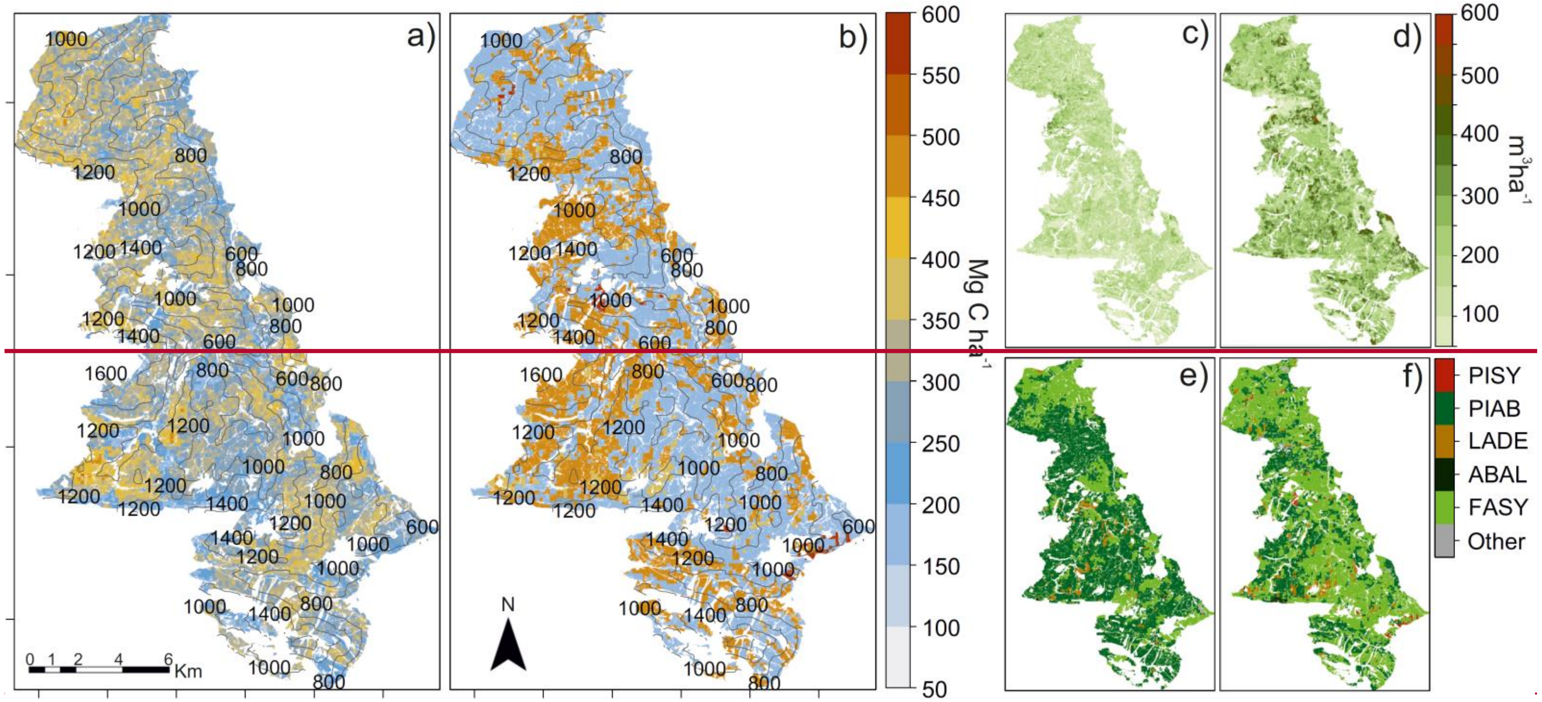
Table 1. Development of total ecosystem carbon stocks (tC ha^{-1}) over time and in different scenarios of disturbance and land use history ~~and~~ as well as future climate. Values are based on iLand simulations and indicate means and standard deviations (SD) over averaged landscape values ~~for~~ of the replicates in the respective scenarios. “Historic climate” assumes the continuation of the climate 1950 – 2010 throughout the 21st century, while “Climate change” ~~denotes~~ summarizes the effect of three alternative climate change scenarios for the 21st century. The first three columns indicate the respective permutation of the simulated disturbance and land use history ~~(see also Fig. 3)~~, with the first line representing the historical reconstruction of landscape development. Y=yes, N=no.

First nat. dist. episode	~~Mgmt~~Land use	Second nat. dist. episode	year 1905	year 1923		year 1997		year 2013		Historic climate year 2099		Climate change year 2099	
			mean	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Y	Y	Y	303.5	331.1	<0.1	403.2	0.7	427.8	0.8	487.7	0.7	466.4	23.7
Y	N	Y	303.5	331.2	<0.1	457.5	0.6	466.7	0.7	487.2	1.0	463.3	20.9
Y	Y	N	303.5	331.0	<0.1	403.2	0.7	430.6	0.7	488.2	0.7	467.0	23.3
Y	N	N	303.5	331.2	<0.1	457.5	0.5	470.9	0.7	487.3	0.7	463.4	21.1
N	Y	Y	303.5	332.7	0.1	404.3	0.8	428.8	0.8	487.8	0.8	466.3	23.7
N	N	Y	303.5	333.0	0.1	458.7	0.5	468.0	0.6	487.8	0.8	464.0	21.3
N	Y	N	303.5	332.7	0.1	404.2	0.7	431.3	0.8	488.3	0.9	466.4	23.6
N	N	N	303.5	333.0	0.1	458.6	0.5	471.7	0.6	487.9	0.9	464.1	21.0

Table 2. Growing stock by tree species (m³ ha^{-1}). Values are based on ~~all~~ iLand simulation runs and indicate species means and standard deviation (SD) over averaged landscape values of the replicates in the respective scenarios. "Historic climate" assumes the continuation of the climate 1950 – 2010 throughout the 21st century, while "Climate change" ~~denotes~~ summarizes the effect of three alternative climate change scenarios for the 21st century.

								Historic climate		Climate change	
	year 1905	year 1923		year 1997		year 2013		year 2099		year 2099	
Tree species	mean	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Abies alba	4.2	2.1	0.0	9.7	2.2	12.7	2.6	28.7	6.1	33.7	7.6
Fagus sylvatica	68.0	76.8	0.6	165.6	39.8	198.5	34.4	286.8	2.8	309.7	19.7
Larix decidua	21.5	23.9	0.2	41.7	5.2	40.5	9.7	17.4	7.9	16.2	7.1
Picea abies	116.3	138.6	0.5	235.7	43.6	250.8	40.5	276.3	36.6	229.9	33.6
Other tree species	2.3	6.0	0.2	14.7	1.4	16.0	1.6	13.4	0.5	23.8	1.7
Total	212.3	247.4	0.8	467.4	79.0	518.5	66.0	622.6	35.4	613.3	46.5

Figures


a)
b)
c)
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Mg C ha^{-1}
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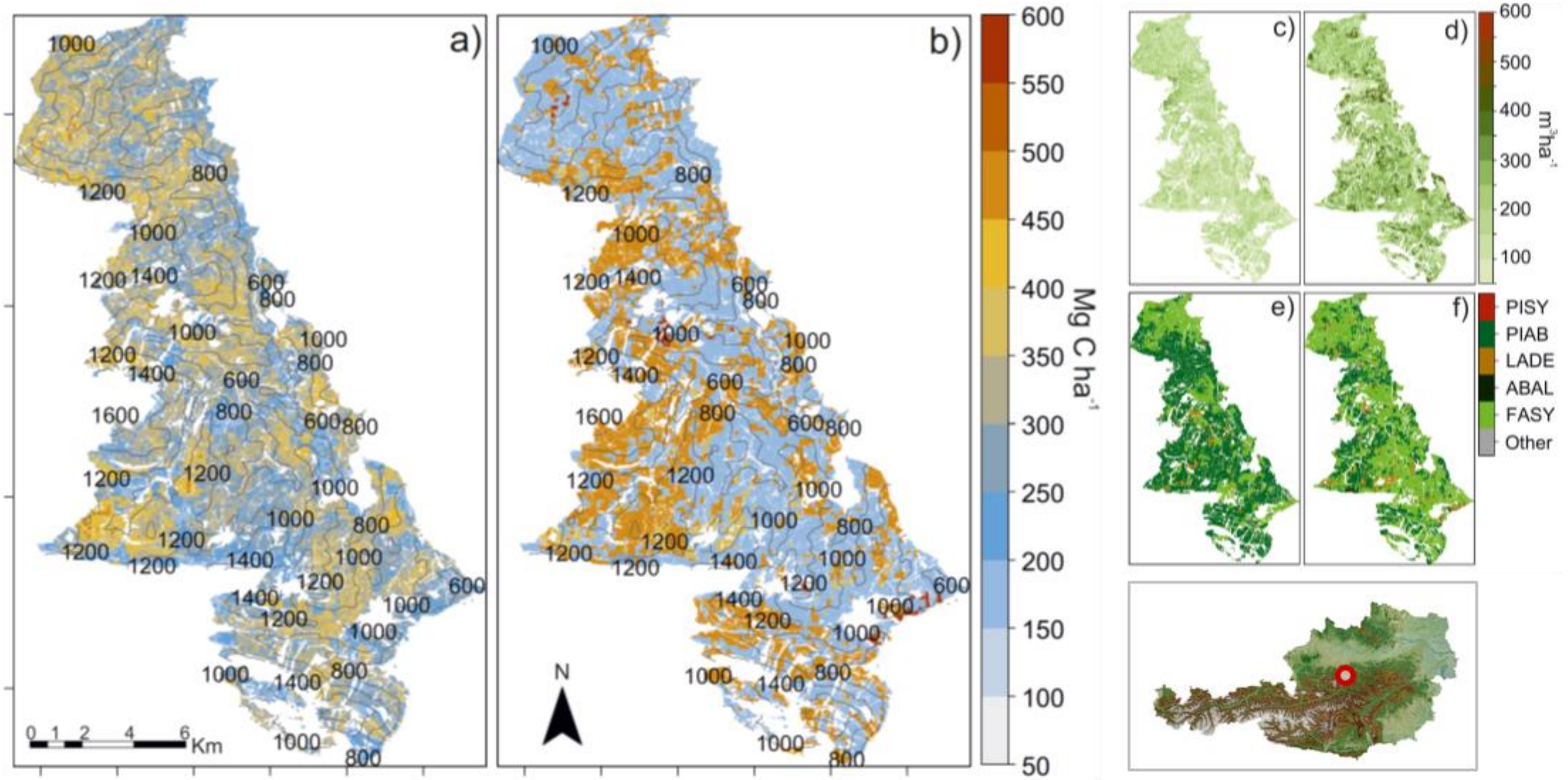
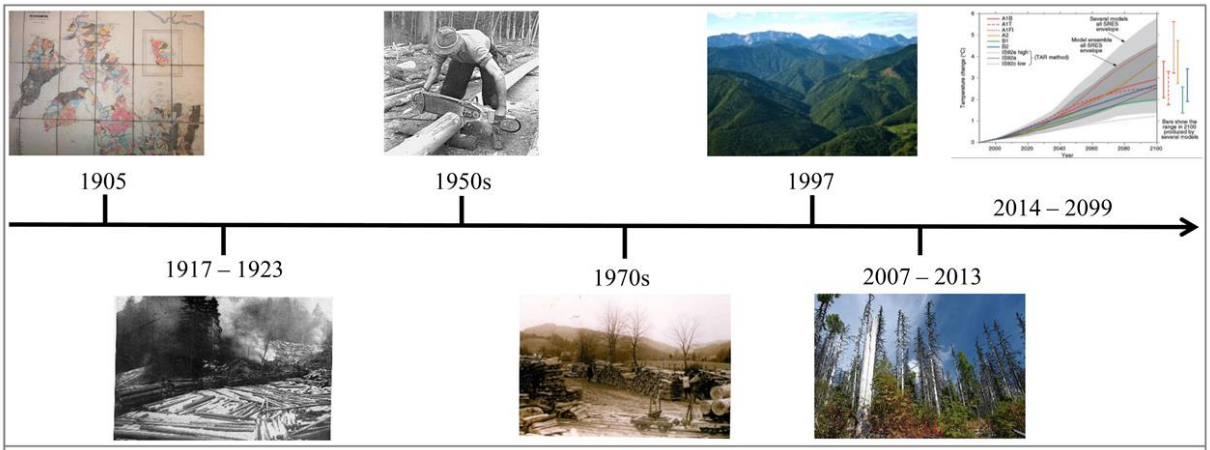


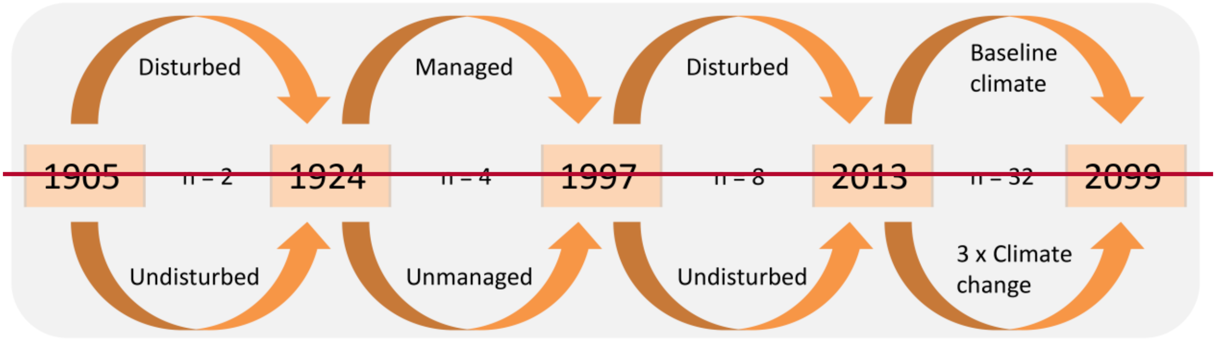
Fig. 1: State of forest ecosystem attributes across the study landscape in 1905 and 2013 as well as location of the landscape in Austria (lower right panel). Panels (a) and (b) show the distribution of total ecosystem carbon, while panels (c) and (d) present ~~the~~ growing stock, and panels (e) and (f) indicate the dominant tree species (i.e., the species with the highest growing stock in a 100m pixel) in 1905 and 2013, respectively. PISY = *Pinus sylvestris*, PIAB = *Picea abies*, LADE = *Larix decidua*, ABAL = *Abies alba*, FASY = *Fagus sylvatica*.~~, and~~ “Other” refers to either other dominant

species~~,~~ not individually listed here due to their ~~scarcity~~low abundance, or areas where no trees are present. Isolines represent elevational gradients in the landscape (in m asl).



1905	First forest inventory
1917 – 1923	First major episode of natural disturbances (wind and bark beetles)
1950s	Using the one-man chainsaw becomes popular
1970s	A rapidly improving infrastructure and mechanization leads to the abolishment of the logging railroad
1997	Kalkalpen National Park was founded
2007 – 2013	Second major episode of natural disturbances (wind and bark beetles)
2014 – 2099	Climate change scenarios

Fig. 2. Timeline of ~~important ~~historic events of relevance for the simulation of the study landscape. ~~Timeline figures originate from various sources~~Image credits:~~.~~ 1905 and 1917 – 1923: archives of the Austrian Federal Forests; 1950s: https://waldwissen.at; 1970s: https://atterwiki.at; 1997: http://kalkalpen.at; 2007 – 2013: photo taken by the authors of this study; 2014 – 2099: http://climate-scenarios.canada.cau.



~~Fig. 3: The disturbance histories and climate futures considered in the simulation. The figure shows the permutation of factors considered between each time step (years in boxes). n denotes the number of unique combinations trajectories resulting from the addition of each individual permutation, each of which was replicated 20 times.~~

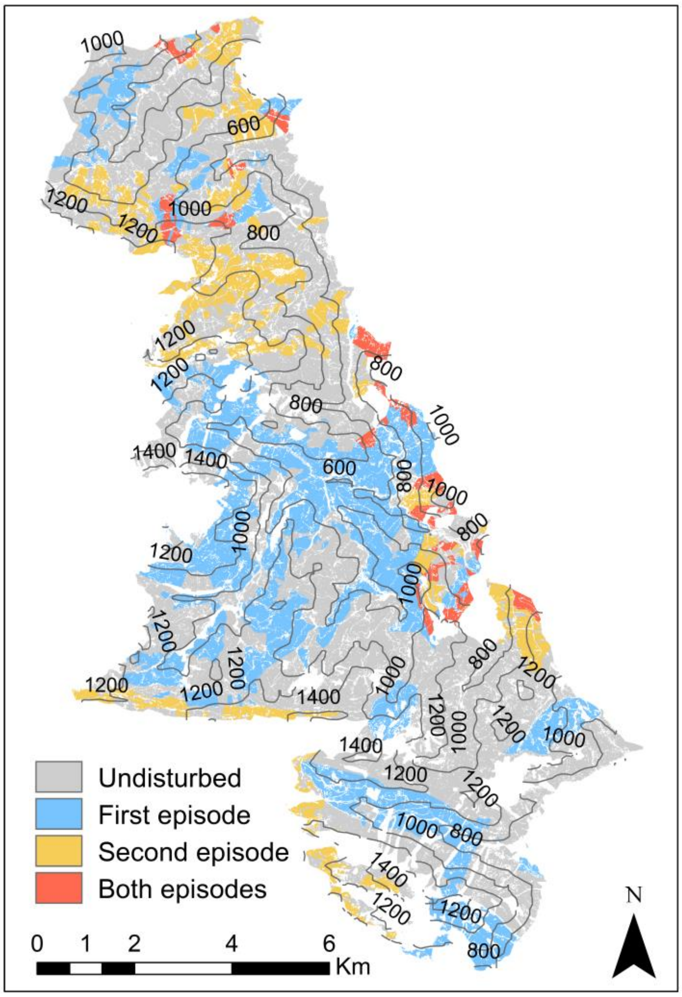
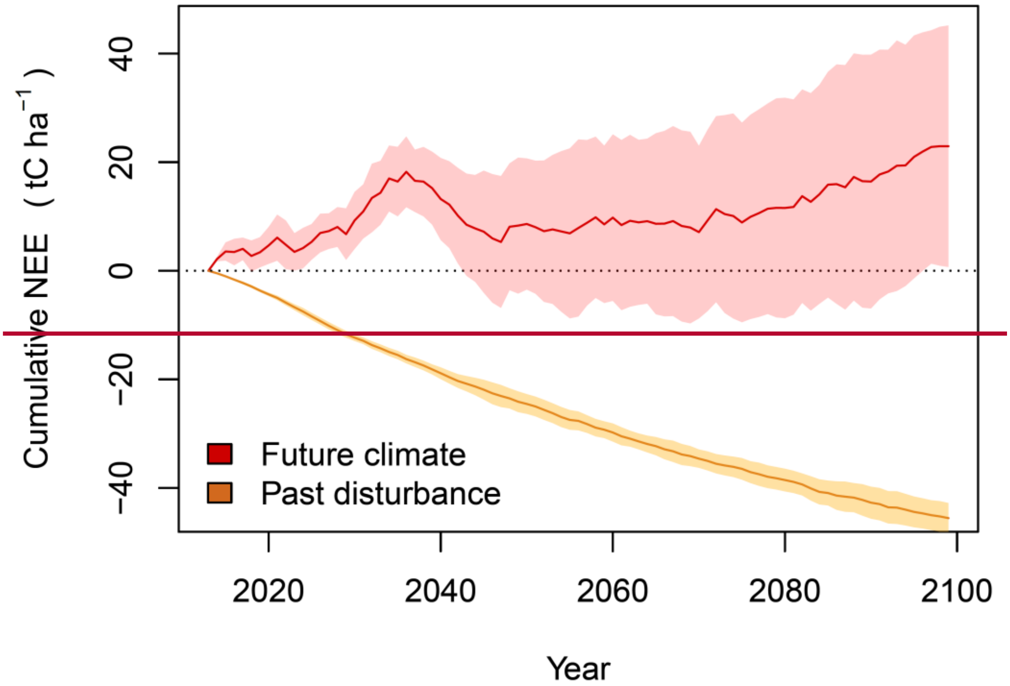


Fig. 3~~4~~: Disturbance activity in two episodes of natural disturbance, from 1917 – 1923 (first episode) and 2007 – 2013 (second episode). Isolines represent elevational gradients (in m asl).


Cumulative NEE (tC ha^{-1})
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20
0
−20
−40
🟥 Future climate
🟧 Past disturbance
2020
2040
2060
2080
2100
Year

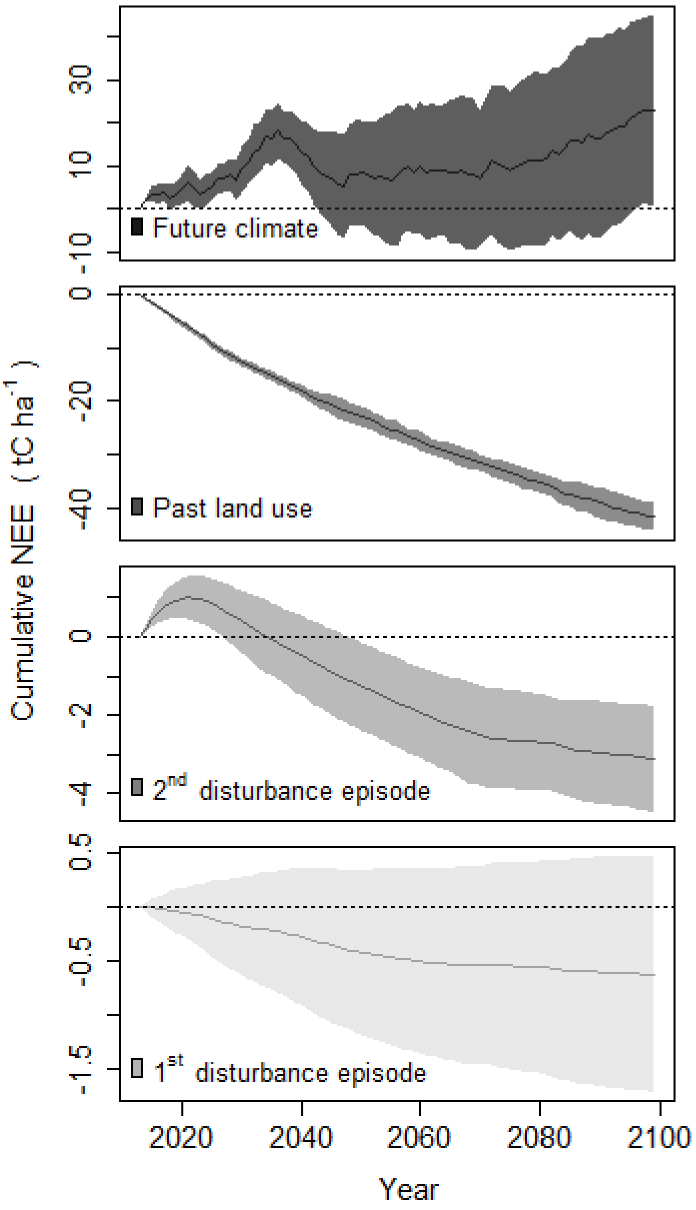
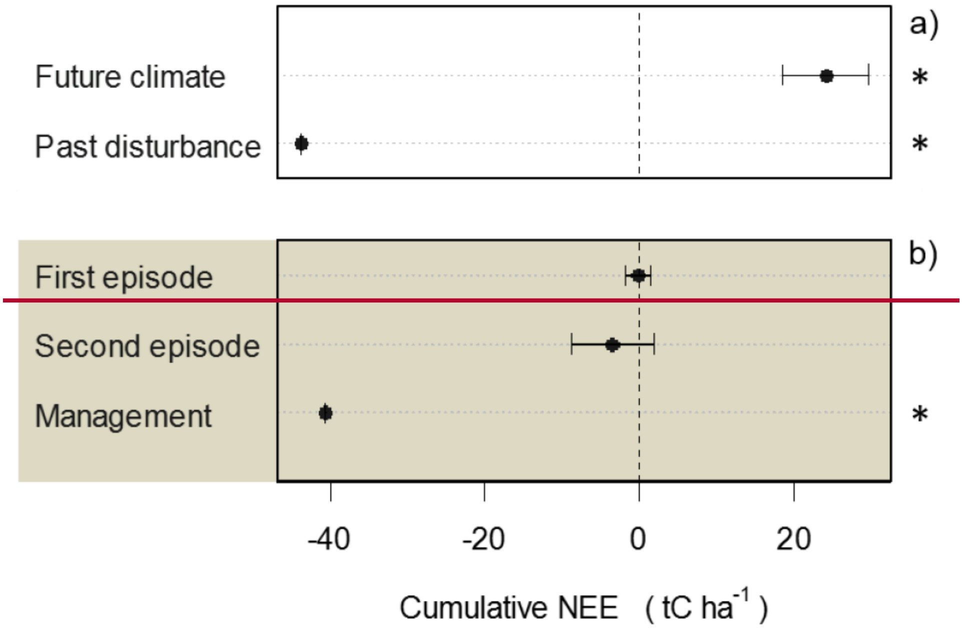


Fig. 4~~5~~. Mean cumulative change in future net ecosystem exchange (NEE) induced by climate change as well as legacies of past land use and natural disturbance (i.e., the first (1917-1923) and second (2007-2013) disturbance episodes, respectively). Differences in NEE were derived from a factorial simulation experiment, comparing each factor to its baseline (e.g., future climate scenarios to baseline climate) while keeping all other factors constant. ~~by comparing NEE outputs including past disturbance (historic management and two episodes of natural disturbance) and future climate with all scenarios excluding past disturbance and baseline~~

~~climate, respectively.~~ Shaded areas denote the standard deviation in NEE for the respective scenarios. NEE is the carbon flux from the ecosystem to the atmosphere (i.e., NEE = -NEP). Note that y-axis scales differ for each panel.



~~Fig. 6. Effects of future climate and past disturbance on the cumulative NEE of the period 2014 – 2099. a) Effect sizes are calculated from a comparison between climate change and historic climate (both without disturbance) as well as disturbed and undisturbed scenarios (both under historic climate conditions), respectively. Whiskers give the 95% confidence interval around the effect size, and asterisks indicate significant indicators (α=0.05). b) In addition to the overall effect of past disturbance, the effect was subdivided into the first and second episodes of natural disturbance as well as human-induced disturbance via management (shaded box).~~

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Section S1: Historical data

Archival sources

All archival sources were obtained from the archives of the Austrian Federal Forests (Österreichische Bundesforste), located in Purkersdorf, Austria. The material consists of maps, quantitative documentations (e.g., tables of growing stock per species and stand), and verbal descriptions of vegetation state, natural disturbances, and forest management. We compiled these sources by means of photographical documentation and subsequent transcription.

The full list of sources ~~includes~~are:

Revisionsoperat des K.K. Wirtschaftsbezirkes Reichraming 1903-1912

Revisionsoperat für den K.K. Wirtschaftsbezirk Reichraming 1913-1922

Wirtschafts-Buch für den k.k. Wirtschaftsbezirk Reichramming 1903-1926

Reichraming 1938-1947 *[data for the period 1927-1937*]

Gedenkbuch 1950-1959 FV. Reichraming

Gedenkbuch 1960-1969 FV. Reichraming

Gedenkbuch Reichraming 1970-1983

Revisions-Operat für den K.K. Wirtschaftsbezirk Weyer (Steiermärkischer Religionsfonds) 1902-1911

Revisions-Operat für den K.K. Wirtschaftsbezirk Weyer (Steirm. Fondsforst) 1912-1921

Weyer 1928-1937

Altenmarkt 1938-1947

WB Weyer 1953-62, I

Wirtschaftsbuch begonnen mit dem Jahr 1902 (Weyer, Oberösterreichischet Religionsfonds)

Waldbesitz Ebenforst der Herrschaft Steyr. Flächentabelle, Bestandsbeschreibung, Altersklassen Verzeichnis nach dem Stande 1898

R. Klöpferscher Waldbesitz Reichraming, Revier Ebenforst. Stand 1. April 1947 *[Map]*

R. Klöpfer'scher Waldbesitz Reichraming, Revier Weissenbach, Stand 1. April 1947 *[Map]*

Nikolaus'scher Waldbesitz Reichraming, Revier Weissenbach, Stand 1. I. 1964 *[Map]*

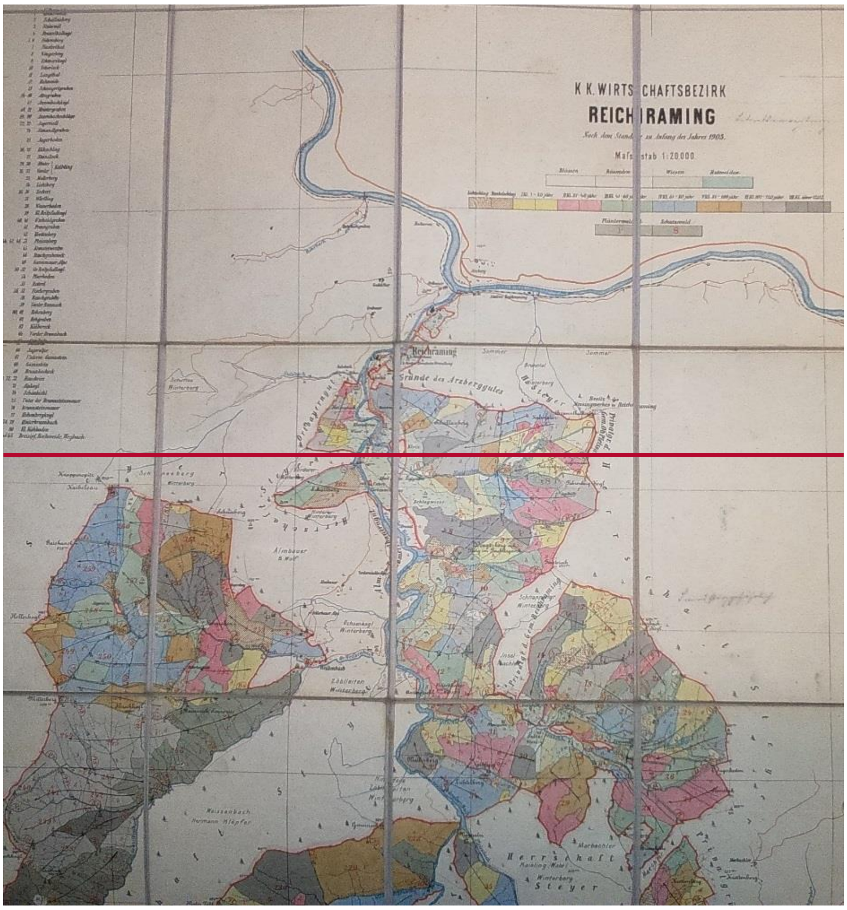
Nikolaus'scher Waldbesitz Reichraming, Revier Ebenforst. Stand 1. I. 1947 *[Map]*

Waldwirtschaftsplan 1974-1983 Forstwirtschaftsbezirk Karl Heinrich NICOLAUS, 4462 Reichraming.

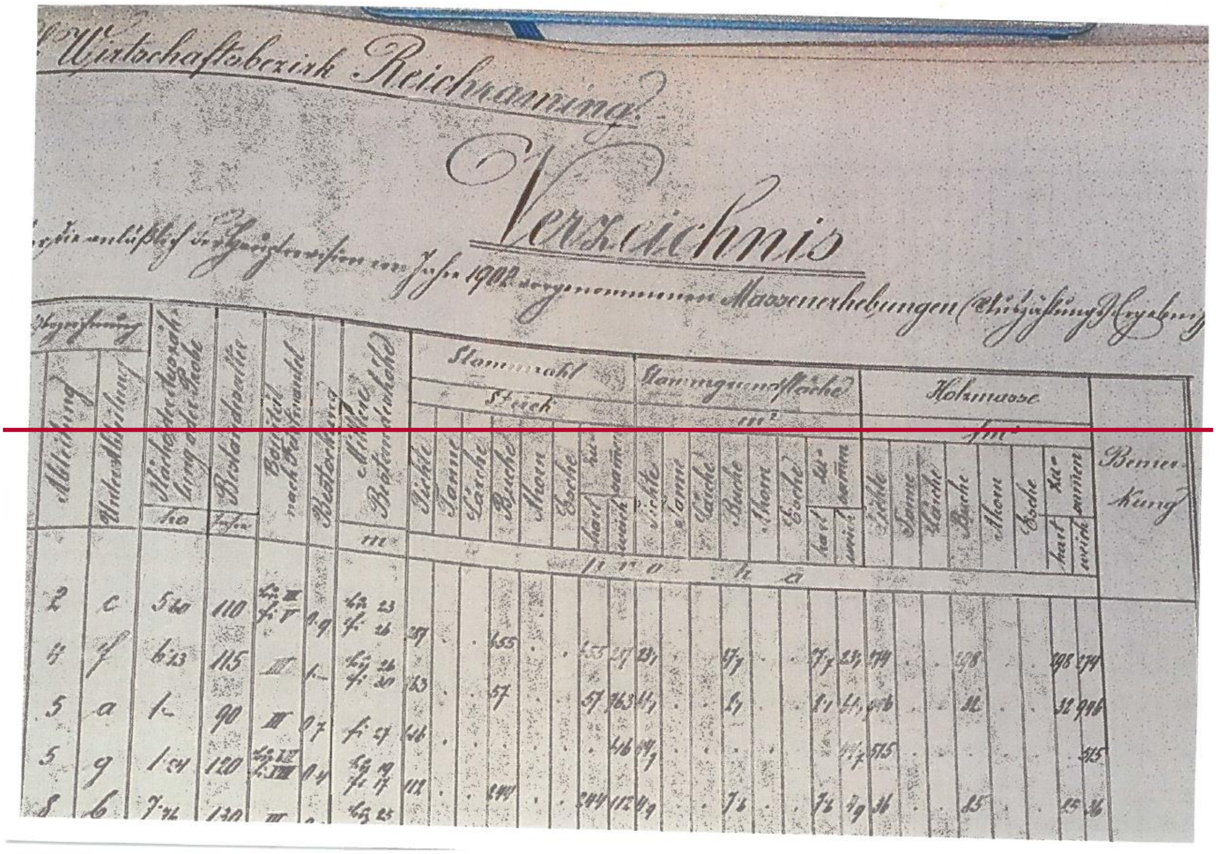
Betriebseinrichtungs-Elabort vom Reviere Zeitschenberg O.Ö. 1907

W.B. Rosenau 1950-1959

From these sources, two types of data were extracted: First, spatially explicit data at the level of stands for the entire study landscape (see Fig. S1~~2~~). These data represent the best available historical information, and were available for certain points in time (or multi-year inventory periods). Specifically, spatially explicit inventories on the forest state were available for the periods 1902/03, 1912/13, and 1926/27 (see Fig. S2~~3~~). In addition, stand-level data on natural disturbances and anthropogenic disturbances (harvesting) were available for the period 1902 – 1927. Second, time series of harvest levels were available for the entire study landscape with annual resolution (source materials for the forest districts Weyer and Reichraming). These data were used to analyze the annual variation in harvest levels. They were furthermore analyzed for major disturbance events. In addition we screened the written protocols and examined meteorological data with a particular focus on detecting major disturbance events outside the two well-documented disturbance episodes 1917-1923 and 2007-2013. These analyses showed that no notable disturbance events occurred between the two major periods analyzed explicitly here.



~~Fig. S2: Example for a map extracted from archival sources, showing a segment of the forest district Reichraming in 1903. The colors denote different age classes of forest stands.~~



Wirtschaftsbezirk Reichraming.

Verzeichnis

~~Fig. S3: Example for an inventory table extracted from archival sources, showing stem number (Stammzahl), basal area (Bestandesgrundfläche) and growing stock (Holzvorrat) per tree species and stand.~~

Identification of spatial units

The delineation of forest stands started in the 1880s in our study area. In most cases, the boundaries of these stands were found to be still valid today, however, minor changes have been made over time (these are well-documented in the forest inventory sources). The spatial identification of stand units was done case by case, comparing toponyms, stand shapes and sizes between historical and recent maps. This approach allowed us to link data spatially between different time periods, and to evaluate the congruence of spatial units between periods. Minor reduction in the size of stand polygons was frequently detected, and was usually attributable to the construction of roads and other infrastructure. In some cases, changes in the stand configuration were made (particularly in remote high-elevation areas of the landscape), which were accounted for by subdividing the respective polygons.

Data gaps

Forests that were under federal ownership throughout the study period were found to be best documented. Two ~~parts~~ areas in the northern reaches of the landscape were under different ownership, but were sufficiently well documented to retain them in our study. These areas have previously been part of the domain Lamberg, and cover about 1/6 of the total landscape. Nonetheless, a number of data gaps had to be filled to achieve a complete and seamless reconstruction of ~~the~~ landscape history.

To fill data gaps regarding the temporal variation in natural ~~and anthropogenic~~ disturbances and land use we assumed equivalence in relative changes, i.e., based on ~~disturbance~~ harvesting ~~percentages~~ rates in a given year for a certain area, we assumed an equivalent change also for areas with missing data. For instance, after 1923 time series on annual harvest and natural disturbance were only available for the forest districts of Reichraming and Weyer (the two main historic forest districts in our study area, covering in total 4492.4 ha). Moreover, Reichraming is lacking data for the years 1938 to 1946, hence the temporal variation of ~~disturbances~~ harvests was only based on the data for Weyer during this period. The data for Weyer terminates in 1952, i.e., only data from the district Reichraming was available for the following years. Where the time series of the two forest districts overlapped, we found similar trends in Reichraming and Weyer, supporting our assumption of equivalence between the two areas.

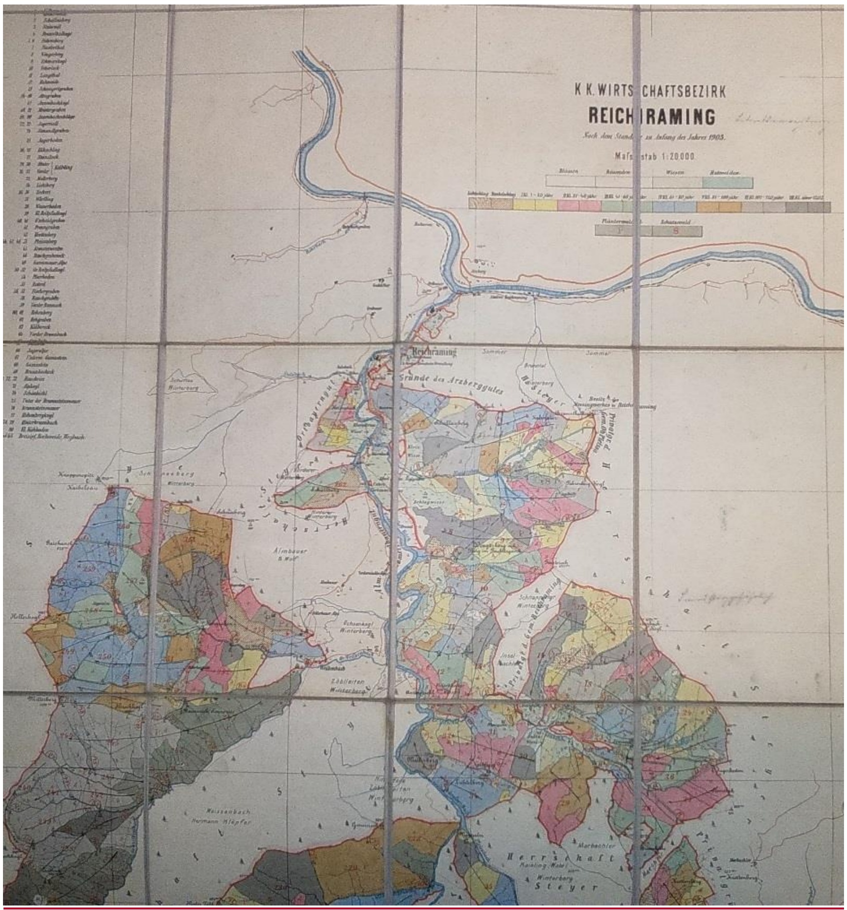
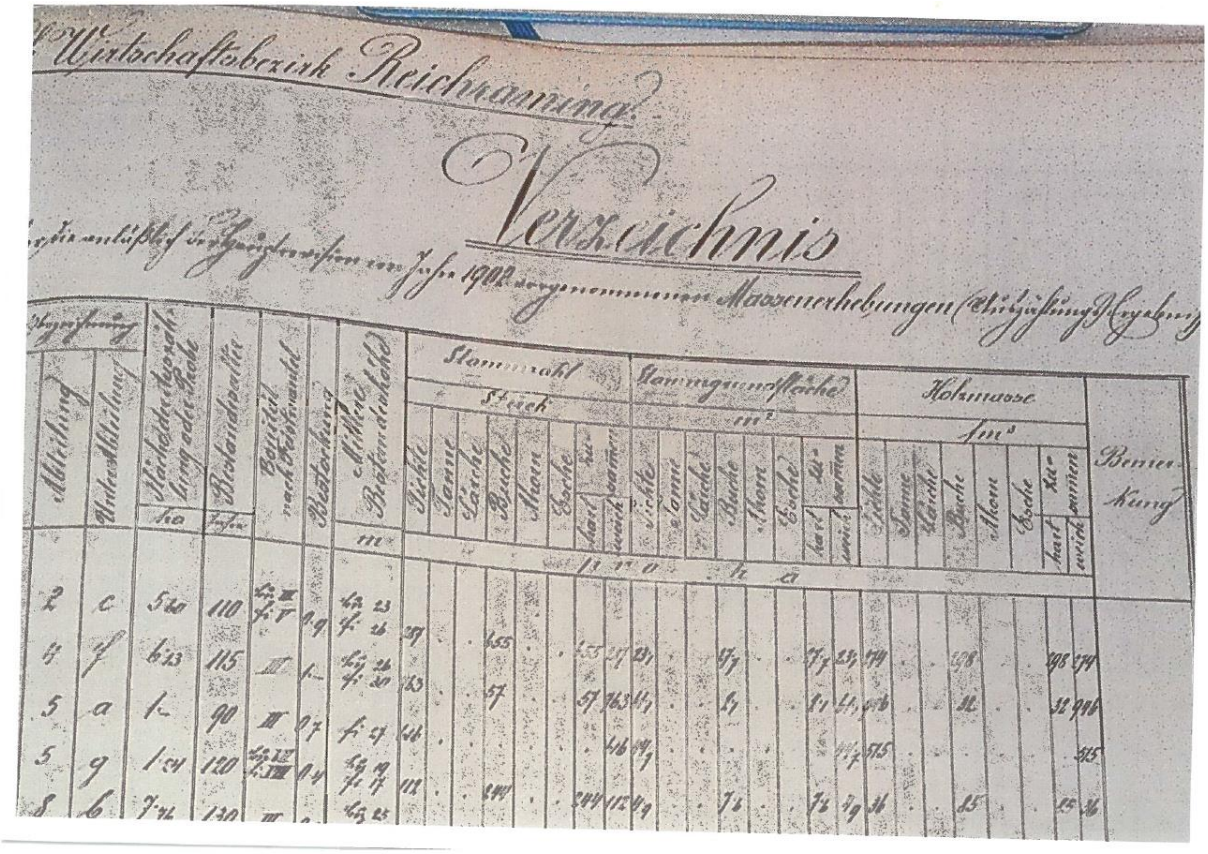


Fig. S1: Example for a map extracted from archival sources, showing a segment of the forest district Reichraming in 1903. The colors denote different age classes of forest stands.



Wirtschaftsbezirk Reichraming.

Verzeichnis

Fig. S2: Example for an inventory table extracted from archival sources, showing stem number (Stammzahl), basal area (Bestandesgrundfläche) and growing stock (Holzvorrat) per tree species and stand.

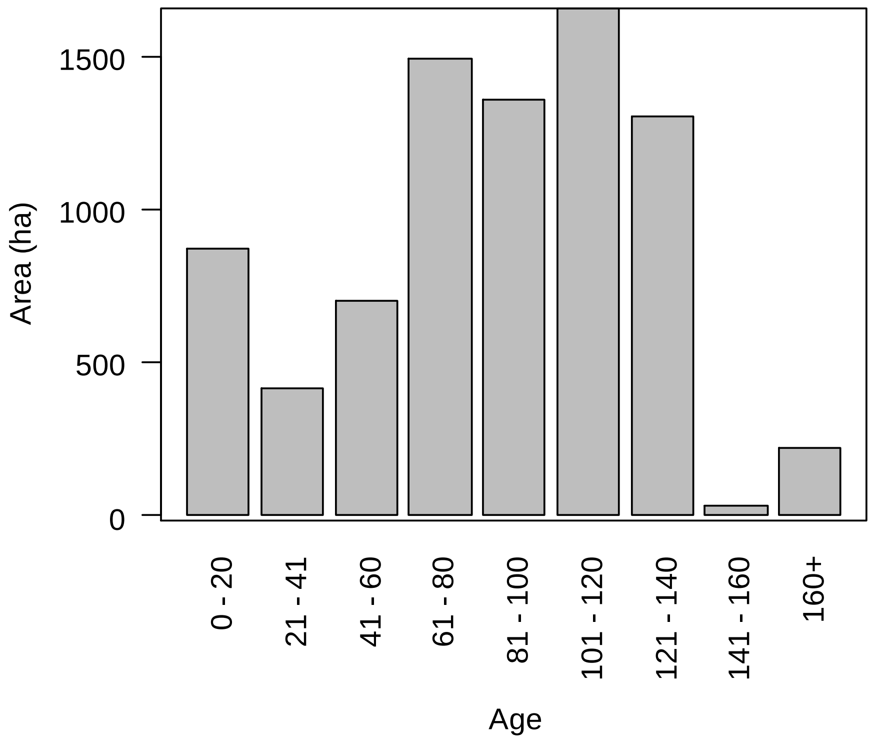


Fig. S3: Age distribution across the study landscape in 1905.

Section S2~~4~~: Legacy spin-up

Legacy spin-up procedure

Management and disturbance history have a long-lasting influence on forest stands, and are important determinants of the state of a forest at any given point in time. In forest landscape models, t~~T~~he initialization of the state of the ecosystem~~s in forest landscape models~~ accounts for legacies of past ~~management~~land use and disturbance~~ legacies, if the data is based on empirically derived records~~. ~~Thereby~~However, the ~~level of detail required for the~~information provided upon initialization differs considerably between models (e.g., Garcia-Gonzalo et al., 2007; Schumacher and Bugmann, 2006; Thom et al., 2017) and is crucially determined by model structure. For instance, while ~~forest~~ structural~~e~~ information plays only a minor role in ~~pixel~~cell-based simulation models (Scheller et al., 2007), individual-based models ~~require~~retain information about tree dimensions, canopy heights, gaps, regeneration etc. (Seidl et al., 2012). Yet, detailed information about forest ~~history~~ ecosystem attributes for initializing simulation models is oftentimes not available (e.g., the spatial patterns of past disturbances or~~).~~ ~~initial belowground~~soil carbon stocks). This is important as ~~U~~uncertainties in initialization can have substantial influence on the simulated trajectories (Temperli et al. 2013).

Using models enables the simulation of past forest development, including past management and disturbances, in the form of a spin-up run. Models can thus help to create realistic and quantitative past and current states of forests. In a conventional spin-up, the model is run for an extended period of time under past forcing, and a snapshot of the simulated state is taken– after reaching a predefined stopping criterion (e.g., elapsed time, variation in certain C pools) – as the starting point for scenario analyses (Thornton and Rosenbloom 2005). This results in meaningful estimates regarding important ecosystem properties, and a system state that is consistent with the internal model logic. However, thus derived ecosystem states often do not correspond well with the information available from past and current observations. For instance, a stand that was recently disturbed in reality could be initialized in a late-seral stage from a spin-up. This lack of structural realism strongly limits the utility of a traditional spin-up approach for initializing models for future projections. Factors such as the spatial distribution of age cohorts on the landscape have important implications for the future ecosystem dynamics, e.g., in the context of future susceptibility to disturbances. Therefore, we have developed a new spin-up approach, termed legacy spin-up, aiming to assimilate available data on the ecosystem state at a given point in time into the spin-up procedure, in order to improve the correspondence of the model state derived from spin-up with the observed state of the system.

Our approach differs from conventional model spin-up by considering the available information of the state of any given stand on the landscape for a reference point in time (Fig. S4~~5~~). As with a conventional spin-up, the legacy spin-up starts by running the model over an extended period of time. This results in a large number of possible states that a given stand on the landscape can be in, given the prevailing climate and soil conditions as well as the past management and disturbance regime. From this state space of each stand, the legacy spin-up procedure selects the state that corresponds most closely to the reference values available for each stand (e.g., observed values from forest inventories, remote sensing, or archival data). In other words, the legacy spin-up does not simply use the vegetation state of the last year of the spin-up run for all stands as initial condition for scenario analysis, but for each stand identifies the specific year of the spin-up run in which the state of the vegetation corresponds most closely to the reference conditions.

To improve the correspondence between the simulated state space for each stand and the reference conditions we harness the adaptive capacity of the agent-based forest management module (ABE) integrated into iLand (Rammer and Seidl, 2015). As detailed information on historic management is ~~not known~~usually not available, we start the spin-up run using generic historic management. The emerging state space in the spin-up simulation is monitored and compared to the reference values, and ABE adapts stand management iteratively to decrease the deviation between the simulated state space and the reference conditions.

For each stand polygon an a priori stand treatment program (STP) is created based on available information on past management regimes and the current state of the system (i.e., the reference state). Such a typical STP for managed forests in Central Europe includes planting, several thinnings and a final cut (Fig. S4~~5~~). For instance, the initial planting could plant trees according to the target species shares (A in Fig. S4~~5~~). During the simulation the defined management steps are executed (e.g., thinnings, B, final cut C). Periodically, the state of the forest is evaluated against the available reference data. A basic evaluation compares, for instance, the growing stock and species shares emerging from the simulation with the respective reference state, and calculates a similarity score (e.g., Bray-Curtis index). When the deviation between the emerging state space from the simulations and the reference state are not satisfactorily, the STP for the next rotation can be altered. In the example in Fig. S4~~5~~, the simulated share of spruce was lower than the spruce share in the reference state, indicating that spruce was likely favored by past management, either by planting spruce (C) or by favoring spruce via selective thinnings. This information is incorporated in the spin-up run, which henceforth uses a ~~-~~modified STP for the given stand and the next rotation (D). This process of iterative adaptation of historic management to increase the similarity between the emerging system state and the reference state is repeated several times. Whenever the simulated forest state has a higher similarity to the reference state than in previous iterations, the state of the stand is stored within a snapshot database (including all ~~the ~~relevant ~~ecosystem ~~information on ecosystem pools and structures), potentially overwriting previously saved states with lower similarity values. This process is executed for all stands on~~f~~ the landscape in parallel. The final step of the process (after, e.g., 1000 years of spin-up) is for each stand to load the saved forest state from the database (i.e., the state that had the highest similarity score relative to the reference state throughout the iterative spin-up run), and to create a single landscape "composite" from all of these saved stand states. This composite is subsequently used as the initial state of the landscape for scenario simulations. The spin-up procedure also creates detailed log files which can be further analyzed (e.g., regarding the deviation of the initialized landscape from the reference state). Technically, the logic of the legacy spin-up is implemented as a JavaScript library. The library is used by application specific JavaScript code (e.g., the historic management regime for the given landscape, or the calculation of similarity indices based on available data) that is provided by the user.

One big advantage of the legacy spin-up procedure is that it can accommodate varying degrees of data availability. If, for instance, only information on stand ages are available, age is the sole criterion used to determine the reference state. However, in many cases there is also information on species composition, growing stock, etc. available (as was the case in the historical data from the 1905 inventory of the landscape studied here), which can be jointly assimilated into the spin-up procedure. If density or growing stock is available in addition to age and species, for instance, the legacies of past non-stand-replacing disturbances and management operations such as thinnings can be captured more faithfully in the spin-up. However, even if no information on the reference vegetation state is available, the procedure can be used to generate a first estimate of landscape-scale vegetation structure and composition based on simulations of historic management and disturbance regimes. The legacy spin-up thus ~~aims to~~ combines the advantages of a conventional spin-up (model-internal consistency of the initialized ecosystem states) with the assimilation of available data on the study system for initializing the model.

Application of the legacy spin-up in the current analysis

For the current study, our aim was to initialize the historic landscape based on stand-level forest management and planning data for 1905, extracted from historical archives. The available information on reference states from archival sources was species composition and age classes per stand, as well as stand-level growing stock. Consequently we defined reference states as the species-specific growing stock and age for every stand, also accounting the possibility of multiple age classes within a stand (representing multilayer and multicohort stands). We developed species and site specific a priori STPs (planting, tending, thinning and harvesting activities) based on common forest management practice in Austria during the 19th century (Stifter 1994). Initially, the share of species in plantings was assumed equal to the reference ~~state~~ species share for each stand. If the Bray-Curties Index, a measure for the similarity of the simulated species composition to the reference state, was above a user-defined threshold at the end of a simulation period, ABE autonomously adapted planting activities, aiming for a species composition closer to the reference state. Shade-intolerant species were planted in groups, while shade-tolerant species were planted in equal spacing in order to improve the competitiveness of shade-intolerant species, and increase the spatial realism of the emerging species distribution patterns. Tending and thinning were specified by the stand age at which these activities are conducted, the amount of timber removed in each intervention, the minimum dbh (diameter at breast height) for tree removal, and the relative share of trees to be removed per dbh class (e.g., in order to differentiate between thinnings from below and from above). The simulation period was defined by the reference stand age. A combined index including the Bray-Curtis-Similarity Index (for tree species composition) and the relative deviation from the reference growing stock level were used to determine the best approximation of the simulated vegetation to the reference state. For an initial estimate of belowground carbon pools in year 0 of the spin-up~~,~~ we used data of Kalkalpen National Park (KANP) as derived by Thom and others (2017) for the year 1999. Only simulated states > year 100 of ~~the~~ legacy spin-up were considered for initialization, in order to allow belowground carbon pools to adjust to historical management.

We started the legacy spin-up procedure from bare ground, assuming ~~the~~ reduced nitrogen pools as described in the section “Landscape initialization and drivers“ (as a result of historic management such as litter raking). We ran the legacy spin-up for 1000 years, assuming constant historic climate conditions. In total 2079 stands were simulated in the legacy spin-up, and subsequently reassembled to the landscape representing the state of forest vegetation in 1905. Our evaluations of the spin-up procedure indicated a good match between reference conditions determined from archival sources and simulation for tree species composition (Fig. S5~~6~~) and growing stock (Fig. S6~~7~~) on the landscape.

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~~Temperli C, Zell J, Bugmann H, Elkin C. 2013. Sensitivity of ecosystem goods and services projections of a forest landscape model to initialization data. Landsc Ecol 28:1337–52.~~

~~Thom D, Rammer W, Dirnböck T, Müller J, Kobler J, Katzensteiner K, Helm N, Seidl R. 2017. The impacts of climate change and disturbance on spatio-temporal trajectories of biodiversity in a temperate forest landscape. J Appl Ecol 54:28–38.~~

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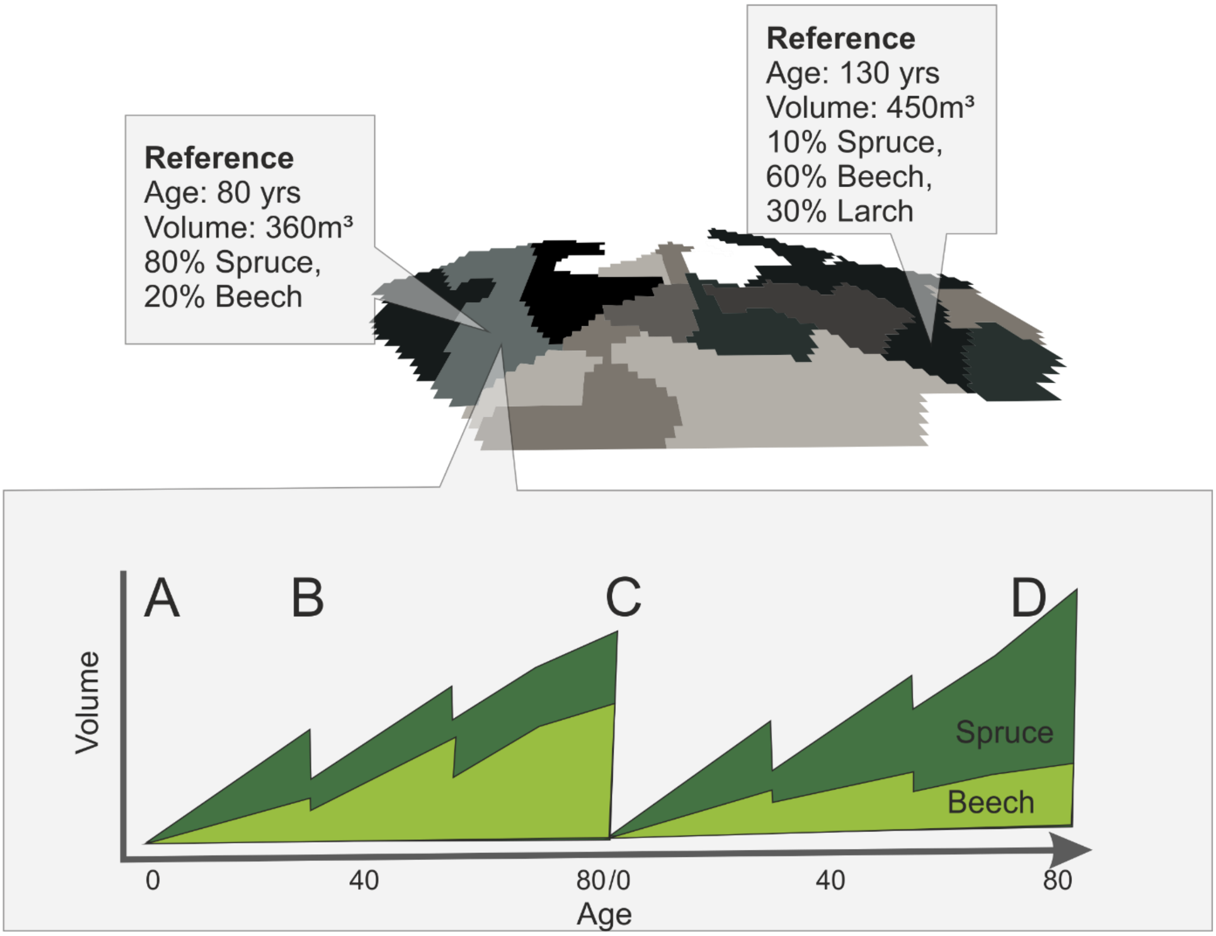


Fig. S4~~5~~: Concept of the legacy spin-up. Upper panel: a fictitious landscape with differing reference states for the spin-up. Lower panel: The development of one stand over two simulated rotations over the course of the legacy spin-up. Letters A to D indicate different phases of the process: A initial planting of target vegetation, B thinnings, C final cut, D modified stand treatment program (STP) for the next rotation period (see text for details).

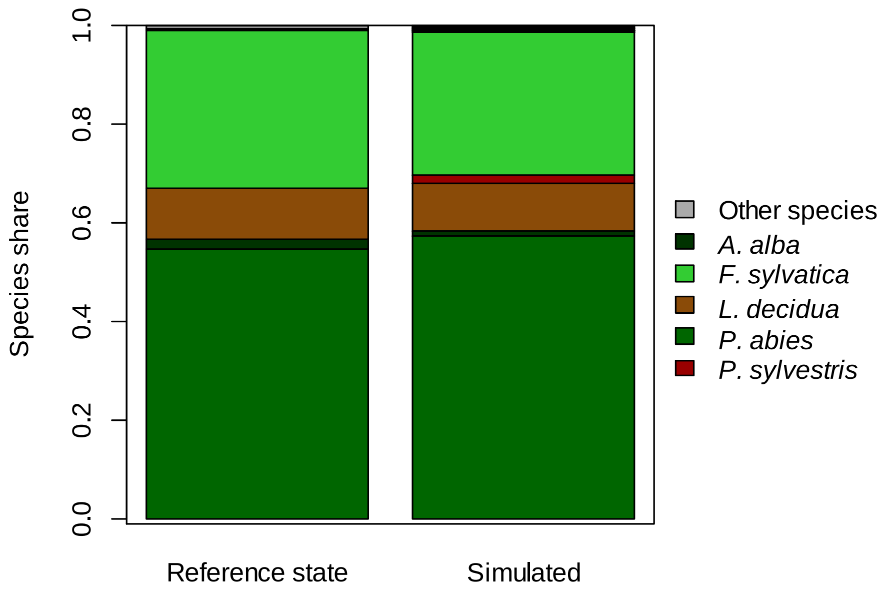


Fig. S5~~6~~: Reference state (from archival sources) and simulated tree species composition emerging as the end point of a legacy spin-up for the year 1905. Species share refers to the relative growing stock per species (1 = 100%).

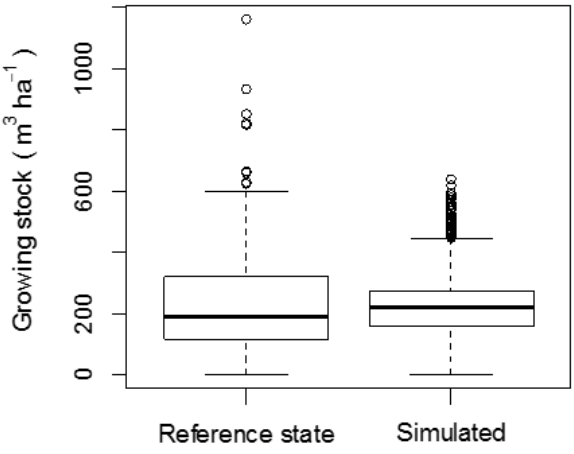
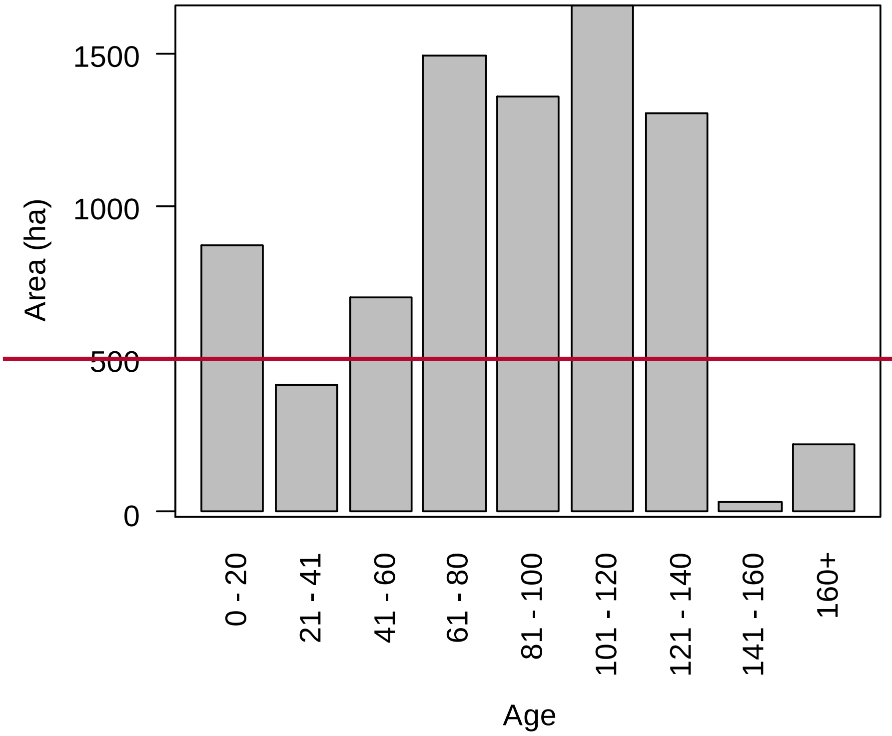


Fig. S6~~7~~: Reference state (from archival sources) and simulated growing stock emerging as end point of a legacy spin-up for the year 1905. Each observation refers to a stand polygon (n= 2079). Mean values: Reference state 216.9 m^3 ha^{-1} and simulated 207.0 m^3 ha^{-1}.



~~Fig. S8: Age distribution across the study landscape in 1905.~~

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Section S3: Model evaluation and forest development after 1905

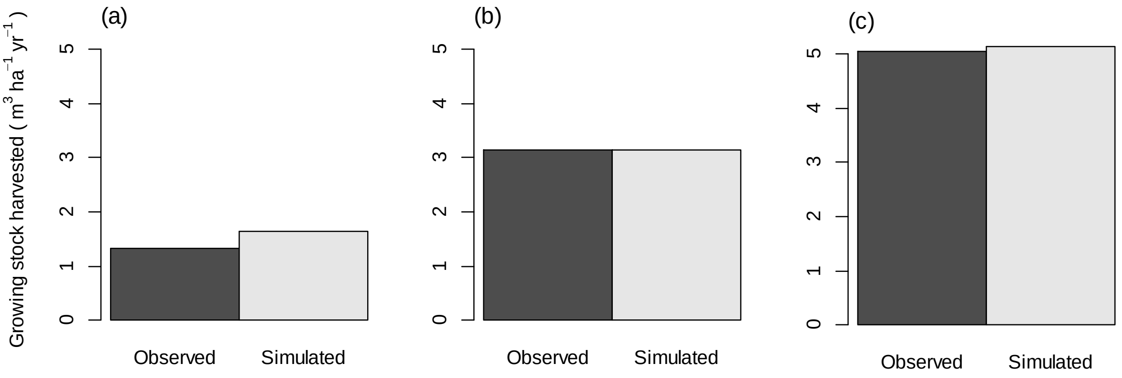


Fig. S7~~9~~: Growing stock (timber volume over bark) harvested in the periods (a) 1924 – 1952, (b) 1956 – 1973, and (c) 1974 – 1983, as reconstructed from archival sources (observed) and simulated with iLand. Simulation data are for the baseline scenario, i.e. assuming historic natural disturbance~~s~~ and management regimes.

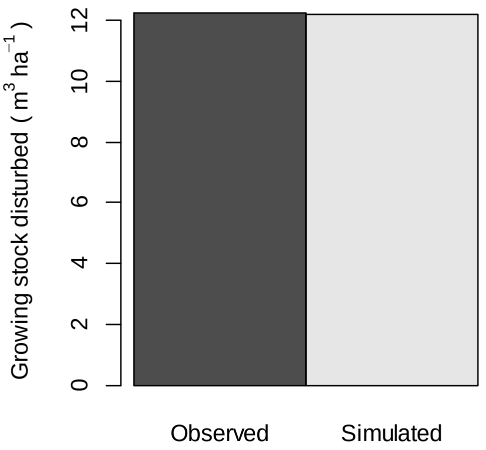


Fig. S8~~10~~: Observed and simulated growing stock disturbed during the second disturbance episode (2007 – 2013). Observed values were derived from disturbance inventories of Kalkalpen National Park, whereas simulated values are for the baseline scenario (i.e., assuming historic natural disturbances and management regimes.

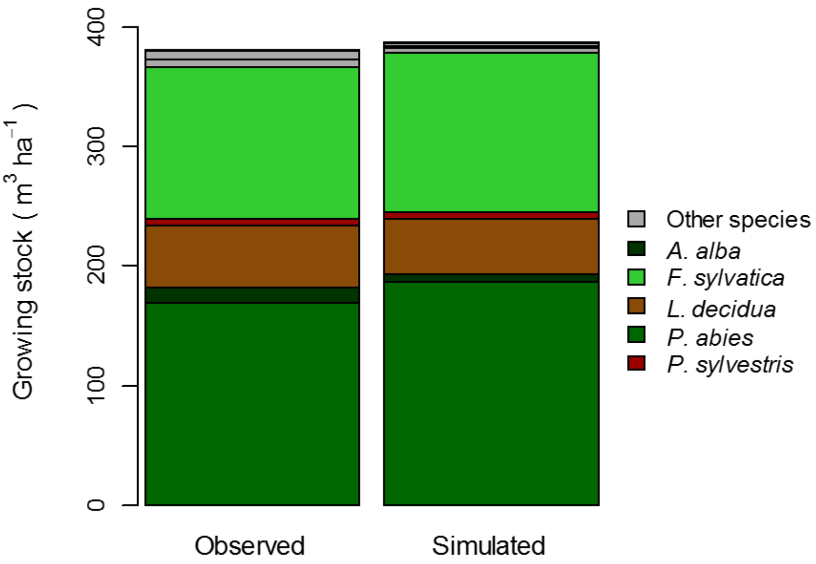


Fig. S9~~11~~: Observed and simulated growing stock by tree species in the year 1999. Observations are from forest management and planning data ~~from~~ of the Austrian Federal Forests, whereas simulated data are for the baseline scenario (i.e., assuming historic natural disturbance~~s~~ and management regimes).

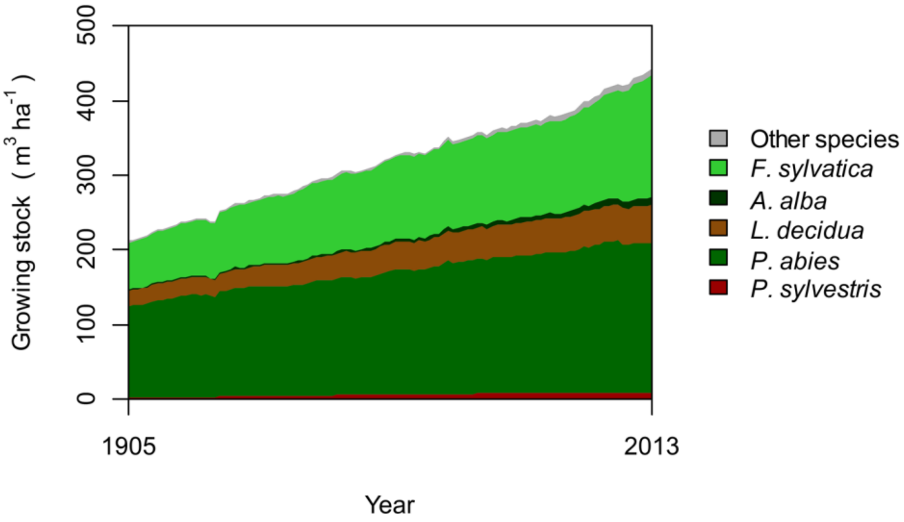


Fig.~~ure~~ S10~~2~~: Growing stock by tree species over time, reconstructed by means of simulation modeling. Data are for the baseline scenario (i.e., assuming historic natural disturbance~~s~~ and management regimes).

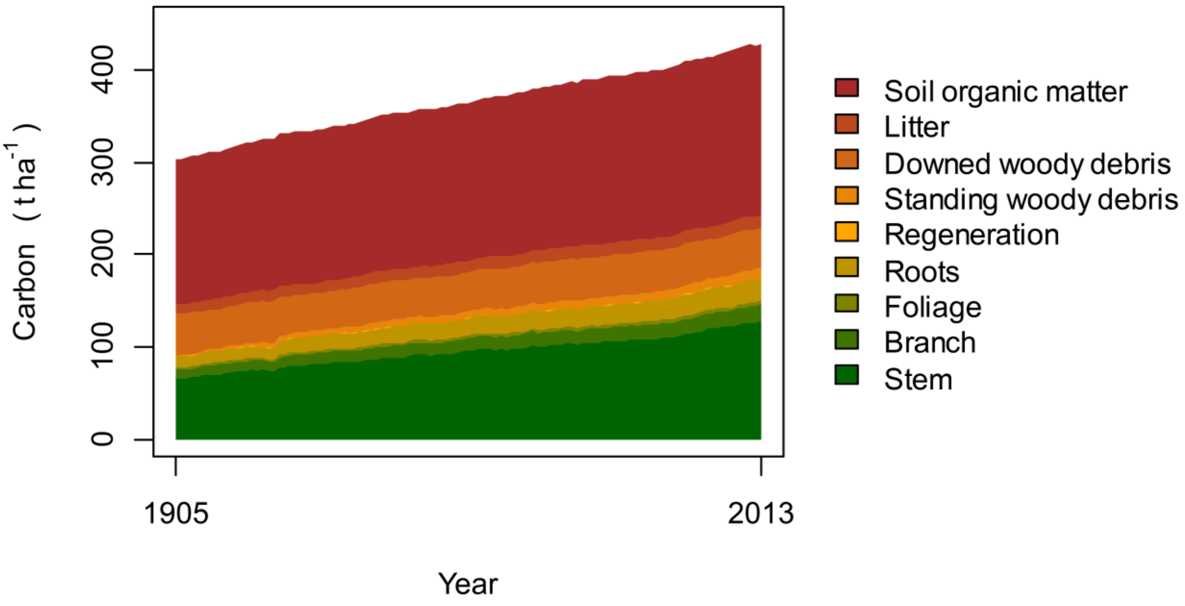
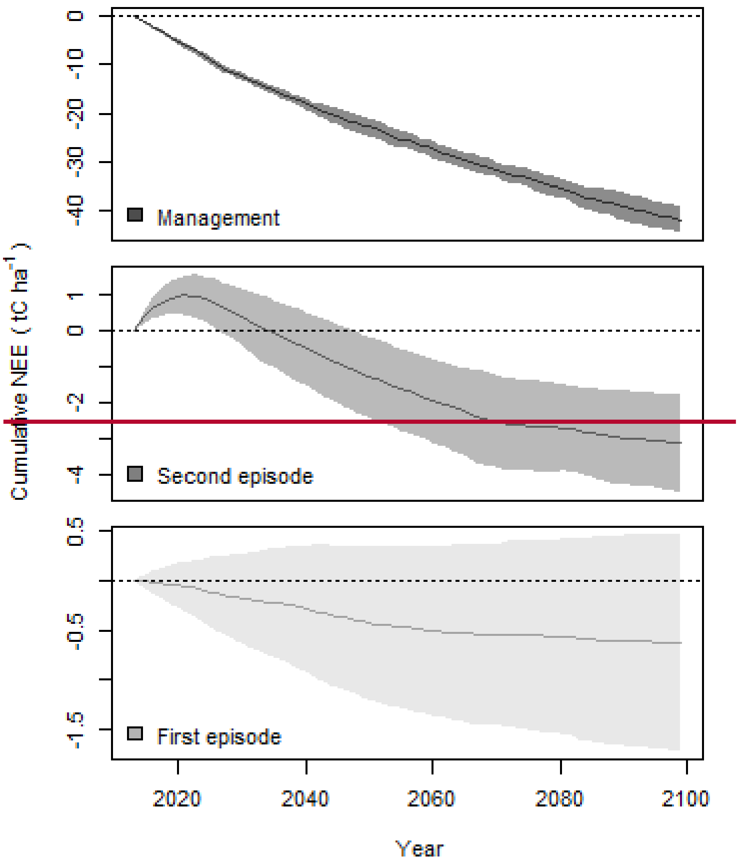


Fig.~~ure~~ S11~~3~~: Carbon storage per compartment, reconstructed by means of simulation modeling. Data are for the baseline scenario (i.e., assuming historic natural disturbance~~s~~ and management regimes).



~~Fig. S14: Mean cumulative change in NEE induced by disturbance, distinguishing the effects of management from that of the first and second episode of natural disturbances. Shaded areas denote the standard deviation (SD) in NEE over the respective scenarios. Please note that panels are scaled individually~~.