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Climate Potential for Apple Growing in Norway—Part 2: Assessment of Suitability of Heat Conditions under Future Climate Change

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Abstract: The commercial apple production in Norway is limited to the small regions along the fjords in the southwest part of the country and around lakes or near the sea in the southeast with favorable climate. Due to the rapid rate of climate change over the recent decades, it is expected that suitable heat conditions for apple growing will expand to the areas that were previously too cold. This study analyses the heat suitability of future climate (2021–2100) under the RCP8.5 scenario for 6 common apple varieties in Norway: Discovery, Gravenstein, Summerred, Aroma, Rubinstep and Elstar. Previously established heat requirement criteria (based on the temperature threshold for the full blooming and growing degree days sum between the full bloom and harvest) are applied to the temperature outputs of the regional climate models downscaled to 1 km resolution. The assessment indicates that as temperature rises, heat conditions suitable for cultivation of all 6 apple varieties will expand. According to the ensemble median value, areas with the favorable heat conditions for growing at least one of the considered apple varieties will increase 25 times in the period 2021–2040 and 60 times in the period 2041–2060, compared to the referent period 1971–2000. At the same time, areas suitable for all 6 apple varieties will increase 3 times in the first, and 3.8 times in the latter period. The favorable areas will advance from south and southeast northwards and inland in the eastern region, along the west and northwestern coastline towards higher latitudes, and along continental parts of fjords. The fastest expansion of heat suitable conditions is expected for Discovery and Gravenstein. The findings of this study are relevant for zoning apple production future potential and for strategical planning of climate change adaptation measures within the sector. Weather-related risks, such as risks from winter low temperatures, spring frost, drought and extreme precipitation were not considered.

Keywords: climate change; apple varieties; heat requirements; growing degree days; zoning

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1. Introduction

Climate change may have direct and indirect impacts on agriculture, horticulture, livestock, and fisheries, consequently influencing food supply [1,2]. It adversely affects fruit production through the occurrence of spring frosts, cold waves, frequent hailstorms, insufficient chilling hours, inadequate soil moisture, poor pollination, reduced yield and fruit quality, occurrence of new insects, pests and diseases, and altered blooming and harvesting times [1]. Study [3] demonstrated that flowering and maturity are the apple phenophases that are most sensitive to climate change. On the other hand, [4] showed that temperature, precipitation, evaporation, and active accumulated temperature, particularly during spring, have the most significant effect on apple production.

Since temperature is considered the most important atmospheric factor for crop phenological and physiological development, global warming is considered as a major threat [5].

Climate change will likely reduce productivity due to high temperatures during flowering and fruit growth and increase the likelihood of fruit sunburn and cracking [5,6]. In the context of climate change, warming shortens the period from leaf appearance to ripening in apple trees [7]. Global warming will most likely shift the production regions, as confirmed by [8] which showed that the favorable regions for apple growing in Japan will gradually move northwards by 2060.

Apple trees require 1200–1500 h of chilling below 7.2 °C depending on the variety. A slight temperature increase can reduce chilling hours, which may delay flowering or alter flower bud differentiation [9]. In some regions, earlier blooming and higher temperatures during maturation can also induce taste and texture changes in certain apple cultivars, leading to lower acid concentration and fruit firmness [10]. In study [11] it was observed that even a slight increase in day and night temperatures may reduce the amount of soluble sugars, amino acids, proteins, and starch in apple.

The occurrence of low temperatures is also a limiting factor that influences both the yield and distribution of deciduous fruit trees [12]. Untimely frosts in fall and spring can cause freezing injuries that seriously constrain fruit production. Temperature fluctuations in the middle of winter are correlated with winterkill or low yields in apple trees [13]. These injuries are highly harmful due to the extended period required to replace adult trees and to the fact that low temperatures can damage reproductive organs, causing significant crop losses [14]. In the light of this, weather conditions impact both the quantity and quality of crops yields, thus being a major driver of farm income volatility [15].

In colder climates, the persistent temperature increase could create opportunities for cultivating new species or varieties in regions where it was previously impossible due to the limiting climatic factors [16]. Although Norway has a long tradition of apple growing, its commercial production is limited by insufficient heat during the vegetation period spanning from May to September [17]. The apple production in Norway is located in the south part of the country having the most favorable climate. The main orchards are along the fjords in the southwest and around lakes or near the sea in the southeast part of the country. Mean annual temperature in these locations vary between 6 and 8 °C.

The fjord areas of the western Norway have a maritime climate, with comparatively cool summers and mild winters. Western winds that are usually coming from the Atlantic Ocean are bringing clouds and rain throughout the year. Majority of the precipitation falls during the winter, mostly as rain. The vegetation grow period, from May to September, can be relatively dry and all orchards have trickle irrigation for supplying the trees with enough water during summer. If located near the water that does not freeze over, the orchards rarely suffer from winter and blossom frost. Another challenge are relatively low temperatures during summer that limit cultivating varieties with higher heat requirements and longer vegetation season in order to produce high yields of good fruit quality. The production is mainly located in the municipalities (from southwest towards northwest) Hjelmeland, Ullensvang, Sogndal, Gloppen and Stryn.

In the southeast Norway, areas where apple production is conducted have a more continental climate with colder winters and warmer summers. If there is no snow cover over winter, severe frost can occur and damage or kill the trees or the rootstocks. From time-to-time spring frost during blossom time can happen, especially during springs with early flowering. At the southeast side, the main production is located in the municipalities Midt-Telemark, Øvre Eiker, Lier and Drammen.

The total apple production for fresh consumption and processing in 2021 was 18,700 t over 1573 ha. The acreage is increasing and is 15% up since 2018 [18]. Apple varieties that can be managed properly and give good quality fruits are those that are of early season in countries southern from Norway. The main commercial cultivars are Discovery, Gravenstein, Summerred, Aroma, Rubinstep and Elstar.

Climate change has already influenced the apple phenology in Norway. In the study [19] it was found that the blooming dates of Gravenstein apples in the Oslofjord region and a fjord in the western region advanced at a rate ranging between 1.3 and 1.9 days per decade over the period 1971–2005. Similar results were obtained by [20], which showed an advancement in full bloom of 16 days for Gravenstein apples cultivated in the Oslofjord region during the period 1966–2016. In addition, they have noted the shift of 9 days in average for 12 apple varieties at the same locations over the period 1986–2016. Both studies established a strong correlation between shifted blooming dates and heat conditions during April and May.

Recent spatial analysis of the heat conditions across the southern region of Norway [21] showed that surfaces with favorable climate conditions for apple growing had increased approximately 2.5 times in the period 2011–2020 compared to the period 1971–2000. The finding also reviled that 15% of the studied area in the period 2011–2020 was suitable for cultivating at least one, while 2.6% had potential to grow all 6 considered apple varieties. Obtained spread of areas with heat favorable conditions for apple growing is a direct consequence of the observed increase in mean temperature of about 1 °C over the period 1900 to 2014, with the largest trends in spring and autumn [16].

The rate of future climate change depends, among other, on the level of greenhouse gasses emissions in the forthcoming decades. If concentrations continue to increase, as the RCP8.5 scenario foresees [22], regional climate models predict that mean annual temperature across Norway may increase by 3.3 to 6.4 °C by the end of the century, compared to the referent period 1971–2000 [16]. This could lead to a longer and warmer vegetation season and expanded areas suitable for agricultural production, providing opportunities for diversification, advancement and growth of Norway's agricultural production [23]. It would contribute to the food security, particularly in situation when global food production may face reduced yields and increased demands [24].

The aim of this study was to evaluate the future heat conditions for apple growing in Norway. Analysis provides the high-resolution zoning of areas with heat conditions suitable for cultivating 6 commonly grown apple varieties in near future, mid-century and the end of the century, under the assumption of continuous increase in emission of greenhouse gasses following one of the Representative Concentration Pathway scenarios from the Intergovernmental Panel on Climate Change (IPCC), the RCP8.5 scenario.

2. Materials and Methods

Domain of the study covers southern part of Norway, from 4.5 to 14.36° E and 57.76 to 65.48° N. It is presented in Figure 1 alongside with approximate locations of areas where apples are currently cultivated.

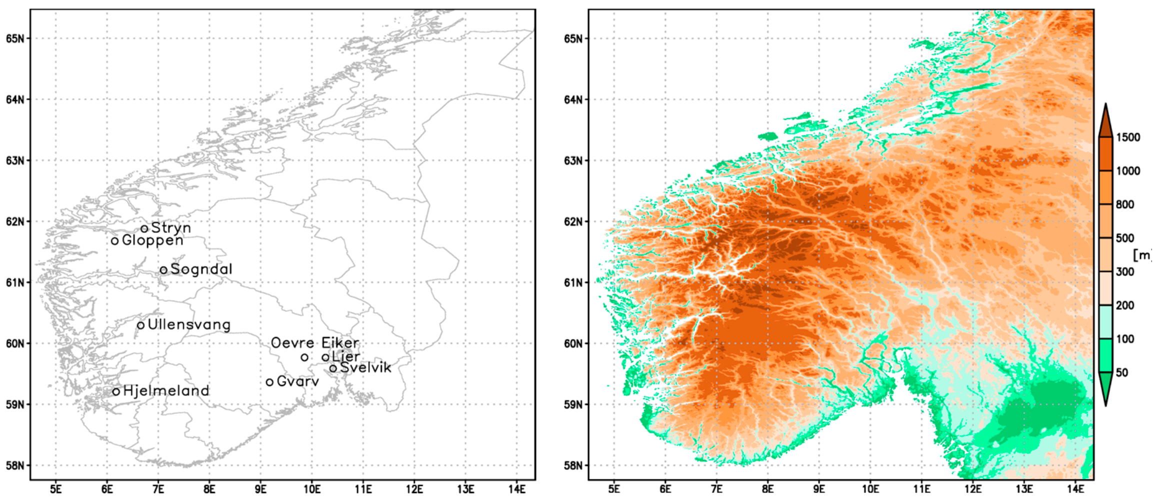

Figure 1. The domain of the study. (**Left panel**): Norway administrative counties. Dots mark locations of areas where commercial apple orchards are currently situated. (**Right panel**): Topography of the domain.

The assessment of heat potential for apple growing is done for 6 varieties of apple that are currently cultivated in Norway, namely: Discovery, Gravenstein, Summerred, Aroma, Rubinstep and Elstar. Criteria for heat requirements for each variety is adopted from [21]. It consists of the base temperature (Tb) required for full blooming and the sum of growing degree days (GDD, mean daily temperatures above Tb) between the full blooming and harvest. The criteria are given for each variety in the Table 1. The order of the varieties in the Table 1, as well as in other tables and figures, aligns with their sequential ripening times.

Table 1. Base temperature (Tb) required for full blooming and minimum sum of growing degree days between full blooming and harvest (GDD) for 6 apple varieties [21].

Variety	Tb (°C)	GDD (°C)
Discovery	11.1	1177
Gravenstein	10.1	1467
Summerred	10.4	1547
Aroma	11.8	1372
Rubinstep	11.1	1597
Elstar	12.0	1361

Climate change simulations daily data are taken from a regional climate model ensemble that was developed by the Norwegian Center for Climate Services. It consists of 10 combinations of global and regional climate models selected from the EURO-CORDEX database [25], whose results are spatially interpolated on a high-resolution grid of 1 × 1 km (0.0219° longitude and 0.0088° latitude) [26]. This dataset enables the assessment of climate change impacts across the complex orography and coastline of Norway. The list of regional climate models and their global drivers is given in Table 2. The dataset is available for download at https://klimaservicesenter.no, accessed on 25 October 2022. The simulations used in this study are based on the IPCC RCP8.5 scenario, which foresees a continual increase of greenhouse gasses concentrations by the end of the century. This scenario was selected over the RCP4.5 that was also available in the database, following the decision of Norwegian government to adopt the RCP8.5 scenario in risk assessment and adaptation planning [24]. It is important to notice that, although widely used in the future climate change impact studies and policies evaluations [27], the RCP8.5 scenario assumes very high fossil fuel emissions, which are evaluated as less likely in [28].

Table 2. List of regional and their driving global climate models that are members of the ensemble [26].

Global Climate Model	Regional Climate Model
CNRM-CM [1]	CCLM [6]
CNRM-CM	RCA [7]
EC-EARTH [2]	CCLM
EC-EARTH	HIRHAM [8]
EC-EARTH	RACMO [9]
EC-EARTH	RCA
HADGEM [3]	RCA
IPSL-CM [4]	RCA
MPI-ESM [5]	CCLM
MPI-ESM	RCA

[1] CNRM-CM—Centre de National de Researches Meteorologiques Climate Model, [2] EC-EARTH—European Community Earth System Model, [3] HADGEM—Hadley Centre Global Environmental Model, [4] IPSL-CM—Institute Pierre-Simon Laplace Coupled Model, [5] MPI-ESM—Max Planck Institute Earth System Model, [6] CCLM—Cosmo Climate Limited-area Model, [7] RCA—Rossby Centre regional Atmospheric model, [8] HIRHAM—High Resolution Limited Area Model (HIRLAM)—European Center Hamburg General Circulation Model (ECHAM), [9] RACMO—Regional Atmospheric Climate Model.

Daily fields of minimum and maximum temperature (*Tn* and *Tx*, respectively) from the dataset are used to calculate fields of mean daily temperature (*Tm*) as follows:

$$Tm = 0.5 \cdot (Tn + Tx) \quad (1)$$

Date of full bloom for each year and each model was estimated following the methodology in [21] and the World Meteorological Organization's definition for the beginning of the growing season [29], as the first appearance (from the beginning of the year) of the 6th consecutive day with the mean temperature above the base temperature.

Growing degree days (*GDD*) are calculated as a sum of mean daily temperatures above the base temperature starting from the estimated full bloom date (*Nstart*) and ending upon fulfilling the criteria given in the Table 1 or after 6 consecutive days with mean temperature bellow the base temperature in the second half of the year (*Nend*).

$$GDD = \sum_{Nstart}^{Nend} Tm_n, Tm > Tb \quad (2)$$

Heat conditions for each variety are found to be suitable if the respective *GDD* is reached in more than 70% of the years within an analyzed period.

Results are analyzed in three 20 years long periods in future: near future (2021–2040), middle of the century (2041–2060) and end of the century (2081–2100); and compared to the referent period (1971–2000). All calculations are done for each model and presented as the median of the ensemble. In order to address the uncertainty of the estimates, the 25th and 75th percentile of the ensemble are also calculated, where it was suitable.

3. Results

3.1. Mean Changes of Heat Conditions during Vegetation

Median anomalies of the mean temperature during vegetation (ΔTveg) and accumulated growing degree days above the 10 °C threshold (ΔGDD) are compared across the future periods in order to quantify the change in heat conditions during the vegetation projected under the RCP8.5 scenario (Figure 2). The mean temperature and accumulated growing degree days are calculated for fixed period from May 1st to September 30th and do not consider increasing length of the vegetation period. This comparison should provide the overall outlook of the heat conditions over the 5 months period.

According to the ensemble median, under the RCP8.5 scenario, the mean temperature for the period May-September in the period 2021–2040 is expected to increase mostly from 1 to 1.5 °C across the domain in comparison to the referent period. The anomaly between 0.5 and 1 °C is projected in high mountains in the western inland region, while the largest change (between 1.5 and 2 °C) is anticipated locally along the coastline and in the north and northwest of the domain. In the same period, accumulated growing degree days are expected to increase between 100 and 200 °C across most of the domain, while in the north, along the northern and northwestern coast, and in the western hinterland, the increase is up to 300 °C.

In the mid-century (2041–2060) mean temperature anomaly for the period May-September is expected to range between 1.5 and 2 °C in respect to the referent period, across the largest part of the domain. The smallest change (between 1 and 1.5 °C) is anticipated along the coast and at the high mountains in the west, while the largest change, above 2 °C, is projected locally in the north, northwest hinterland and southeast inland. Accumulated growing degree days are expected to increase between 200 to 300 °C across most of the domain. The projected increase is the smallest (less than 200 °C) in the western and south coastline.

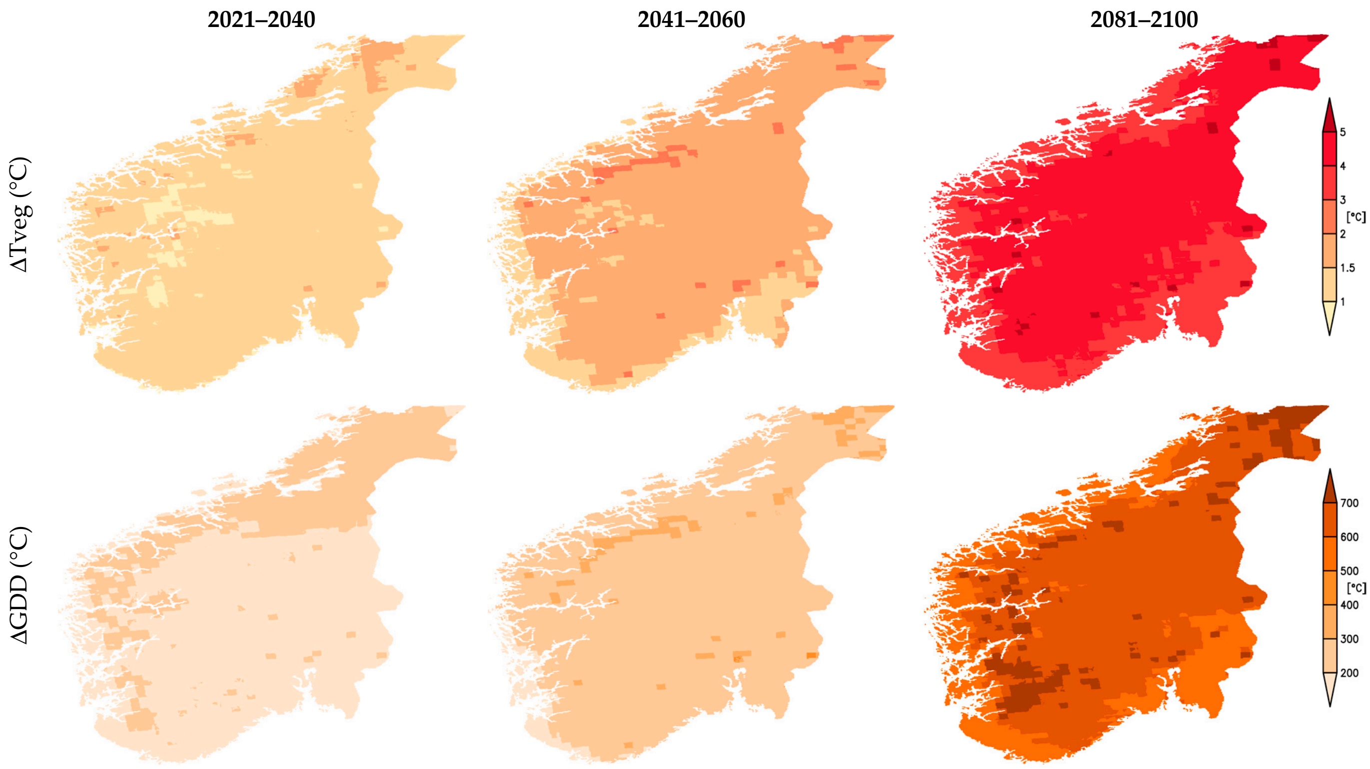

Figure 2. Median anomaly of the mean temperature (**upper row**) and accumulated growing degree days (**lower row**) from May 1st to September 30th for future periods in comparison to the referent period 1971–2000, under the RCP8.5 scenario.

Projected changes are the greatest for the end of the century (2081–2100) when the anomalies of the mean May-September temperature are expected to be between 3 and 4 °C along the coastline, and between 4 and 5 °C elsewhere. In the same period the projected increase of growing degree days is between 600 and 700 °C. The smallest increase, between 500 and 600 °C, is anticipated along the coast, while anomalies above 700 °C are expected locally inland and in north of the domain.

Uncertainty of these results, as expected, increase with time. Spatially, it is prevalent in continental parts of large fjords in hinterland of the western and northwestern regions, as well as in the north of the domain (Figure A1).

3.2. Future Climate Suitability

Areas in which established heat criteria for cultivating at least one of considered apple varieties (blue) or all 6 of them (red) is fulfilled in at least 70% of years (i.e., 14 years out of 20), in at least 5 models (i.e., the half from all models in the ensemble), are marked in Figure 3 for the referent and three future periods.

Within the referent period, according to the ensemble median, favorable heat conditions for cultivating all 6 considered apple varieties were not found within the domain. However, southern and southeastern coastline were suitable for cultivating at least one of the varieties, as well as some locations along the fjords of the western coast. The same regions that were found to suite at least one variety in the referent period, are estimated favorable for cultivating all 6 of them in the period 2021–2040. Areas in which at least one variety could be grown are found to expand inland (northward) in the south and southeast, as well as along the western coastline and its fjords, and locally in fjords of the northern and northwestern coast.

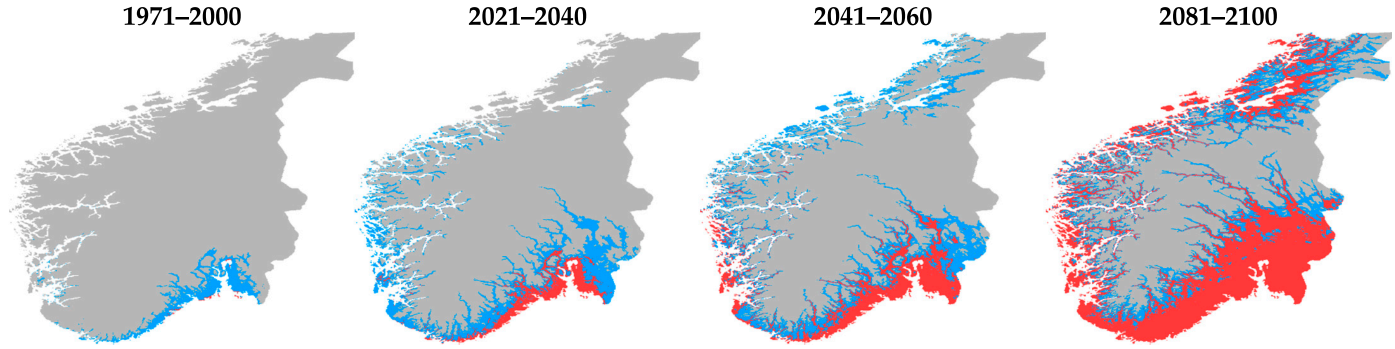

Figure 3. Areas with heat suitability criteria under the RCP8.5 scenario fulfilled for at least one considered apple variety in at least 70% of years within the period, in at least 5 models of the ensemble, are designated in blue, while areas where the criteria are met for all 6 varieties are noted in red.

In the period 2041–2060 areas in the south and southeast suitable for growing all 6 considered apple varieties will further expand inland, along the western coast, and locally in fjords in the west and northwest. At the same time, areas suitable for at least one variety will spread along the western and northern coastline, inland in the south and southeast, but also will appear northern of 63.5° N, especially along the fjord and coastline.

By the end of the century (2081–2100) areas suitable for cultivating all 6 considered apple varieties will cover a wide area in the south, southeast and east, as well as most of the western, northwestern and northern coastline and fjords. Some areas northern of 63° N are expected to become suitable for growing at least one of the considered apple varieties.

For each of the considered varieties, areas with suitable heat conditions in referent and future periods according to the ensemble median are designated in red in Figure 4. Surfaces of suitable areas according to the ensemble median, as well as 25th and 75th percentile of the ensemble for each variety are given in Table 3.

In the referent period favorable heat conditions suitable for cultivating Discovery were found at the largest total surface of 12,497 km^2, followed by Gravenstein (7924 km^2). The smallest total surface was suitable for Rubinstep (340 km^2). Heat conditions were met for all 6 varieties in the wider or narrower belt along the southern and southeastern coast, while Discovery and Gravenstein could also be grown in some locations in the western coast.

In the period 2021–2040 the potentially heat suitable areas for cultivating Aroma, Elstar and Rubinstep are located along the southern and southeastern coast, around lakes in the inland part of the southeast region, and locally in the western coast and its fjords. In addition, Summerred could cover larger areas in the western coast and its fjords, while Gravenstein could be spread also along the fjords of the northwestern and north coast (to total surfaces of 31,252 km^2). Discovery has the largest prospective according to heat conditions (at total surfaces of 38,956 km^2), potentially expanding even along the fjords northern of 63.5° N.

In the period 2041–2060 heat favorable conditions for growing Aroma, Elstar and Rubinstep varieties will expand northward inland in the south and southeast, as well along the western coast and fjords on the west and northwest. Areas suitable for cultivating Gravenstein and Discovery will expand northern of 63.5° N, potentially covering 49,036 and 59,150 km^2 respectively.

By the end of the century (2081–2100), under the scenario RCP8.5, Aroma, Elstar, Rubinstep and Summerred will potentially expand northern of 63° N, while Gravenstein and Discovery could cover 104,697 and 147,446 km^2 respectively.

Figure 4. Areas with heat suitability criteria under the RCP8.5 scenario fulfilled for different apple varieties in at least 70% of years within the period, in at least 5 models of the ensemble, are designated in red.

Table 3. Surface (km^2) of areas within the domain where the heat conditions are suitable for cultivating considered apple varieties. Estimates are done for the 25th, median and 75th percentile values of the ensemble of climate models for different time periods.

Period/Variety		Discovery	Gravenstein	Summerred	Aroma	Rubinstep	Elstar
1971–2000	25th perc.	10,831	6835	2787	908	201	590
	Median	12,497	7924	3417	1222	340	823
	75th perc.	15,400	9444	4154	1843	532	1308
2021–2040	25th perc.	32,735	26,732	16,448	9416	6029	7818
	Median	38,956	31,252	20,695	13,102	8607	10,964
	75th perc.	49,699	40,768	29,404	21,342	15,625	18,508
2041–2060	25th perc.	47,681	40,368	29,543	20,434	15,868	17,722
	Median	59,150	49,036	35,713	27,119	21,122	24,779
	75th perc.	71,453	61,929	48,411	37,826	31,733	35,280
2081–2100	25th perc.	94,903	85,679	72,473	62,048	54,716	58,402
	Median	115,358	104,697	90,524	78,514	72,518	75,360
	75th perc.	147,446	136,320	121,228	109,276	101,366	105,261

4. Discussion

Despite numerous challenges that climate change brings to the fruit production all over the world, regions with cold climate may experience benefits by expanding fruit cultivation areas, broadening the varieties choices, and intensifying production. Similar studies on increased potentials of fruit production have been conducted in other cold regions such as Canada [30], the USA [31], and Finland [32].

Projected warming from May to September and consequent increase in accumulated growing degree days will result in a longer vegetation period and more available heat. In future periods, the slowest changes in these parameters are found along the Norwegian coast, while continental areas, including interior parts of large fjords, will experience faster changes.

In the referent period (1971–2000), the ensemble median was able to accurately identify 7 out of 9 areas where apple production is currently located. The only exceptions were the two northernmost locations, Stryn and Gloppen. This demonstrates the ensemble median's ability to effectively reproduce heat conditions of the past.

The results of this study indicate a continual increase in the areas suitable for cultivating all 6 considered apple varieties in the domain. The spread is expected to occur in three general directions: (1) northwards (inland) in the south and southeast, (2) along the western and northwestern coastline towards higher latitudes, and (3) along continental areas of fjords.

The apple varieties, Discovery and Gravenstein, will experience the fastest expansion in areas with favorable heat conditions. Within the next two decades, it will be possible to cultivate these two varieties in locations north of 63° N. Following them, Summerred is the third variety according to the rate of the spread of the favorable heat conditions. Aroma and Elstar heat suitable climate will reach 62–63° N by the mid-century, while Rubinstep will spread north of 63° N at the end of the century.

Comparable results were found for Finland in the study [32]. The study revealed that there is potential for an expansion of commercial apple growing areas in the southeastern part of Finland by the mid-century, as well as widening selection of apple varieties in latitudes up to 65° N. Within the analyzed period 2011–2040, very early maturing apple varieties were projected to be able to ripen at latitudes up to 66° N, while late-maturing varieties may ripen up to 62–64° N. The study also indicated that Aroma, as a late-maturing variety, may be suitable for cultivation at latitudes up to 62° N by the middle of the century in Finland. These findings are similar to the current study's results that heat suitable areas for cultivating Aroma in Norway will be possible al latitudes up to 62–63° N by the mid-century.

Uncertainties in this study arise from the selection of the greenhouse gasses concentration scenario, climate models and heat requirements criteria. To account for uncertainties related to future greenhouse gasses concentrations, multiple scenarios should be used. The choice of the scenario in this study was based on the adoption of the RCP8.5 scenario for adaptation planning in Norway [24]. This scenario was criticized for assuming implausible fossil fuel emissions [33] and was evaluated as less likely [28]. However, ranges of projected temperature changes across an ensemble of climate models often overlaps across different scenarios. For the ensemble used in this assessment, projected temperature change ranges for Norway under the RCP8.5 partially overlaps with those under the RCP4.5 by 2080. Median ensemble value under the RCP4.5 falls into the lower half of the ensemble range under the RCP8.5 up to 2050, while after 2080 these two ranges diverge [16]. Projected temperature changes under both scenarios have the same character but develop with different rate. Therefore, expected temperature changes at the end of the century under the RCP4.5 are comparable to the changes in the mid-century projected under the RCP8.5 [16], while differences at the end of the century are substantial.

Uncertainty related to model selection mainly originate from the parameterizations of complex or small-scale process within the models. To assess it, an ensemble of multiple models can be used, and the range of its results should be analyzed alongside the median values. The ensemble used in this study consists of 10 combinations of 5 different global and 4 regional climate models.

Finally, the uncertainties originating from the choice of heat requirements criteria in this study were minimalized by employing criteria established based on time series of phenological and meteorological observations in Norwegian climate, specifically at Ullensvang [21]. The fact that the ensemble median value was capable to identify locations with heat favorable conditions within the referent period indicates that the last two sources of uncertainty are adequately mitigated.

This study is limited to the analysis of heat conditions previously found to be necessary for cultivating common apple varieties. It does not involve the analysis of soil types, land cover, or the weather-related risks, which are critical information for planning of apple production at the local level. However, some conclusions about future impacts of weather-related risks can be drawn from the available literature. Although in many fruit production regions insufficient accumulation of chilling units during dormancy is a significant concern [5,34] among others, in Norway, even with the projected temperature increase, this is not expected to be a problem [24,35]. The risk of low temperatures during dormancy will decrease which could enable the cultivation of new varieties [24]. However, the risk of spring frost requires further analysis due to the shift of blooming, the most vulnerable development phase, towards earlier dates [36]. The maximum daily temperatures during vegetation are not expected to increase enough to pose a considerable risk to the production [16].

The primary future concern for apple production in Norway is likely to be an increase in precipitation, which may enhance occurrence of insects and diseases [23], inhibit pollination [37] and affect activities in orchards. According to the projections, annual precipitation in the regions relevant for future apple production is expected to increase by 8% (under the RCP4.5) to 17% (under the RCP8.5) by the end of the century, while the number of days with heavy precipitation is estimated to double [16]. This may result in a larger share of intensive events and less of moderate and weak precipitation in the total accumulated water. Long term observations indicate increasing trends in seasonal precipitation across these regions, ranging from 1.2 to 2.5% per decade during winter, from 0.1 to 2.7% per decade during spring, from 0.4 to 1.6% per decade during summer, and from 1 to 3% per decade during autumn [16]. This requires further analysis of future precipitation change within sensitive periods such as blooming and pre-harvest. Nevertheless, it is important to consider the high uncertainty of models' precipitation projections, as well as large spatial heterogeneity of precipitation over the complex terrain such is Norway.

5. Conclusions

This study investigates the potential impact of climate change, under the RCP8.5 scenario, on heat conditions favorable for apple cultivation in Norway. The assessment found that rising temperatures will result in an expansion of suitable heat conditions for the 6 commonly grown apple varieties. Over the next 20 years, heat conditions along the western and northwestern coast and fjords will become suitable for cultivating at least one of the apple varieties, while areas around and further north of the Oslofjord and along the south and southeastern coast will be favorable for all 6 varieties.

By the middle of the century, heat conditions will be adequate for cultivating all 6 apple varieties in the south and southeast coast, expanding inland in the southeastern part of the country, as well as along the western coastline and locally along continental areas of fjords in the western and northwestern region.

By the end of the of the century, all 6 varieties could potentially be grown in the large area of the eastern and southeastern region, along the western and northwestern coastline and fjords, as well as north of 63.5° N. The Discovery and Gravenstein varieties, which require less heat, are expected to have the fastest and largest expansion.

This assessment, due to its high spatial resolution, may be useful for strategic planning and developing climate change adaptation measures in apple production. The findings can help in identifying suitable locations for new experimental and commercial orchards, developing policies to support apple production in specific areas, maximizing the potential benefits of the changing climate, and promoting sustainability through efficient use of natural resources and reduced environmental impacts. Due to the choice of the scenario which creates large uncertainties towards the end of the century, for long-term planning it is recommended to update this assessment using new relevant scenarios.

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Appendix A

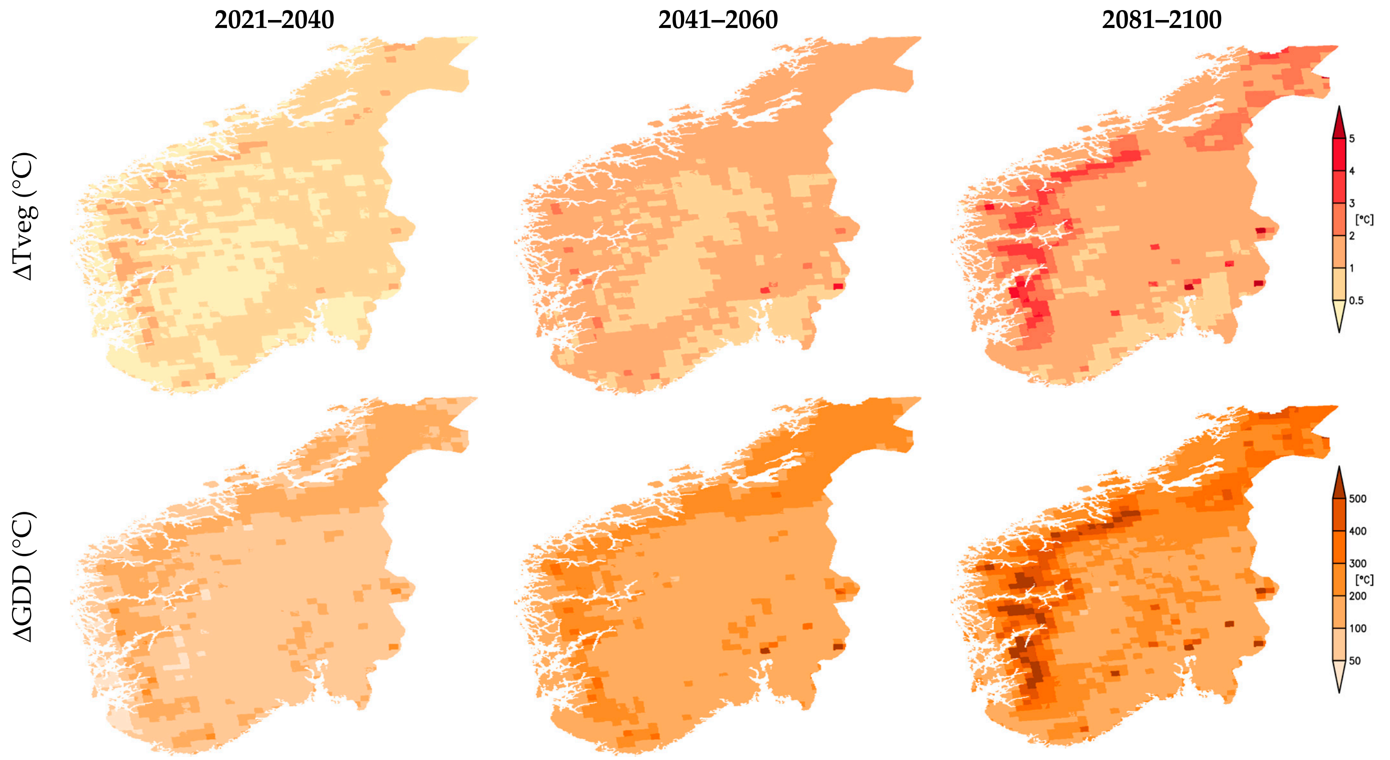

Figure A1. Differences in 75th and 25th percentile of anomaly of the mean temperature (upper row) and accumulated growing degree days (lower row) from May 1st to September 30th for future periods in comparison to the referent period 1971–2000, under the RCP8.5 scenario.

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