**Impact of Quasi-Idealized Future Land Cover Scenarios at High Latitudes in Complex Terrain**

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**Abstract** Afforestation is gaining popularity as a climate mitigation policy in many countries, including high latitude regions such as Norway. However, the impacts of afforestation on local-to-regional climate is poorly understood. This study uses the Weather Research and Forecasting model to investigate the biogeophysical impacts of different forestry scenarios on the local-to-regional climate of Norway. The forestry scenarios considered are the conversion of open spaces to either evergreen forest by active afforestation or to mixed forest by natural succession. Results show both forestry scenarios lead to additional warming of surface temperatures in winter and spring (between 1.0°C and 1.5°C) and cooling in summer (between −1.6°C and −1.3°C). A temperature decomposition analysis shows that the warming in winter and spring is driven by surface albedo changes while summer cooling is driven by changes in sensible heat fluxes for afforestation and surface albedo for natural succession. Maximum 2 m air temperature increases considerably in spring in both forestry scenarios (≈0.8°C to 1.0°C). Analysis of precipitation, multiple climate indices and extremes, reveal little or no response to the different forestry scenarios. The largest societally relevant response to the forestry scenarios is the partial mitigation of the reduction in snow days expected from global warming by 10–20 days. This suggests that implementing current afforestation policies for climate mitigation in Norway may adversely exacerbate some effects of global warming locally while mitigating others. As such, the impacts of afforestation on the local-to-regional climate at high latitudes are complex and cannot support or dismiss afforestation as a climate mitigation policy.

**Plain Language Summary** The conversion of existing open spaces such as grasslands and shrublands to forests is gaining popularity as a climate mitigation policy in many countries, including high latitude regions such as Norway. However, the impacts of such afforestation policies on the local-to-regional climate is poorly understood, particularly at high latitudes. This study uses a state-of-the-art regional climate model to show that at high latitudes afforestation warms surface (or skin) temperature in winter and spring (between 1.0°C and 1.5°C) and cooling in summer (between −1.6°C and −1.3°C). This study also shows that afforestation considerably increases the maximum 2 m air temperature in spring (≈0.8°C to 1.0°C) but has no impact on precipitation, multiple climate indices, and extremes. The largest societally relevant response to the forestry scenarios is the partial mitigation of the reduction in snow days expected from global warming by 10–20 days. This suggests that implementing current afforestation policies for climate mitigation in Norway may adversely exacerbate some effects of global warming locally while mitigating others. As such, the impacts of afforestation on the local-to-regional climate at high latitudes are complex and cannot support or dismiss afforestation as a climate mitigation policy.

1. Introduction

Enhanced CO₂ sequestration by terrestrial ecosystems through afforestation is of growing interest as a mitigation option for International Climate Policy (IPCC, 2019) as this is regarded as a safe and inexpensive solution. It is particularly attractive to high latitude countries with relatively small populations, existing forestry industries, and ample open space available for tree planting and forest restoration (e.g., Norway, Finland, Sweden, Canada, Russia; Bastin et al., 2019). For example, under the current Norwegian climate mitigation plans, afforestation of currently unforested land is considered the fourth most viable mitigation method. This has motivated the development of a “climate forest” plan which involves planting 5,000 ha year⁻¹ with spruce, with a total cost of 10 million Euros per year over 20 years (Haugland et al., 2013). In 2015, the Climate and Environment Ministry took action and began a 3-year pilot program wherein 1.5...
million Euros was allocated for planting forest in new areas in three counties (Nordland, Nord-Trøndelag, and Rogaland). The proposed measure was motivated by studies which stated that forests obtain higher carbon sequestration in tree biomass than open landscapes (Grenlund et al., 2010). Coincidentally, many open landscapes are naturally succeeding to mixed forests. This is a consequence of urbanization which has led to the abandonment of open landscapes traditionally managed by grazing. These historically open landscapes are now naturally succeeding to mixed forests which are dominated by deciduous trees. Some European countries also see afforestation as a viable measure to help their drive toward carbon neutrality.

While the potential for afforestation on a massive scale to remove atmospheric CO₂ is the main argument for using afforestation as part of climate mitigation (e.g., Bastin et al., 2019), less is known about the overall climate impacts of these strategies especially at local-to-regional scales. This needs to be addressed as land cover change influences the climate system through combined effects of biogeochemical (CO₂ uptake) and biogeophysical (albedo, evapotranspiration, and turbulence) processes. Global scale modeling studies show that afforestation in the tropics has a more or less straightforward cooling effect on climate, where the biogeochemical and biogeophysical effects are aligned (Bonan, 2008). Afforestation in mid to high latitudes, however, shows little to no effect on climate or has a warming effect due to the dominating effect of decreased albedo during snow season compared to less strong evapotranspirative effects (Arora & Montenegro, 2011; Davin & de Noblet-Ducoudre, 2010; Longobardi et al., 2016; Montenegro et al., 2009). These results suggest that only considering CO₂ uptake capacity without considering other localized physical system impacts limits our understanding of the effects of afforestation and hence its suitability as a mitigation strategy.

Many studies use idealized simulations to investigate the impact of deforestation or afforestation on the regional (e.g., E. L. Davin et al., 2020; Strandberg & Kjellström, 2019) or global (e.g., Lawrence et al., 2016) climate. Typically, the approach involves replacing all present-day land cover with forest and again with grassland to study the effects of afforestation and deforestation. Such studies with global climate models and even some regional climate models are generally performed at coarse resolutions of 50 km or more. Despite their coarse resolution, these studies still provide useful insights to land-atmosphere interactions over large scales (e.g., subcontinental). Most global modeling studies on this topic show that forests in tropical regions increase precipitation and decrease temperature compared to grasslands. Various modeling studies (E. L. Davin et al., 2020) demonstrate that these biogeophysical impacts are driven by changes in the partitioning of net surface radiation into latent and sensible heat fluxes. Forests can support higher latent heat fluxes than grasslands when evaporative demand is high (Bright et al., 2017). Other modeling studies (e.g., Akkermans et al., 2013) convert only “patches” of the land cover in a domain to forest or grassland to examine the impacts of more realistic forest scenarios on the local climate. Results from these two different, yet widely used, approaches demonstrate different biogeophysical impacts for land cover change from forest to grassland.

Land use and land cover change (LULCC) effects on climate can be highly localized; especially in complex, heterogeneous landscapes. However, only a few high-resolution modeling studies assess the long-term impacts of afforestation on the local to regional climate (e.g., Vanden Broucke & Van Lipzig, 2017). Land surface structure created by vegetation is heterogeneous, which requires models that approach convection permitting, or kilometer scales, to adequately represent processes associated with imposed land cover change. For instance, Vanden Broucke and Van Lipzig (2017) showed that convection permitting simulations were better than nonconvection permitting simulations at reproducing the land cover change signal due to improved representation of daytime shortwave radiation, daytime sensible heat, and nighttime incoming longwave radiation. Simulations at these scales also offer a host of other benefits such as: more faithful representation of precipitation, climate extremes, diurnal cycles (both precipitation and temperature) and dynamics in the presence of complex topography (see Prein et al., 2015 and refs. therein). As such, regional climate models run at kilometer scales can allow a more comprehensive understanding of land cover change effects on local and regional climate.

Here we establish a series of regional climate model simulations to understand the varying effects of afforestation (active mitigation strategy) and natural succession (passive mitigation strategy) in Norway on regional climate under present day and future warming scenarios. The goal is to understand whether proposed mitigation strategies might bring with them unexpected and/or undesirable climate effects. One might expect some localized exacerbation of warming due to afforestation during the cold half year due to decreased
albedo (compared to natural succession). However, current understanding is not strong enough to determine whether proposed strategies offer advantages/disadvantages when weighed against each other.

The following sections detail our experiment design and approach followed by a presentation of the results. The focus is primarily on the physical climate system with some investigation of relevant impacts indices. Other effects such as those impacting ecosystem functionality, the economy and society are also important but are left for future work as they cannot be comprehensively addressed in the current framework. The discussion section places our findings into the broader context and we conclude by describing what our findings can, and cannot, tell us about the viability of the LULCC scenarios considered.

2. Data and Methods

2.1. Experiment Design (Model Domain and Details)

A detailed description of the simulations used in this study are described in Mooney et al. (2020) along with a comprehensive evaluation of the model performance. Only details of the simulations and model configuration pertinent to this study are provided here. The Advanced Research Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) was used to downscale the European Center for Medium Range Weather Forecast Interim Reanalysis (ERA-Interim) for a 10-year period. The model setup uses a 1-way nesting strategy that consists of an outer domain that covers most of Europe with a 15 km grid spacing. The inner nested domain covers the Scandinavian Peninsula (Figure 1) with a grid spacing of 3 km. Although, the climate response to LULCC in this region is not significantly influenced by coarser resolutions (Mooney et al., 2020), a study by Vanden Broucke and Van Lipzig (2017) showed that higher resolutions better represent the physical processes underlying the climate response. The computational costs of multiyear convection permitting simulations are very expensive which prohibits long simulations. Although there is no “standard” length, most convection permitting modeling studies in the literature use only 10 years. This has limitations, for example, the length of the simulation is not long enough (without a large ensemble) to capture rare climate extremes (e.g., 1 in 100 year events). But it is sufficient to capture climatological changes such as shifts in seasonality and thermodynamic responses in the system (see Berthou et al., 2020). Further, the high temporal resolution allows a robust calculation of important subdaily features such as diurnal cycles and subdaily precipitation. Table 1 lists the parameterizations used in the WRF model and related details of the model configuration that are common to all simulations. The land surface is represented in our WRF simulations by the Noah-MP model which uses a dominant land cover type. This means that each grid box contains only one land cover type.

Four of the simulations described in Mooney et al. (2020) and listed in Table 2 are used to explore the possible impacts of current afforestation policies under consideration in Norway on the local and regional climate (see Table 1). These policies consider the conversion of existing open spaces to forested regions either by active afforestation or by natural succession. The first of these simulations (hereafter called Control-Hist) uses the historical land cover as described by the United States Geological Survey (Figure 1) and

| Outer domain | Inner domain |
|--------------|--------------|
| Grid spacing (dx) | ~15 km | ~3 km |
| Spatial extent | Europe | Scandinavian Peninsula |
| Cumulus parameterization | Kain-Fritsch (Kain, 2004) | - |
| Microphysics parameterization | Thompson Microphysics (Thompson et al., 2008) | - |
| Planetary boundary layer | Yonsei University scheme (Hong et al., 2006) | - |
| Land surface parameterization | Noah-MP (Niu et al., 2011) | - |
| Surface layer scheme | Monin-Obukhov scheme (Jimenez et al., 2012) | - |
| Shortwave radiation | Rapid Radiative Transfer model for Global Climate Models (RRTMG) scheme (Iacono et al., 2008) | - |
| Longwave radiation | - | - |
This simulation serves as the reference climate for the other three simulations which are performed under a future climate scenario designed to represent the projected climate in the middle of this century under RCP8.5 representative concentration scenario (van Vuuren et al., 2011). While other RCPs better represent land cover changes e.g., RCP2.6, the RCP8.5 scenario was chosen to impose 1.5°C mid-century global warming conditions on the future climate simulations. It is also noted that a new study by Mooney et al. (2020) shows that the background climate has only a minimal effect on the climate response to afforestation in this region. This means that performing this analysis with other RCPs would have only a minimal effect on the results presented here.

A pseudo-global-warming (PGW) approach to regional downscaling is employed here. This approach has a rich history and several attractive features such as reduced computational costs and removal of well-known mean circulation biases common to driving GCMs (Schär et al., 1996). Our approach follows the method used in Liu et al. (2017) and Parker et al. (2018). This approach adds a monthly climate change signal to the 6 h ERA-Interim data. The monthly climate change signal is calculated for each prognostic variable (i.e., horizontal winds, temperature, geopotential, specific humidity, sea surface temperature, soil temperature, sea level pressure and sea ice) using the ensemble mean of 19 different CMIP5 models listed.
in Mooney et al. (2020). The calculation is performed using a reference 30-year period (1976–2005) and a future 30-year period (2036–2065) that is, centered on the middle of this century and corresponds to approximately 1.5°C warming globally. A benefit to this approach is that it removes uncertainty arising from global model differences and mitigates against global model biases associated with poorly represented physics. As such, it effectively isolates the externally forced thermodynamic response to global warming. A limitation to this approach is that both the present day and future simulations share the same variability. In other words, each simulation has the same weather at the lateral boundaries with the climate change signal added to the boundaries of the future climate simulations. Hereafter, we use the term “mid-century” to refer to the 10 years simulated by WRF using these boundary conditions that are perturbed by this 30-year mean monthly future climate change centered on the middle of this century. A more detailed description of the specific PGW approach used in the three future climate simulations investigated here is provided in Mooney et al. (2020).

The three future simulations differ by land cover. One of the simulations (hereafter called Control-PGW) uses the same land cover data as Control-Hist and it enables analysis of the future climate in the absence of land cover changes. The remaining two simulations are designed to represent two possible forestry policies. In these two simulations, current land cover below timberline that is, considered to be grasslands or shrublands over Norway are converted into forests. Other land cover types such as croplands are unchanged. One of these two quasi-idealized simulations (hereafter called afforestation) replaces grasslands and shrublands over Norway with evergreen forest to represent active afforestation while the other uses mixed forests to represent the natural succession of open spaces to forests (hereafter called natural-succession).

### 2.2. Temperature Decomposition Method

The surface radiative temperature ($T_s$) is decomposed to aid identification of the biogeophysical processes that underlie the impacts on the local climate. The method used here follows the method outlined in Juang et al. (2007) which is refined in Luysaert et al. (2014). Decomposition of the surface radiative temperature is obtained by taking the first order derivative of the surface energy budget (i.e., net longwave [LW] and shortwave [SW] surface radiation = sensible [H] + latent [LE] + ground [G] heat fluxes). This yields the following equation:

$$
\delta T_s = \frac{1}{4e_{t_s}T_s^4} \left( -SW_{in} \delta \alpha_s + \left[ 1 - \alpha_s \right] \delta SW_{in} + \delta LW_{in} - \delta LE - \delta H - \delta G - \sigma T_s^4 \delta e_s - \delta I \right)
$$

All quantities in this equation (e.g., $SW_{in}$, $LW$, $T$, $LW_{in}$, $LE$, $H$, $G$, $e_s$) are simulated by the WRF model. Each term in this equation is calculated using these modeled quantities which enables the attribution of changes in the surface radiative temperature to the following components of the surface energy budget (starting with the first term inside the round brackets):

**Term 1. Surface albedo ($\delta \alpha_s$):** Positive values indicate that forested areas have a lower surface albedo than open spaces and thus absorb more of the incoming solar radiation leading to increases in surface temperatures. This term is dependent on the incoming shortwave radiation from the control simulation which means similar albedo changes can have higher contributions in seasons when incoming shortwave radiation is high (i.e., summer and spring) than in seasons when it is lower (i.e., winter).
**Term 2. Incoming shortwave radiation** ($\delta S W_{in}$): Positive values suggest the incoming solar radiation is higher over forested regions which could be a result of feedbacks including changes in cloud cover, atmospheric moisture, etc. These values are negligible during periods of darkness such as nighttime.

**Term 3. Incoming longwave radiation** ($\delta L W_{in}$): Positive values mean that incoming longwave radiation is higher over forested regions compared to open spaces which could be a result of feedback including changes in cloud cover, atmospheric moisture, etc.

**Term 4. Latent heat flux** ($\delta L E$): Positive values imply that evaporative cooling of the surface is lower for forested regions.

**Term 5. Sensible heat flux** ($\delta H$): Positive values suggest a reduction in convective surface cooling over forested regions. Changes to $H$ can result from a change in the surface roughness or a change in the temperature difference between the surface and the atmosphere.

**Term 6. Ground heat flux** ($\delta G$): A positive change in $G$ shows that during the day less heat is lost from the surface to the subsurface over forested regions. At nighttime, a positive value of $G$ means that more heat is transferred to the surface from the subsurface over forested regions. This may be caused by a reduction in the difference between surface temperature and subsurface temperature.

**Term 7. Surface thermal emissivity** ($\delta \epsilon_s$): Positive changes in this term mean the surface thermal emissivity of the forested regions have increased.

**Term 8.** This term is the residual that results from taking the first-order derivative of the surface energy budget to yield this equation for decomposing the surface radiative temperature. Since it cannot be quantified (Huang et al., 2020), it is not discussed further in the manuscript.

3. Results

The results focus attention on the future responses most likely to be affected by the changes in forest composition; namely, surface and near-surface air temperature. We also examine the surface flux components driving these temperature changes. Lastly, economically relevant impacts indices are explored. We should note that the precipitation response is not presented in this study as the differences between the three experiments are negligible (not shown). This is consistent with previous work that have investigated the impacts of afforestation/deforestation on precipitation using idealized, coarser resolution, regional climate models at pan-European scales (e.g., E. L. Davin et al., 2020; Strandberg & Kjellström, 2019).

3.1. Surface Temperature ($T_{sfc}$)

Figure 2 shows the future warming in $T_{sfc}$ and the air temperature at 2 m for each season in response to the high emissions concentration pathway (RCP8.5) in the middle of the 21st century. In all seasons, the daytime $T_{sfc}$ increases with the largest increases expected in summer at altitudes above 800 m ($\sim 3.0^\circ C$) and the smallest expected in spring also at high altitudes ($\sim 1.6^\circ C$). This behavior is associated with changes in snow cover which is strongly linked to $T_{sfc}$ in these seasons through surface albedo. Analysis of snow cover (not shown here) exhibits little change in spring at altitudes above 800 m but snow cover is considerably decreased in summer. This is consistent with previous studies (e.g., Dyr达尔 & Vikhamar-Schuler, 2009), which showed that changes in snow cover are more pronounced in lowlands than higher altitudes in Norway.

Night time $T_{sfc}$ warms more than daytime $T_{sfc}$ in winter, summer and autumn. However, spatial variations in the response of night time $T_{sfc}$ to global warming are less pronounced compared to daytime temperatures. Nonetheless, there are small variations that are also related to the aforementioned changes in snow cover. At higher altitudes, the surface temperature warms by more than $2.7^\circ C$ in summer while the lowlands ($<800$ m) warm by less than $2.2^\circ C$. A similar pattern is evident in spring.

Figure 3 shows changes in $T_{sfc}$ for the two quasi-idealized simulations (afforestation and natural succession) relative to the Control-PGW simulation; only statistically significant changes at the 95% confidence level calculated using Student’s t-test are shown in Figure 3. Differences between the quasi-idealized simulations and the Control-PGW simulation are only statistically significant in regions that have undergone the land
use change shown in Figure 1b. This shows that the response of surface temperature to these land use changes is localized. Daytime temperatures in winter and spring increase in response to land use changes while daytime summer temperatures decrease in response to the land use changes. Daytime surface temperatures in autumn exhibit no significant change in response to land use changes. As such, they will not be considered any further in this manuscript.

Nighttime surface temperatures in the afforestation and the natural succession simulation show considerable warming in winter, spring and autumn. Nighttime \( T_{\text{sfc}} \) in summer is more uncertain with fewer grid boxes exhibiting a statistically significant change. This is further complicated by the geographical variation evident in the \( T_{\text{sfc}} \) response in the afforestation simulation (Figure 3b). In the Northern part of Norway, \( T_{\text{sfc}} \) exhibits a warming response in the afforestation experiment while the Southern part of Norway, the \( T_{\text{sfc}} \) undergoes a cooling response. This pattern is not evident in the natural succession simulation which shows little change in the Northern region. Nighttime summer temperatures are the only temperatures that exhibit a spatial variation. This is evident from Figure 3 which shows that typically the surface temperature response is spatially homogeneous. Based on this result, the surface temperature in the LUC grid boxes with

![Figure 2](image-url)
a statistically significant response (shown in Figure 3) are averaged spatially and the results are presented in Figure 4.

Figure 4a shows that there is very little difference in the daytime surface temperatures between the two quasi-idealized land use scenarios in winter and spring; the afforestation (natural succession) simulations show that future temperatures in winter and spring will warm on average by an additional 1.5°C and 1.0°C (1.2°C and 0.7°C) in regions where grasslands and shrublands are converted to forests. In summer, there are differences between the two quasi-idealized simulations with the natural succession simulation experiencing a cooling response during the day of approximately −1.6°C while the afforestation simulation shows a cooling of approximately −1.3°C. Figure 4b shows that the percentage of LULCC grid boxes that exhibit a...
A statistically significant change in surface temperature is above 50% in all three seasons and there is almost no difference between the two quasi-idealized simulations.

At nighttime, surface temperature changes range from approximately −0.4°C in summer to 1.2°C in winter (see Figure 4c). There are small differences in the surface temperature changes between the two simulations in all seasons. Figure 4d shows that the percentage of LULCC grid boxes that experience a statistically significant change in surface temperature are greatest in winter and spring for both the natural succession and the afforestation simulations.

The two quasi-idealized simulations show similar results in most cases, but Figure 3 demonstrates that there are some differences between them such as the nighttime response in summer. These differences will be investigated in the next section by decomposing the surface radiative temperature into the surface energy components that underlie the changes in the surface temperature.

### 3.2. Role of Surface Energy Fluxes (Temperature Decomposition)

Results from the temperature decomposition method for both the afforestation and natural succession experiments under historical climate conditions are presented in Figure 5. During the day, changes in surface temperature are attributable to changes in components of the surface energy budget that differ from those during night time, and also changes from season to season.
During the winter day, the following components of the surface energy budget that primarily contribute to the change in surface temperature: sensible heat fluxes (H), latent heat fluxes (LE) and surface albedo. Changes in surface albedo cause the surface to warm while changes in both the sensible (H) and latent heat (LE) fluxes act to cool the surface temperature. These components work in concert to warm the surface by approximately 1.5°C as shown in Figure 4. These patterns are consistent with previous research (e.g., Davin et al. 2020), which show that changing grasslands to forests at high latitudes significantly alters the surface albedo in winter and spring due to the widespread snow cover during these seasons.

The significant warming during the day in spring is also driven primarily by changes in the surface albedo with a small contribution from the ground heat flux (G). The magnitude of the ground heat flux (G) is lower in both the afforestation and natural succession simulations compared to the control simulation which means less heat is transferred from the surface to the subsurface in the afforestation and natural succession simulations. Consequently, the changes in the ground heat flux (G) component has a positive contribution for the surface temperature change. These positive contributions that lead to warming are partially counteracted by large changes in the sensible heat flux (H) and small changes in incoming shortwave radiation (SW$_{in}$). The magnitude of the albedo contribution to the surface temperature change in spring is considerably higher than its counterpart in winter. This can be attributed to the seasonal variations of solar irradiance, which is considerably higher in spring.

In the summer daytime, both the afforested and the natural succession experiments show a similar mean change in surface temperature in response to the associated land cover changes. However, this change in temperature is driven by different components of the surface energy budget; the sensible heat (H) component dominates the effects in the afforestation scenario while the surface albedo component plays the main role in the natural succession simulation. Surface albedo plays a dominant role in the natural succession but not in the afforestation because most of the grid boxes converted to forestry are shrublands which have a higher albedo in summer than mixed forests (natural succession) but a similar albedo to evergreen
needleleaf forests (afforestation). This is shown in the Figure S1. In the afforestation scenario, the changes in sensible heat flux (H) and a reduction in incoming solar radiation (SWin) contribute to the cooling of the surface temperature. This is partially counteracted by changes in the latent heating (LE). Latent heat fluxes are less in the afforestation simulation than the control simulation which results in a warming contribution from the latent heat fluxes in the afforestation scenario. Another considerable difference is that the response in the heat fluxes for the afforestation simulation is notably larger than the natural succession simulation.

The latent heat (LE) component also makes a warming contribution in the natural succession scenario, although it is smaller than the afforestation scenario. There is a small contribution to the cooling from the sensible heat (H) component but it is changes in the albedo that dominate the cooling in the natural succession scenario. This is largely a result of the fact that most of the open space that is, converted to forest is shrubland, which has a lower albedo in summer than mixed forests.

In winter, spring and autumn, the warming of nighttime surface temperature in both the afforestation and natural succession experiments is attributable to changes in the sensible heat flux (H). At nighttime, the atmosphere is typically warmer than the surface, leading to heat being transferred to the surface by advection. The positive contribution of the sensible heat flux (H) to the warming surface temperature means that more heat is transferred to the surface in the afforestation and natural succession simulations than in the control simulation. The surface energy components that counteract some of this positive contribution from the sensible heat component differ from season to season.

In winter, the nighttime changes in the latent heat (LE) flux counteract the change in the sensible heat flux. In spring and summer, it is the changes in ground heat (G) flux that counteract the changes in the sensible heat (H) fluxes. At night time the subsurface is warmer and heat flows from the subsurface to the surface, leading to a warming at the surface. In the afforestation and natural succession simulations less heat flows from the subsurface than in the control simulation. This gives rise to the negative contribution of the ground heat (G) component in summer and spring. In autumn, both the sensible heat and latent heat components partially counteract the sensible heat flux contribution.

3.3. Air Temperature at 2 m

As shown in the previous section, sensible heat fluxes, which are responsible for the exchange of energy between the surface and the atmosphere, are sensitive to land use changes. This means that changes in the surface temperature in response to LULCC are transmitted to air temperatures. As such, this section explores the response of air temperature to the different forestry scenarios and to the changes in concentration of emissions under RCP8.5 for the middle of the 21st century.

Figure 2b shows the changes in the maximum and minimum air temperature at 2 m (hereafter, $T_{2\text{max}}$ and $T_{2\text{min}}$) under the RCP8.5 pathway for the middle of the century. There are spatial variations throughout Norway; the greatest changes in $T_{2\text{max}}$ are observed at high altitudes in summer with temperatures increasing by more than 4°C. Smallest increases in $T_{2\text{max}}$ occur in winter and spring with temperatures increasing between 1.5°C and 2°C in the western part of Norway while the southeast and the northern part warm by more than 2°C. The warming in the eastern part of Norway is more widespread during autumn. Minimum air temperature at 2 m also shows the greatest warming in summer at high altitudes with temperature increasing between 2.7°C and 3.3°C. There are also spatial variations in the $T_{2\text{min}}$, with the eastern part of Norway warming faster than the western part. These results are consistent with recent analyses of the Norwegian climate by Hanssen-Bauer et al. (2017).

Figure 6 shows the response of $T_{2\text{max}}$ and $T_{2\text{min}}$ to different forestry scenarios. Less than 20% of the LULCC grid boxes show a statistically significant change in $T_{2\text{max}}$ in response to the LULCCs during winter, summer and autumn. This means $T_{2\text{max}}$ is not very sensitive to LULCC in these seasons. Differences between the two forestry simulations emerge in summer, with almost no grid boxes in the afforestation simulation showing a change in $T_{2\text{max}}$ whereas almost 20% of the grid boxes in the natural succession simulations show $T_{2\text{max}}$ cooling by almost 0.5°C.

In autumn, $T_{2\text{max}}$ does not respond to LULCCs with fewer than 2% of the LULCC grid boxes showing a statistically significant change. This is a stark contrast to spring when more than 60% of the LULCC grid boxes
exhibit a statistically significant response in $T_{2\text{max}}$. The mean change in spring for $T_{2\text{max}}$ is 1.1°C and 0.9°C for the afforestation and natural succession simulations, respectively. The difference between the responses for the two forestry scenarios is very small in spring.

Less than 50% of the LULCC grid boxes show a statistically significant response in $T_{2\text{min}}$ to the LULCC in winter and spring with less than 5% showing a significant change in autumn. This means that $T_{2\text{min}}$ is not very sensitive to LULCC during winter and spring, and shows no statistically significant response in autumn. There are no clear differences in the $T_{2\text{min}}$ response between the two forestry scenarios in spring and summer. Winter also exhibits no clear difference in the mean temperature response but there is greater spatial spread in the response of the natural succession simulation compared to the afforestation simulation.

While $T_{\text{sfc}}$ warms in response to LULCC in both winter and spring, 2 m surface air temperature cools in winter (in less than 20% of the grid boxes) and warms in spring. This happens because the surface is colder than the atmosphere in winter which leads to turbulent heat exchange from the atmosphere to the surface i.e., sensible heat flux. This turbulent exchange of heat is enhanced by the surface roughness of forests which means more heat is transferred from the atmosphere to the surface over the afforested grid boxes. This leads to greater cooling of surface air temperatures over the afforested regions. Thus, surface air temperatures cool slightly in response to LULCC in winter. The opposite occurs in spring when surface temperatures are warmer than air temperatures, and heat flows from the surface to the atmosphere. Again, increased surface roughness over afforested regions enhances the sensible heat fluxes which causes air temperatures to warm in response to LULCC.

Figure 6. Mean difference in daily maximum 2-m air temperature between the Afforestation simulation and the Control-PGW simulation (dark green) and between the natural succession and Control-PGW simulations (light green) (b) Percentage of LULCC grid boxes with a statistically significant change in daily maximum 2-m air temperature to total number of LULCC grid boxes as a percent. (c and d) Same as (a and b) except for daily minimum 2-m air temperature. PGW, pseudo-global-warming.
As shown above, the surface air temperature at 2 m changes considerably in winter and spring in response to LULCC. These changes then imprint upon various climate impacts indices that have implications for nature and society. In particular, LULCC at these latitudes affects indices that are concerned with cold temperatures such as frost days, ice days and heating degree days as well as the number of snow days. The frost days index is defined as the number of days when daily minimum air temperature is less than 0°C while the ice days index is the number of days when daily maximum air temperature is less than 0°C. Heating degree days index, which is a measure of demand for heating by buildings, is defined as the sum of 17°C less daily mean temperature ($T_{\text{mean}}$) where only days when $T_{\text{mean}} > 17°C$ are considered. Changes in these indices can have implications for a number of sectors such as infrastructure, ecosystem services, hydropower production and winter tourism to name a few.

Figure 7 shows the responses in our experiments of three temperature defined indices. The analysis focuses solely on grid boxes that undergo LULCC. The global warming responses (red boxplots) are generally consistent with ensemble-based studies focused on roughly the same level of global warming but employing coarser resolution Euro-CORDEX simulations (e.g., Preuschmann et al., 2017). It should first be noted that all three indices exhibit strong decreases under a warming climate. For example, heating degree days index (Figure 7c) declines by 150 to 200-degree days per year in winter, summer and autumn irrespective of experiment design. Likewise, frost days and ice days also show robust declines throughout most of the year.

3.4. Climate Impacts Indices

Figure 7. (a) Change in number of ice days per season for all LULCC grid boxes resulting from global warming under mid-century RCP8.5 scenario (red boxplots; Control-PGW—Control-Hist). The dark/light green box plots denote the change in the number of ice days resulting from global warming under mid-century RCP8.5 scenario and the conversion of existing grasslands and shrublands to evergreen forests (afforestation—Control-Hist)/mixed forest (natural succession—Control-Hist). (b) same as (a) except for frost days. (c) same as (a) except for heating degree days. PGW, pseudo-global-warming.
Earth's Future

summer excluded. In spring, the conversion of open spaces to forestry reduces the ice days and heating degree days even more than the effects of global warming. This result is even more evident in analysis of grid boxes that experience a statistically significant change in 2 m air temperature (analysis not shown here). Other than this, the LULCC experiments do not show any marked differences compared to the control (i.e., these impacts occur regardless of the LULCC). We also note that other indices such as those associated with the warm season (e.g., heatwaves, droughts, tropical nights, etc.) were also explored and these exhibited even smaller differences than those shown in Figure 7.

Unsurprisingly, the number of snow days (number of days per year with snow depth greater than 1 cm) also declines in all three experiments (Figure 8). However, unlike the impacts discussed above, there are now some differences between the experiments. The analysis focuses on the length of the snow season in LULCC grid boxes that are either over or under 800 m above sea level. There are an approximately equal number of LULCC grid boxes above and below 800 m. Both the length and the reduction in the length of the snow season varies with elevation, in agreement with the latest report by the Norwegian Center for Climate Services on the “Climate in Norway 2100” (Hanssen-Bauer et al., 2017). At low elevations (<800 m), the snow season is shortened by ∼40 days in response to the RCP8.5 forcing (control simulations), but by only ∼30 days under RCP8.5 when open spaces naturally succeed to mixed forests (natural succession simulation) and by only ∼20 days when the open spaces are converted to evergreen under the afforestation scenario (afforestation simulation). At higher elevations this pattern is repeated but with a shift towards an overall less pronounced shortening of the snow season which is likely due to slight increases in snowfall at higher elevations (Frei et al., 2018). This behavior results from the effects of forest cover on subcanopy snowpack evolution that leads to snow persisting on the ground longer into the season. Observational studies (e.g., Roth & Nolin, 2017) have shown that higher wind speeds in open sites at high elevations significantly increase turbulent energy exchanges and snow sublimation, thus, reducing the snow cover more in open spaces than in forests. Overall, the proposed forestry scenarios show that changing the land use from grass and shrublands to forests can mitigate somewhat the global warming driven decline in the snow season by approximately 50% in areas above 800 m and by 25%–50% in areas below 800 m depending on forestry type.

4. Discussion and Conclusions

In this study, different land cover strategies were explored in a quasi-idealized modeling framework. We examined the effects of afforestation and natural succession on local to regional climate and whether these tend to exacerbate or mitigate various climate impacts arising from increased greenhouse gas concentrations. The strongest response in the climate system to the LULCC can be found in the surface temperatures. Winter and spring surface temperatures during the day warmed between 1°C and 1.5°C while summer surface temperatures showed a cooling response between 1.5°C and 2°C during the day. In autumn, there was no discernible response to the LULCC during the day. Nighttime surface temperatures also showed a response to the LULCC in all seasons but the response is considerably weaker (between 0.5°C and 1.0°C) with fewer grid boxes exhibiting a temperature change. The surface temperature response in winter and spring is largely driven by albedo changes in both the afforestation and natural succession scenarios. In summer, the surface temperature response is driven by different factors for the different scenarios; nonradiative factors dominate the response in the afforestation simulation while surface albedo changes underlie the temperature response in the natural succession simulation. These changes in the surface temperature manifest in the surface air temperatures at 2 m.

It should be recognized that there are limitations to the approach taken here. For one, single model studies run the risk that the results are model dependent. For example, the WRF model has well known issues in
representing cloud and land-surface processes that can lead to radiation errors and surface temperature biases (Aas et al., 2015; Katragkou et al., 2015; Mooney et al., 2013). Nonetheless, the winter and spring results described for 2 m air temperature and surface fluxes agree qualitatively with the ensemble-based study of Davin et al. (2020). Notably, there are differences between the response simulated by our model and the RCA model which is used in both the single model study of Strandberg and Kjellström (2019) and the multimodel study of Davin et al. (2020). However, the RCA model response to afforestation/deforestation in the multimodel study of Davin et al. (2020) is a clear outlier in the ensemble of nine RCMs. More generally, there are quantitative differences and also qualitative differences in summer between this study and the multimodel study of Davin et al. (2020). However, direct comparisons with Davin et al. (2020) are challenging due to differences in experimental design e.g., the use of different grid scales (50 km vs. our 3 km) and different LULCC scenarios; Davin et al. (2020) performed an idealized study that compares forests and grasslands, while this study uses a quasi-idealized approach that compares forests with existing land cover which is mostly shrublands. Shrublands have a similar albedo to boreal forests in summer but a grass-like albedo in winter when they are covered in snow. The comparison is further complicated by the use of 2 m air temperature in studies by Davin et al. (2020). Recent studies such as the multimodel study of Breil et al. (2020) have demonstrated the fallibility of using 2 m air temperature, a diagnostic variable, to assess LULCC. In particular, they show that different models can provide conflicting results in summer when using 2 m air temperature but that differences can be reconciled when surface temperature is used instead.

Our work extends on previous studies by contributing new information on the localized effects of LULCC on this and other variables, indices and extremes that can only be obtained via very high-resolution modeling. Benefits to such high-resolution models include their ability to separate snow and rain based on microphysical processes instead of the temperature based threshold that is applied in most land surface models at nonconvection permitting simulations such as those in Davin et al. (2020) and Breil et al. (2020). This is important for snow related variables (e.g., snow depth, cover/extent and snow water equivalent) that are critical for representing accumulation and ablation processes at the surface. An additional benefit of these high resolutions was demonstrated by Vanden Broucke and Van Lipzig (2017). Their study showed that although spatial resolution does not substantially impact the temperature response, it does better represent the biogeophysical processes that underly the temperature response i.e., surface energy fluxes. Furthermore, the km-scale simulation permits a more realistic representation of current afforestation policies as they can apply afforestation/deforestation on local scales; this is not possible in coarser models that convert large 50 km by 50 km grid boxes to forests/open spaces which is more representative of large regions/counties/municipalities.

A key finding of societal relevance is that both afforestation and natural succession have a significant warming effect on daily maximum surface air temperatures in the spring. Conversely, significant cooling effects on daily minimum surface air temperature are observed in spring and summer. In the context of global warming, Figure 9 shows that converting open spaces to forest considerably enhances maximum air temperatures in spring but mitigates some of the warming in the minimum air temperatures in both spring and summer. These effects are largely consistent with our understanding but the lack of substantial differences between the two strategies is notable. As such the results suggest that the proposed policy implementation in Norway to convert existing open spaces to forests, either actively through afforestation or passively through natural succession, may exacerbate some effects of global warming while mitigating others. In other words, from a physical climate impacts perspective, there is no reason to choose one over the other. Of course, there might be other reasons for choosing one strategy or the other, it depends on the purpose of the strategy.

With respect to climate impacts that are of particular relevance for Norwegian economic sectors the two strategies have little effect, particularly when considered over larger regions such as all of Norway. The possible exception being frost days in spring, which exhibit larger reductions when forests are introduced. Cold season impacts such as frost days, ice days and heating degree days are significantly reduced in a warming climate irrespective of approach to land cover. One impact where the decision between the scenarios would have an effect is the length of the snow season. Both afforestation and natural succession mitigate the reduction in the snow days with afforestation having a larger effect. This may be beneficial to the hydropower and winter tourism industries.
The primary motivation of this study was to understand the potential climate impacts of current policy application in Norway, namely planting trees to mitigate climate change. Our results show that the impacts of afforestation in Norway using the two different forestry scenarios, afforestation of spruce versus natural succession to mixed forests, leads to significant additional warming in winter and spring but cooling in summer. Our results further suggest that the overall physical effects of afforestation on regional climate neither strongly supports nor undermines the viability of using afforestation as part of climate mitigation options. As this study only assesses physical climate effects of afforestation, other aspects of change arising from these scenarios such as biogeochemical and biogeophysical effects, should also be taken into consideration. Therefore, the conclusions of this study are limited to the local-to-regional climate system and should be considered as just one “piece of the puzzle.”

LULCC brings many other consequences that need to be considered before taking action. Although the climate effects were shown to be similar between the two forestry scenarios, active afforestation will cause disturbance to the surrounding environment and has substantial costs associated with planting compared to passive natural succession. It is important to recognize the importance of assessing and integrating other impacts of afforestation such as biodiversity change, carbon storage above and below ground, local economy, and social well being in addition to the effects on global and local climate before implementing the policy to action.

Data Availability Statement

The ERA-Interim data downscaled by the WRF model was obtained from https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/ and the CMIP5 data used to calculate the future climate perturbation can be obtained from https://esgf-node.llnl.gov/projects/cmip5/. The WRF ARW model code used in this study can be downloaded from the developers’ user website https://www.doi.org/10.5065/D6MK6B4K with additional modifications described in Fita et al. (2019) and the associated code available at https://doi.org/10.5281/zenodo.1469647. The model output was analyzed using climate data operators (http://www.doi.org/10.5281/zenodo.3539275.

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