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Bachelor thesis

Financially Optimized Afforestation of Abandoned Agricultural Land in Trøndelag, Norway:
An Application of the Modern Portfolio Theory

Bachelor of Science in Forestry / Bachelor i skogbruk

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Contents

1. Introduction

Agricultural land abandonment is a global process observed on a specially large scale in regions with economies in transition, such as Eastern Europe, where a significant number of studies have been undertaken to estimate the extent of land use and land cover change and identify correlations with socioeconomic factors (Alcantara, Kuemmerle, Prishchepov, & Radeloff, 2012; Prishchepov, Radeloff, Dubinin, & Alcantara, 2012).

The farmland abandonment problem is much less acute in the Nordic countries, however similar processes are observed, though to a smaller extent and at a finer spatial scale. in Norway, land abandonment is reported to be primarily associated with changes in smallholder land use practices and abandonment of outfield pastures (Øyen & Kystskogbruket, 2008). Abandoned land is slowly colonized by woody vegetation and converted into unproductive scrubland. Replanting with trees requires in this case additional investment in the clearing of existing vegetation to suppress competition. For this reason, it might be desirable to as early as possible identify areas prone to regrowth and establish managed forest stands for timber production and carbon sequestration and storage (Haugland, 2013). Very few studies attempting to identify abandoned farmland are available in Norway: for instance, Bryn, Dourojeanni, Hemsing, & Donnell (2012) developed a nationwide map of area prone to forest regrowth based on a modeling approach i a geographical information system (GIS).

In a large-scale afforestation project, the central question is the choice of tree species compositions of the forest stands being established. Multiple factors need to be considered — both silvicultural (growing site suitability, viable combinations of tree species, treatment programs, risk of natural hazards) and economic (cash flow balance and liquidity, net present value of the project, soil expectation value, optimal rotation age from the economic perspective, discounting rate, timber price risks).

In the context of a planting project, tree species can be treated as components of an investment portfolio of assets. In the finance industry, one of the approaches to optimizing investment portfolios is the modern portfolio theory, originally proposed by Markowitz (1952). In the Markowitz portfolio theory, a combination of multiple assets in a portfolio is optimized by finding the so-called efficient frontier — a curve plotted as pairs of best possible return values for given levels of risk. The efficient frontier is thus formed by asset combinations that cannot be further improved by reducing risk or increasing return. The best of the portfolios forming the frontier is then defined as the one at the highest slope of the curve, where the additional return achieved by increasing the risk is the largest.

The modern portfolio theory has been applied in forest management in a few studies. For instance, Neuner, Beinhofer, & Knoke (2012) this approach was used to suggest the optimal tree species composition for a corporate forest owner in Germany.

This study applies a simplified approach based on Neuner, Beinhofer, & Knoke (2012) and is an attempt to find the optimal tree species composition for afforestation of forest expansion areas within patches of potentially abandoned agricultural land in the Norwegian county of Trøndelag.

2. Materials and Methods

2.1. Data

The Norwegian county of Trøndelag was selected as the study area for two reasons. Firstly, Trøndelag was the first region, for which high-resolution forest resource maps — the SR16 Skogressurskart — were made available by the Norwegian Institute of Bioeconomy Research (NIBIO). SR16 has a spatial resolution of 16x16 m, is based on the existing nationwide AR5 maps and National Forest Inventory (Landsskogtakseringen) data updated with 3D remotely sensed data, including LiDAR, and is offered in vector and raster versions (NIBIO, 2017). SR16 is currently available for online viewing as a Web Map Service (WMS) only and was therefore mainly used as a visual reference in assessing spatial tree species and site index distributions.

Secondly, Trøndelag is characterized by a combination of coastal and interior areas, making it possible to model forest regrowth in both settings. This is illustrated by the study area map in Figure 1 below.

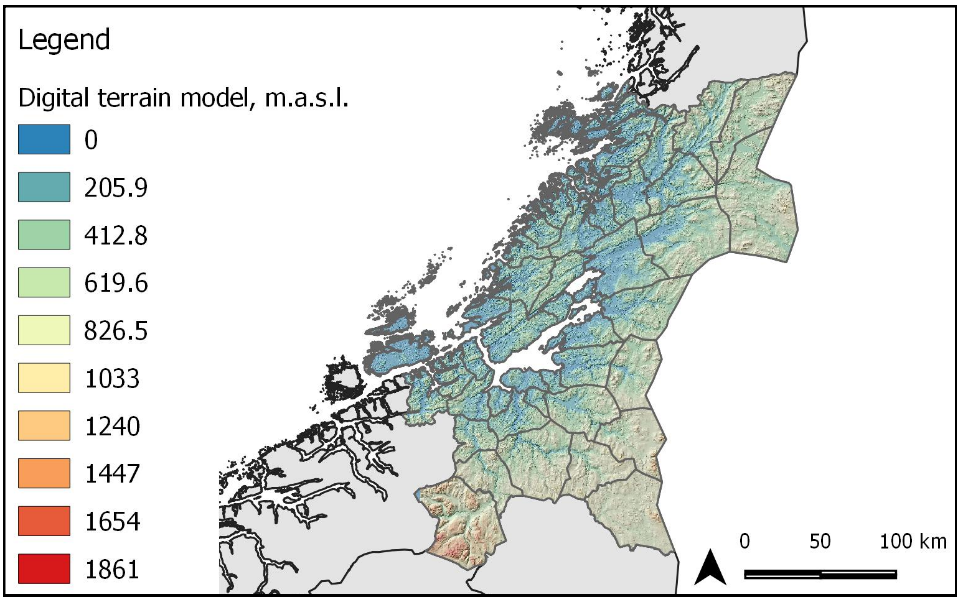

Figure 1. Study area map. Trøndelag, Norway, with a digital terrain model superimposed.

Following datasets were obtained from Geonorge for use in the study (Kartverket, 2018):

- county and municipality shapefiles to compose the base map,
- SR16 tree species and site index (SI species spruce) WMS-maps of the study area for use as a visual reference when processing coarser-resolution forest resource data available for download,
- AR50 (50 m resolution) land use and land cover vector map for identification and analysis of potential forest regrowth areas,
- DTM10 (10 m resolution) raster digital terrain model in tiles covering the study area for analyzing the distribution and stratifying forest regrowth areas by elevation, and for visualization purposes,
- Potential Forest Regrowth (‘Potensiale for gjengroing’) raster dataset representing the results of GIS-based modeling of potential agricultural land abandonment processes in Norway as described in Bryn, Dourojeanni, Hemsing, & Donnell (2012).

Forest regrowth was simulated using the tree growth models implemented in the Heureka forest planning system developed by the Swedish University og Agricultural Sciences (SLU) (Elfving, 2010). Swedish growth models had to be used as Heureka does not explicitly support adjustments via import of custom yields tables or tree species (e.g. Sitka spruce). In calculating the financial performance of the simulated silvicultural treatments, Heureka uses detailed price lists, where the log value is determined by its quality grade — in turn, approximated by whether the log originates from the tree’s butt, middle, or top section — and diameter class and further corrected for bucking length. These so-called ‘price matrixes’ are not published by Norwegian forest owner associations; to circumvent the problem, the current price list available from the Swedish forest owner association Norrskog was adopted and loaded into Heureka (Norrskog, 2018). The price list was chosen considering the proximity of Norrskog’s area of operations to the study area and the fact that the prices are close to their Norwegian counterparts reported by the

Norwegian Agriculture Agency for Trøndelag as of March 2018 (Landbruksdirektoratet, 2018). The Norrskog's price list was supplemented with sawlog prices of Sitka spruce (set equal to Norway spruce sawlogs), larch (set equal to Scots pine sawlogs), and lodgepole pine (*Pinus contorta*, set equal to 80% of Scots pine sawlogs). As indicated in the price list, lodgepole pine pulpwood was priced at 85% of regular softwood pulpwood and aspen pulpwood at 80% of regular hardwood pulpwood. Hardwoods were graded exclusively as pulpwood.

To assess returns and price volatility, historical time series of timber and pulpwood prices in Trøndelag covering the period from 1980 to 2016 were downloaded from Statistics Norway (Statistisk sentralbyrå, 2018) and aggregated. These were the time series 06216 (*Gjennomsnittspris, etter sortiment (kr per m³) (F)*) and 06986 (*Gjennomsnittspris, etter sortiment (kr per m³) (F) (avslutta serie)*), shown in the table below.

	Spruce sawlogs	**Spruce pulpwood**	**Pine sawlogs**	**Pine pulpwood**	**Hardwoods**
2016	506	202	524	181	177
2015	475	204	528	182	169
2014	450	209	238	208	192
2013	422	222	427	218	210
2012	474	258	429	246	210
2011	437	291	410	248	210
2010	442	244	474	220	184
2009	394	253	458	241	206
2008	529	273	559	246	226
2007	499	237	517	202	260
2006	425	224	445	199	218
2005	404	225	410	183	209
2004	405	211	436	181	277
2003	364	209	408	184	263
2002	380	237	422	177	239
2001	514	257	509	178	228
2000	372	243	409	182	224
1999	373	258	477	191	244
1998	400	272	410	174	268
1997	391	252	399	180	237
1996	355	275	395	205	235
1995	347	287	393	221	231

1994	430	275	451	210	235
1993	332	225	372	160	213
1992	327	245	344	198	212
1991	424	296	411	213	224
1990	445	310	440	215	219
1989	372	309	427	231	212
1988	361	297	410	229	203
1987	356	281	436	226	200
1986	323	262	377	223	197
1985	324	231	404	213	171
1984	291	221	359	205	163
1983	293	186	338	174	186
1982	252	177	299	178	165
1981	275	195	307	186	151
1980	268	176	278	155	105
StDev	**70**	**36**	**68**	**24**	**34**

2.2. Methods

All GIS processing of the spatial datasets and imagery was done in QGIS 3.0, with some supplementary data processing in Microsoft Excel 2016. Of the several attributes included in the AR50 map, three were selected for further analysis, namely AREALTYPE, SKOGBONITET, and JORDBRUK. The AREALTYPE attribute describes current land use and land cover types, such as built-up areas, agricultural land, forest, bare land, wetlands and swamps, glaciers, and water bodies. Of these, agricultural land was selected and further classified into croplands and pastures using the JORDBRUK attribute.

The Potential Regrowth raster was converted to polygons and smoothed to avoid the noise generated at the intersections of the coarse-scale raster cells with feature polygons in the AR50 layer. The intersect operator was used to extract potential regrowth areas within the existing extent of agricultural land. Isolated regrowth patches smaller than 1 ha were discarded as too small to be considered for afforestation planning.

DTM10 tiles were merged into a single raster covering the entire study area. The DTM was used to supplement the identified potential regrowth areas with an elevation attribute, approximated as the mean elevation value within the respective polygon. A hillshade raster was also generated to assist in the visual interpretation of the resulting map. To identify areas suitable for planting of Sitka spruce, a 5 km wide buffer was built along the coastline, representing the zone of exposure to salt spray and wind, well tolerated by Sitka spruce, but potentially detrimental to other tree species (Woxholtt, 2007). The resulting elevation histograms served as the basis for stratifying the regrowth areas into elevation and proximity-to-coast classes (Fig. 2).

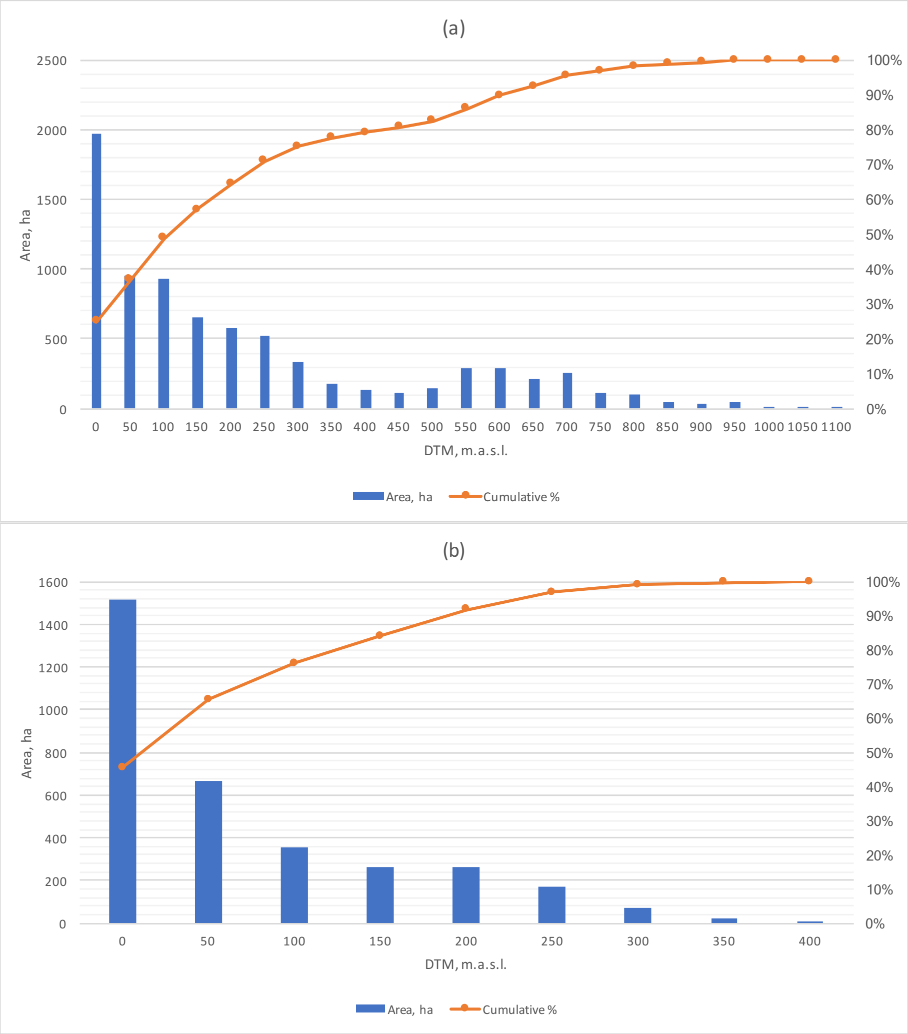

Figure 2. Histograms of potential afforestation distribution by elevation: (a) all areas, (b) areas within 5 km from the coastline.

To classify the above distributions into strata and describe typical growing conditions, a measure of site productivity was needed. Since the identified regrowth areas are currently classified as agricultural land, no site index (SI) information is available neither in the AR50 nor in the SR16 maps. Vegetation type maps available from Geonorge have poor coverage in the study area and could not be used to estimate site productivity, even though Heureka supports SI estimation (on a H100 scale) based on inputs such as elevation, latitude, climate type,

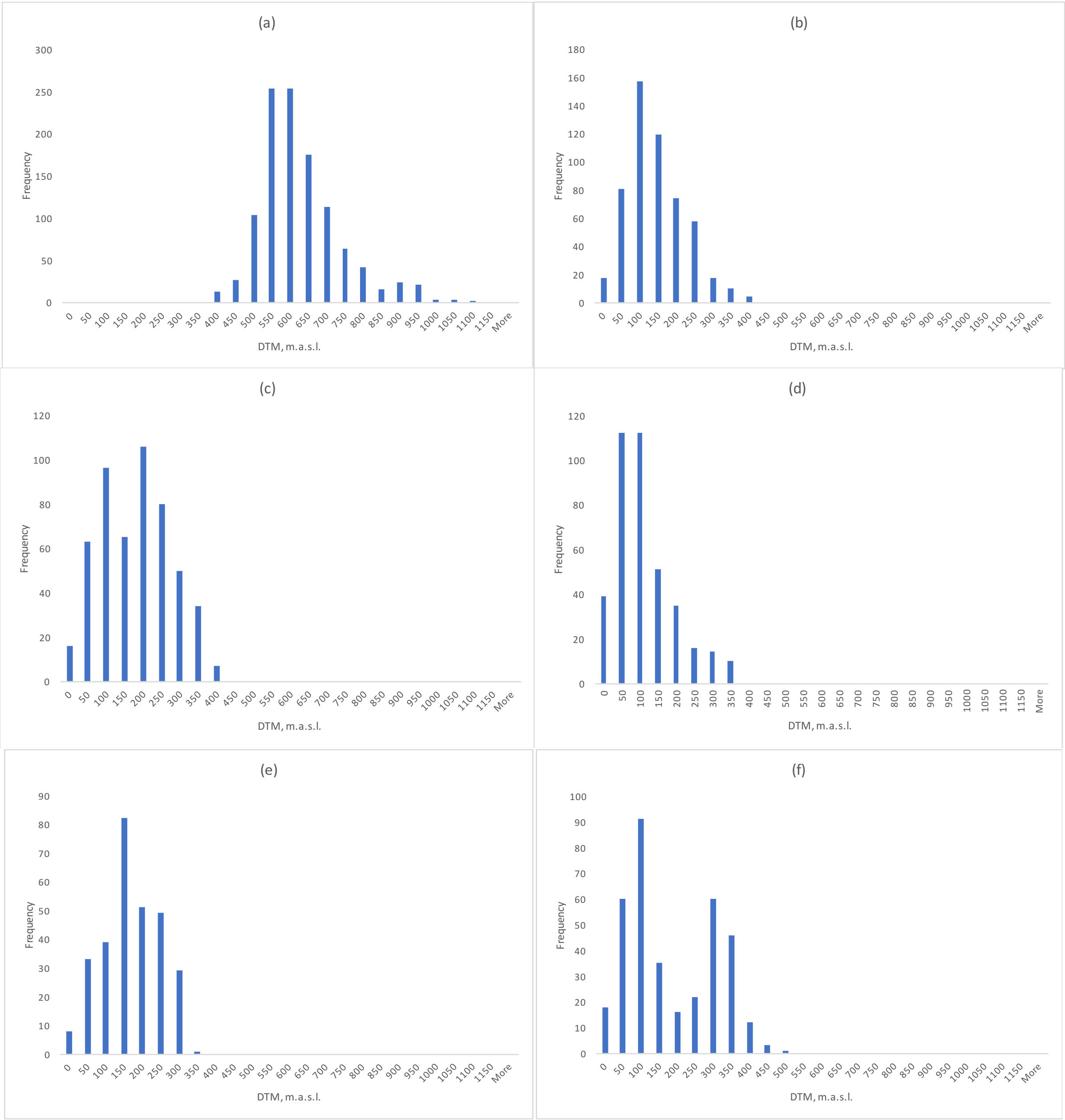

Figure 4. Histograms of forest regrowth areas by elevation and municipality: (a) Oppdal, (b) Orkdal, (c) Indre Fosen, (d) Stjørdal, (e) Skaun, (f) Melhus.

vegetation type, bottom layer, soil moisture, texture, and lateral water — the inputs used to make a growing conditions SI estimate in the Swedish forest site index classification (Hägglund & Lundmark, 1983). As a workaround, the correlation between site productivity (as described by the SKOGBONITET attribute in the AR50 map) and DTM10 elevation was examined by taking multiple point DTM samples within areas currently classified in AR50 as forestland (Fig. 3).

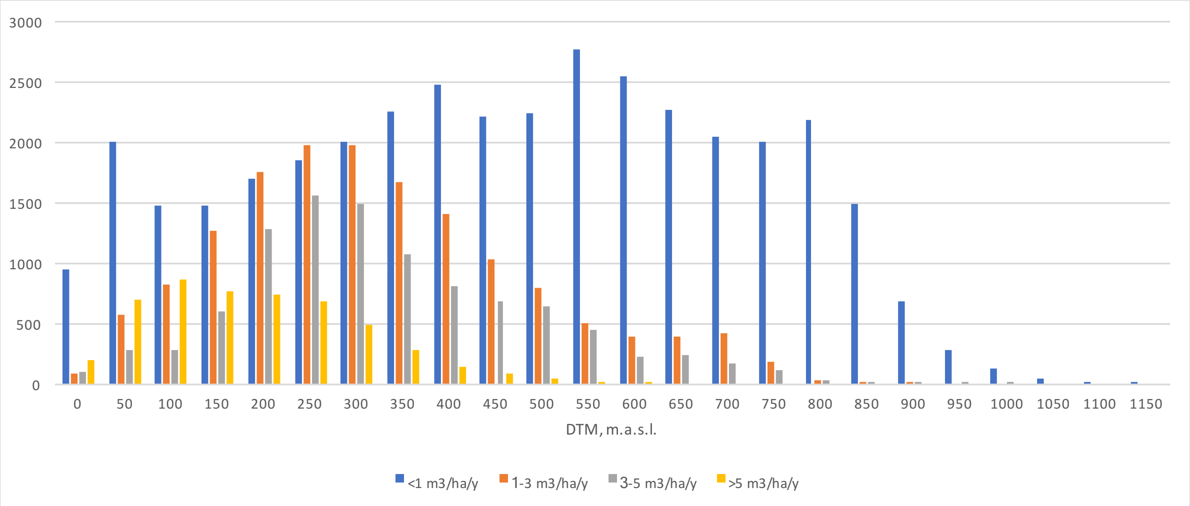

Figure 3. Histogram of site productivity distribution by elevation. Site productivity classes match those in the AR50 classification.

Based on this distribution, five strata were formed and H100 site index values were assigned (area of each stratum is also given):

Site productivity strata				
SI	DTM	m3/ha/y	H100	Area, ha
18 Coast	0–200	>5	38	2949
18 Non-Coast	0–200	>5	32	1847
13	200–450	3–5	28	1532
12	450–750	1–3	24	1300
11	750–1100	<1	20	295
			Sum	**7923**

The H100 site index values were chosen somewhat arbitrarily, but generally in line with the site index to site productivity conversion tables suggested by the Swedish Forestry Agency (Skogsstyrelsen) (Skogsstyrelsen, 1985) and mean annual increment values observed in Norway in the coastal areas (Øyen & Kystskogbruket, 2008).

It was found that the six municipalities in Trøndelag representing 50% of the combined forest regrowth area are Oppdal (1303 ha), Orkdal (677 ha), Indre Fosen (588 ha), Stjørdal (489 ha), Skaun (450 ha), and Melhus (347 ha). Elevation distributions of the six municipalities were plotted to identify the most widely represented strata (Fig. 4). Based on the distributions and location of the municipalities (Fig. 5), the high-elevation stratum 750-1100 m was excluded from the study both as underrepresented and of low economic significance given its marginal site productivity measure (a H100 of 20 m corresponding to a H50 of 11 m).

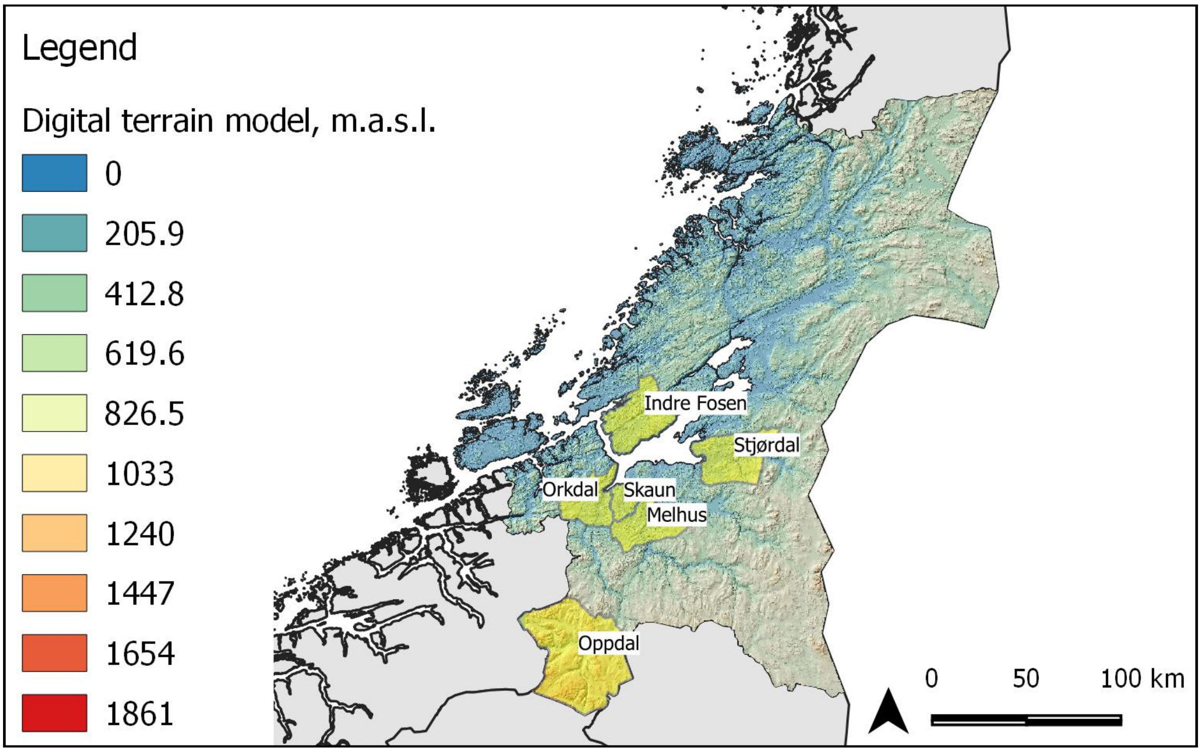

Figure 5. The six municipalities in Trøndelag accounting for 50% of the potential forest regrowth areas.

Several forest stand types were created in Heureka Beståndsvis/Standwise for each of the five resulting strata. Heureka Standwise is one of the applications in the Heureka suite intended for simulation of stand and tree development and value production under different silvicultural options (Elfving, 2010). Since Heureka does not have a growth model for Sitka spruce, the difference in the growth dynamics of Sitka spruce and other species in the coastal zone was approximated by modeling Sitka spruce stand under slightly better growing conditions and reducing the site index from 38 to 32 for the other species.

Stratum	**Stand type**	**Site Index, H100**	**Establishment method**	**Regeneration method**	**Intermediate treatments**	**Rotation age**
Coast 0-200m	Sitka spruce	38	Soil preparation; planting	Soil preparation; planting	Cleaning in yr 10	60
	Norway spruce	32	Soil preparation; planting	Soil preparation; planting	Cleaning in y 10 Thinning in yr 45	65
	Scots pine	32	Soil preparation; planting	Seed trees with soil preparation	Cleaning in yr 15	Harvest 70 Seed tree removal 80
	Birch	32	Natural propagation	Seed trees with soil preparation	Cleaning in yr 5	Harvest 45 Seed tree removal 55
	Aspen	32	Natural propagation	Seed trees with soil preparation	Cleaning in yr 5	Harvest 45 Seed tree removal 55
	N. spruce + Birch	32	Natural propagation	Soil preparation; planting	Cleaning in yr 5 Thinnings in yr 20, 30, 40	55
	S. pine + Birch	32	Natural propagation	Seed trees with soil preparation	Cleaning in yr 5	Harvest 50 Seed tree removal 60
Non-coast	Norway spruce	30	Soil preparation; planting	Soil preparation; planting	Cleaning in yr 10 Thinning in yr 45	65
	Scots pine	30	Soil preparation; planting	Seed trees with soil preparation	Cleaning in yr 15	Harvest 65 Seed tree removal 75
	Birch	30	Natural propagation	Seed trees with soil preparation	Cleaning in yr 10	Harvest 45 Seed tree removal 55

Stratum	Stand type	Site Index, H100	Establishment method	Regeneration method	Intermediate treatments	Rotation age
Non coast 0-200m	Aspen	30	Natural propagation	Seed trees with soil preparation	Cleaning in yr 10	Harvest 45 Seed tree removal 55
	N. spruce + Birch	30	Natural propagation	Soil preparation; planting	Cleaning in yr 5 Thinnings in yr 20, 30, 40	55
	S. pine + Birch	30	Natural propagation	Seed trees with soil preparation	Cleaning in yr 5	Harvest 50 Seed tree removal 60
200-450m	Norway spruce	28	Soil preparation; planting	Soil preparation; planting	Cleaning in yr 15 Fertilization in yr 30, 40	65
	Scots pine	28	Soil preparation; planting	Seed trees with soil preparation	Cleaning in yr 15 Fertilization in yr 25, 35, 45	Harvest 65 Seed tree removal 75
	Larch	28	Soil preparation; planting	Soil preparation; planting	Cleaning in yr 15 Fertilization in yr 25, 35, 45, 60	70
	Lodgepole pine	28	Soil preparation; planting	Soil preparation; planting	Cleaning in yr 10 Fertilization in yr 20, 30, 40	55
	Aspen	28	Natural propagation	Seed trees with soil preparation	Cleaning in yr 10	Harvest 45 Seed tree removal 55
	Birch	28	Natural propagation	Seed trees with soil preparation	Cleaning in yr 5	Harvest 45 Seed tree removal 55
	N. spruce + Birch	28	Natural propagation	Soil preparation; planting	Cleaning in yr 5 Selection cut of birch in yr 35	70

Stratum	Stand type	Site Index, H100	Establishment method	Regeneration method	Intermediate treatments	Rotation age
	S. pine + Birch	28	Natural propagation	Seed trees with soil preparation	Cleaning in yr 5 Selection cut of birch in yr 50	Harvest 75 Seed tree removal 85
	N. spruce + S. pine	28	Natural propagation	Soil preparation; planting	Cleaning in yr 5 Fertilization in yr 15, 40, 60 Selection cut of pine in yr 40	85
450-750m	Scots pine	24	Soil preparation; planting	Seed trees with soil preparation	Cleaning in yr 15	Harvest 70 Seed tree removal 80
	Larch	24	Soil preparation; planting	Seed trees with soil preparation	Cleaning in yr 15 Fertilization in yr 30, 40, 50	Harvest 70 Seed tree removal 80
	Lodgepole pine	24	Soil preparation; planting	Seed trees with soil preparation	Cleaning in yr 15 Fertilization in yr 25, 35, 45	Harvest 55 Seed tree removal 65
	Norway spruce	24	Soil preparation; planting	Soil preparation; planting	Cleaning in yr 15 Fertilization in yr 30, 40, 50, 60	70

In total, 27 stands were modeled. The adopted treatment programs are based on Heureka recommendations, however many of them had to be optimized manually to achieve the highest possible financial performance, as measured by the given stand’s annuity. Annuity is the amount that can annually be withdrawn from an investment without a reduction in its value (Klemperer, 1996). In the forestry context, an annuity can be calculated by the formula:

$$A = NPV \times EF \times r,$$

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where *NPV* is the net present value of the 1st rotation (sum of positive and negative cash flows from the forest stand, all discounted to year 0), *EF* is the eternity factor expressed as $\frac{r(1+r)^{T-t_0}}{(1+r)^{T-t_0}-1}$, r is the discounting rate, t_0 is the stand year 0, and T is the rotation age. A relatively low discounting rate of 2.5% was chosen to reflect the long planning horizon and the low investment and systemic risk. By introducing the eternity factor, an assumption is made that the treatment program adopted in the first rotation will be reproduced indefinitely (which is of course a simplification). Since the annuity is derived from NPV and is strictly increasing in NPV, the rotation age was optimized by maximizing the annuity. The reason for using annuities in this study, rather than the customary NPV or soil expectation value (SEV), is that the optimization principle in the modern portfolio theory is minimizing the asset's volatility for a given level of return on it (Berk, 2016). The absolute value of a forest asset, as measured by NPV or SEV, must, thus, first be converted into annual return on it.

Volatility was characterized by the standard deviation of the timber price time series. An average had to be taken of the sawlog grades because of a functional limitation in Heureka — logs are tallied and graded internally and the only visible output is harvest revenue broken down into sawlogs and pulpwood. It is thus impossible to apply different prices to different grades of timber other than sawlogs and pulpwood classified by species. The volatility of returns was estimated for each of the stand types by weighing the standard deviation of each of the four timber prices in the time series with the fractions of the respective timber grades in the combined harvested volume.

The final step was to optimize the forest stand portfolios by applying the modern portfolio theory. Two optimization methods were tried: in the first, a simpler one, the annuities of the 27 simulated stands based on Norrskog's current price list were plotted against the respective volatilities calculated as described above.

The second method is a more thorough application of the modern portfolio theory. Here, only monocultures of six species simulated in the elevation stratum 200-450 m were considered — aspen, birch, larch, lodgepole pine, Norway spruce, Scots pine. This elevation stratum was chosen as the most reliable and generally representative of both coastal and inland areas, because the Heureka simulations of the coastal and non-coastal 0-200m strata appeared slightly inconsistent; one of the reasons for this might be that the growth models need calibration to more precisely describe the Norwegian growing conditions. No mixed stands were included to avoid the problem of interpreting the performance of a mixed portfolio of mixed stands.

A covariance matrix of the price time series was built, then average return, standard deviation, and slope (the Sharpe ratio) of a dummy portfolio were calculated. Average return was calculated as the summed products of portfolio component annuities and their shares in the portfolio; standard deviation — as the square root of the portfolio's variance sum; the Sharpe ratio — as the portfolio's average return divided by its standard deviation (Berk, 2016; Sharpe, 1999). In this method, annuities were calculated for each of the tree species and each year in the time series to reflect the effect of price volatility. Then, an objective function was set up in the Excel's Solver tool to minimize the standard deviation for a given annuity, subject to the condition that the shares of the individual portfolio components (tree species) must add up to 100%. Finally, the portfolio's efficient frontier was plotted in an iterative process by manually specifying target annuities and running the Solver and the optimal portfolio was identified as the one with the highest Sharpe ratio, i.e. slope of the efficient frontier.

Results

The identified potential forest regrowth areas in Trøndelag are shown in Figure 6, highly exaggerated on purpose to make the regrowth 'hotspots' visible at this spatial scale.

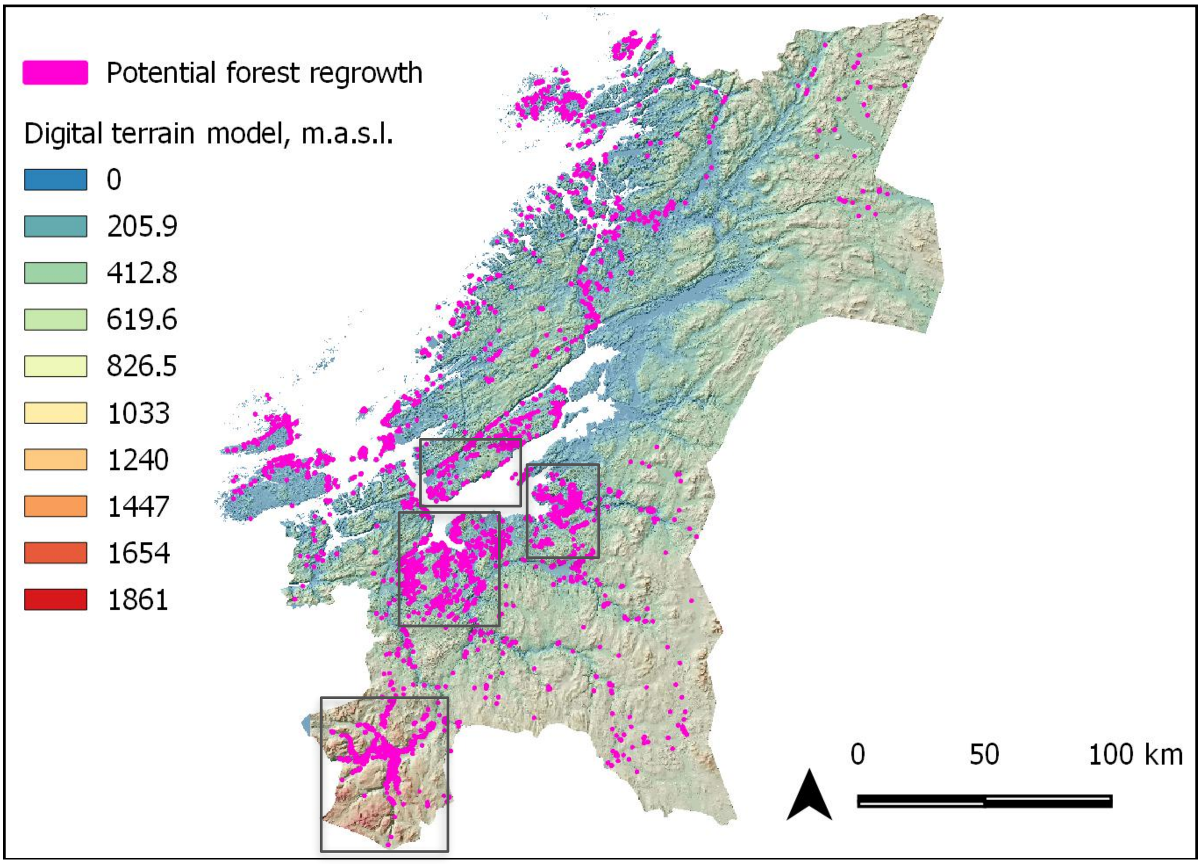


Figure 6. Potential forest regrowth areas in the entire Trøndelag (not to scale, exaggerated for visualization purposes).

Correctly scaled, stratified by elevation maps of the regions corresponding to the six municipalities containing 50% of the regrowth areas are also shown below (framed in black in Fig. 6). As seen in the histograms in Figure 4 above, in Oppdal, forest regrowth areas are concentrated in the 450-750 m stratum, and the strata correlate well with the site productivity distribution by elevation (Fig. 9). In the 'lowland' municipalities Indre Fosen, Orkdal, Skaun, Stjørdal the identified regrowth areas tend to be concentrated in the 0-200 m range. In Melhus, the distribution has a more noticeable shift to the right, into the 450-750 m stratum (Fig. 7, 8, 10).

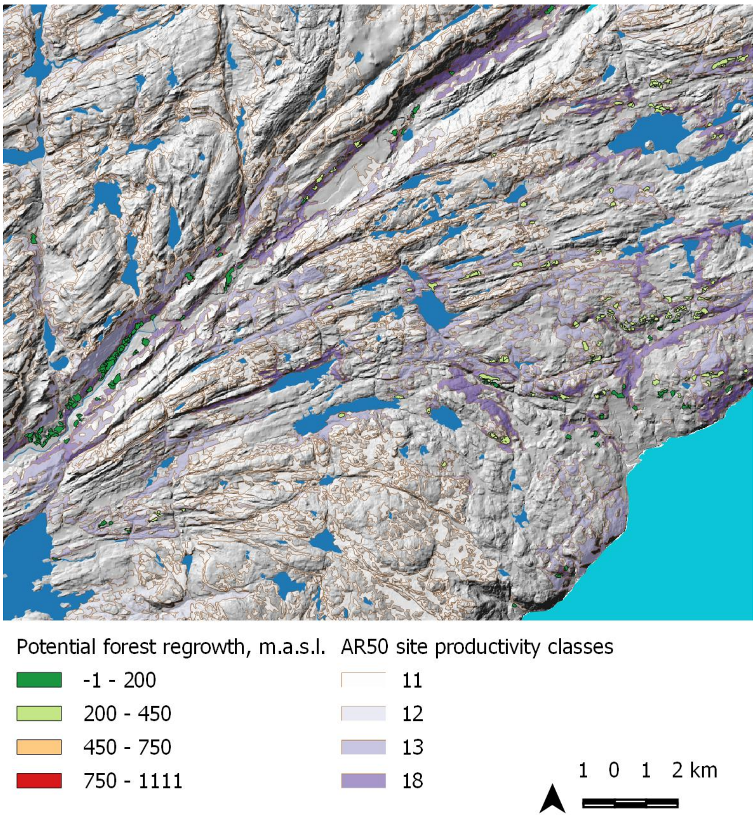


Figure 7. Potential forest regrowth areas in Indre Fosen.

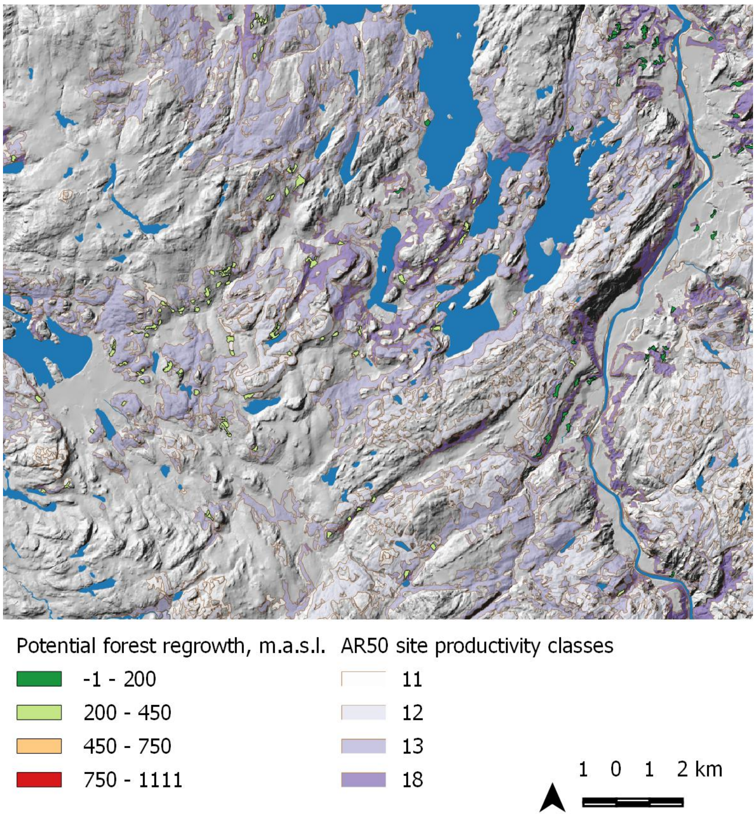


Figure 8. Potential forest regrowth areas in Melhus.

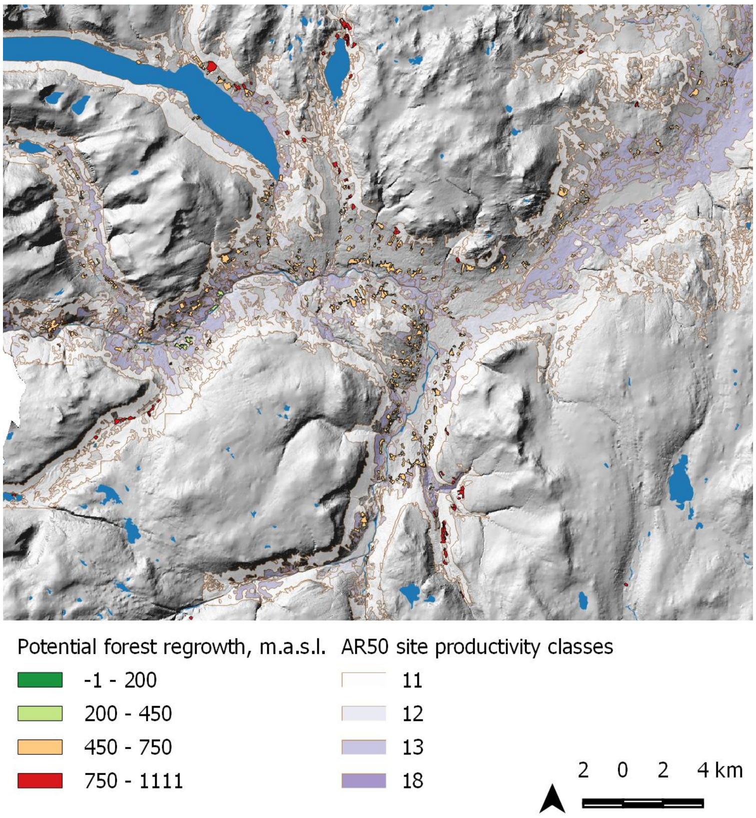


Figure 9. Potential forest regrowth areas in Oppdal.

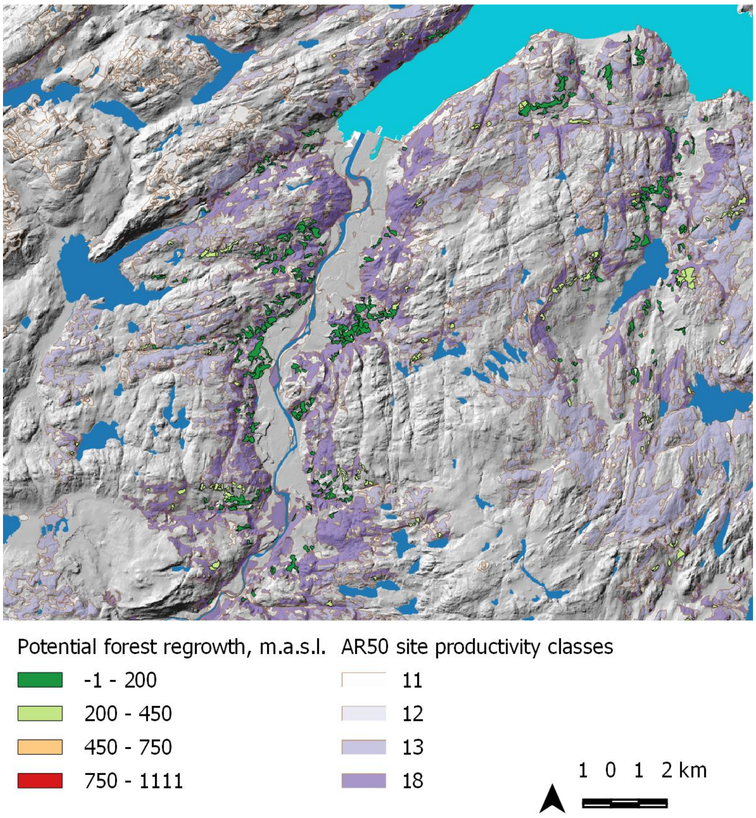


Figure 10. Potential forest regrowth areas in Orkdal and Skaun.

Distribution of the forest regrowth area by elevation and SI classes was shown in the Methods section above.

The results of stand growth simulations made in Heureka are summarized in the table below (rotation age copied from the table above for reference).

Stratum	**Stand type**	**Mean annual increment, m^3/ha/y**	**Total timber yield, m^3/ha**	**Sawlogs/ pulpwood ratio, % of total harvested volume**	**NPV, 1st rotation, NOK**	**Annuity, NOK**	**Weighted StDev, Nok**	**Rotation age**
Coast 0-200 m	Sitka spruce	16.01	893	66/25	35610	1152	55.07	60
	Norway spruce	13.84	838	66/24	22706	710	54.84	65
	Scots pine	12.17	692	68/19	10090	293	50.79	70/80
	Birch	7.39	311	-/91	4350	146	31.24	45/55
	Aspen	7.35	352	-/90	4466	150	30.83	45/55
	N. spruce + Birch	5.88 4.85	579	34/14 -/43	12357	416	43.38	55
	S. pine + Birch	6.05 3.61	432	18/12 -/60	11084	359	35.58	50/60
Non-coast 0-200 m	Norway spruce	17.7	1085	68/23	38186	1195	56.01	65
	Scots pine	12.03	646	68/19	10401	308	50.83	65/75
	Birch	7.39	311	-/88	2419	81	30.35	45/55
	Aspen	7.35	353	-/90	4466	150	30.83	45/55
	N. spruce + Birch	6.35 3.41	523	39/18 -/33	10268	346	45.23	55
	S. pine + Birch	4.41 5.46	440	20/15 -/33	12604	408	35.83	50/60
200-	Norway spruce	12.23	672	65/25	15791	494	54.32	65
	Scots pine	10.71	596	66/22	6238	185	50.26	65/70
	Larch	11.20	635	63/18	3469	105	47.12	70
	Lodgepole pine	16.24	753	61/19	9351	315	46.31	55
	Aspen	5.4	224	-/89	1305	44	30.55	45/55

Stratum	Stand type	Mean annual increment, m³/ha/y	Total timber yield, m³/ha	Sawlogs/ pulpwood ratio, % of total harvested volume	NPV, 1st rotation, NOK	Annuity, NOK	Weighted StDev, Nok	Rotation age
450m	Birch	5.5	218	-/89	1966	66	30.46	45/55
	N. spruce + Birch	6.09 4	626	35/19 -/37	14105	429	43.96	70
	S. pine + Birch	4.82 3.8	547	32/12 -/45	11028	314	40.17	75/85
	N. spruce + S. pine	1.71 10.39	963	26/7 44/12	25008	710	53.52	85
450-750 m	Scots pine	5.95	456	70/17	-1677	-49	51.92	70/80
	Larch	7.47	446	60/20	-2986	-87	46.05	70/80
	Lodgepole pine	11.12	552	57/22	-2639	-83	44.37	55/65
	Norway spruce	9.65	589	60/30	6450	196	52.39	70

A correlation matrix of the timber prices sorted by species and grade was obtained for the time period 1980–2016.

	Birch	*Aspen*	*Spruce*	*Pine*	*Larch*	*P.Contorta*
Birch	1					
Aspen	1	1				
Spruce	0.459437769	0.459437769	1			
Pine	0.408394381	0.408394381	0.774920816	1		
Larch	0.409848108	0.409848108	0.772567147	0.999842074	1	
P.Contorta	0.409115199	0.409115199	0.77381042	0.999962891	0.999958071	1

By applying the first approach to analyzing the return vs. volatility performance of the simulated stands, a scatter plot of the annuity and standard deviation values was made (Fig. 11).

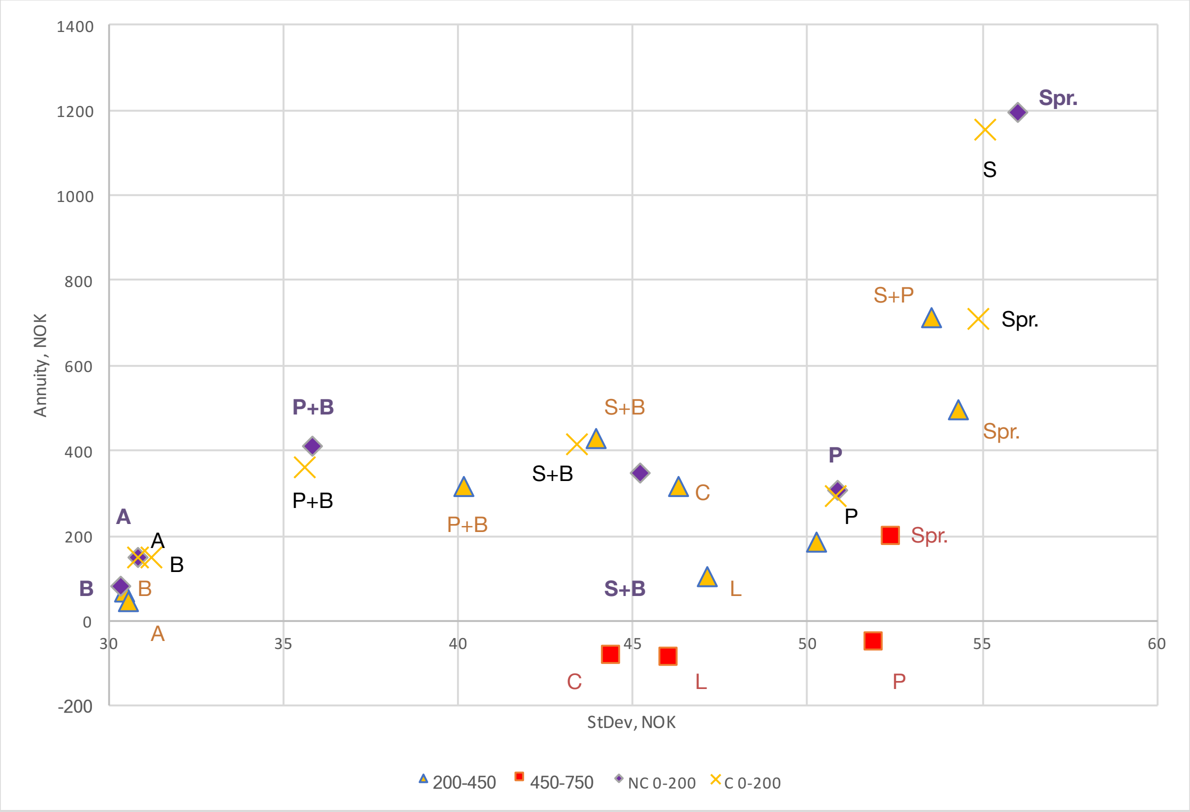
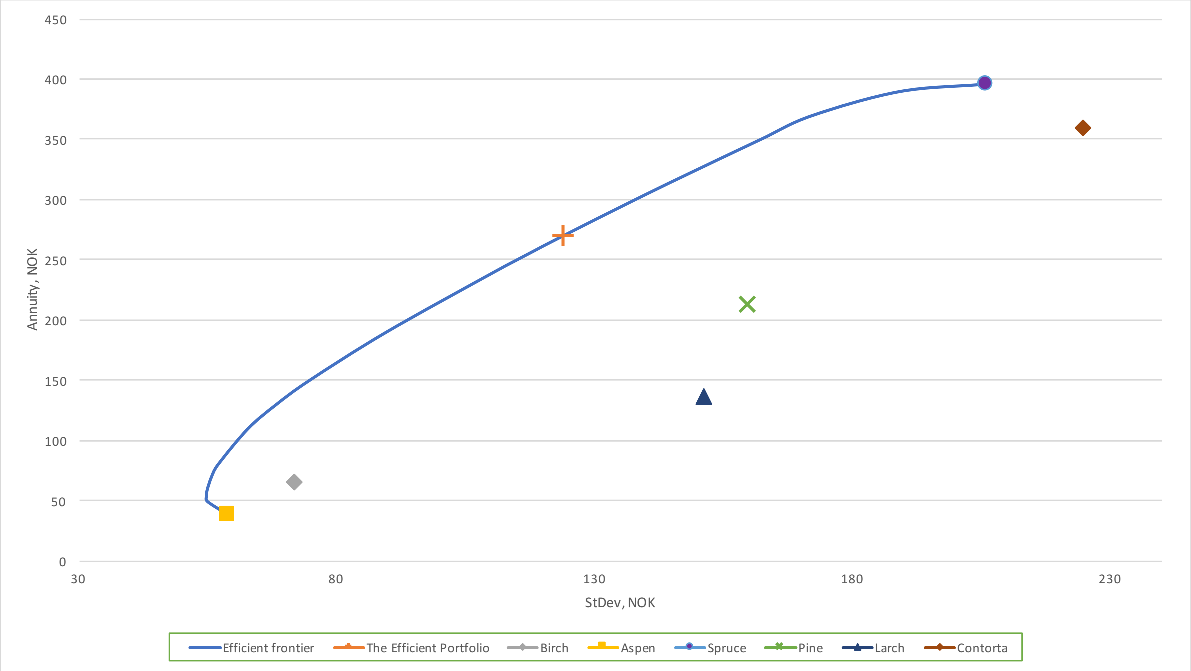


Figure 11. A scatter plot of annuities vs. standard deviations of the 26 simulated stands using the first (simpler) approach: A = aspen, B = birch, C = P. contorta, L = larch, P = Scots pine, S = Sitka spruce, Spr. = Norway spruce, S+B = Norway spruce + birch, S+A = Norway spruce + aspen, S+P = Norway spruce + Scots pine.

Following the second approach, more closely implementing the modern portfolio theory, as described above, the efficient frontier was constructed and the portfolio offering the highest slope (the Sharpe ratio) was identified (Fig. 12). The attached table shows the tree species proportions forming the efficient frontier and the respective annuity and volatility values. The portfolio highlighted in green (55; 55) has the lowest volatility of all possible combinations and can be thus considered the safest investment. The portfolio highlighted in orange (270; 124) is the best performing one with the highest ratio of reward-to-volatility, or the efficient (also known as tangent) portfolio.

The modern portfolio theory suggests that the investor contemplating an investment in an afforestation project in Trøndelag at elevations between 250 and 450 m.a.s.l. should choose the best performing tree species mix — 30% birch, 39% Norway spruce, 11% Scots pine, 21% lodgepole pine — and combine it at any ratio of his or her choice with an investment in a risk-free asset. This investment decision is expected to bring the highest possible return for any given volatility level.

Applying this finding to the area distribution of the forest expansion areas in Trøndelag, it can be concluded that at elevations between 200 and 450 m, 460 ha should be planted with birch, 597 ha with Norway spruce, 169 ha with Scots pine, and 322 ha with lodgepole pine.



Annuity, NOK	40	50	55	60	80	110	150	190	240	270	300	350	370	396
StDev, NOK	58	55	55	55	57	63	74	89	110	124	138	162	172	205
Slope	0.7	0.9	1.0	1.1	1.4	1.8	2.0	2.1	2.2	2.2	2.2	2.2	2.2	1.9
Birch	*2%*	*27%*	*28%*	*29%*	*30%*	*31%*	*31%*	*32%*	*33%*	*30%*	*20%*	*5%*	*0%*	*0%*
Aspen	*98%*	*69%*	*66%*	*63%*	*57%*	*48%*	*35%*	*22%*	*6%*	*0%*	*0%*	*0%*	*0%*	*0%*
Spruce	*0%*	*0%*	*0%*	*1%*	*5%*	*10%*	*17%*	*24%*	*33%*	*39%*	*45%*	*55%*	*59%*	*100%*
Pine	*0%*	*0%*	*2%*	*4%*	*5%*	*7%*	*8%*	*9%*	*10%*	*11%*	*11%*	*11%*	*8%*	*0%*
Larch	*0%*	*4%*	*4%*	*4%*	*2%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
P.contorta	*0%*	*0%*	*0%*	*0%*	*2%*	*5%*	*9%*	*13%*	*18%*	*21%*	*24%*	*30%*	*33%*	*0%*

Figure 12. The efficient frontier with the location of the efficient portfolio highlighted and a scatter plot of annuities vs. standard deviations of the 6 tree species forming the portfolios.

Discussion

This study shows that approximately 7923 ha of agricultural land, composed of both croplands and pastures, is or may become abandoned in Trøndelag, Norway, and is thus suitable for afforestation projects. An afforestation effort of this scale would be a significant contribution to the existing forest-based carbon capture and storage programs (Haugland, 2013). This finding is in general agreement with the assessment given in the so-called Øyen Report (Øyen & Kystskogbruket, 2008) that the available area of productive forestland in Trøndelag is expected to grow by up to 3500 ha annually; this figure includes, however, areas where forest can expand due to processes other than land abandonment — for example, as a result of the climate change pushing the tree line in alpine areas to higher elevations. According to estimates, the tree line rose by 40 m in 1918-1968 alone (Larsson, 2004). The conclusion that can be drawn from the Potential for Forest Regrowth dataset used as one of the main inputs in this analysis is that the share of forest expansion due to the described climatic processes is much larger that the share of forest expansion due to agricultural land abandonment (Bryn et al., 2012). Nevertheless, surprisingly little quantitative and spatially-explicit research into land abandonment processes in Norway is available. As a result, this study had to be based on modeled, rather than observed, estimates of the extent of this process, and the uncertainty concerning the area estimates is high. Another challenge was reliably assessing the productive potential of former farmland when converted to a forest plantation. In forestry, it is customary to estimate the site index either by the height development of the dominant trees or by the site's growing conditions judging by the natural vegetation type. Abandoned farmland typically lacks dominant trees and the site vegetation might have been altered by farming practices, grazing, or fertilization. Site conditions may have to be interpolated based on observations of adjacent forest stands, if any, or estimated by the annual shoot length of early-successional tree species if they have colonized the site (the intercept method, as described by Hägglund & Lundmark (1983)).

The forest planning software suite Heureka is not widely used outside Sweden and apparently needs calibration to better model growth on tree and stand level in the

Norwegian climatic and forest conditions. The simulation results appear to underestimate the performance of Sitka spruce as Norway spruce demonstrated a higher mean annual increment and timber yield on poorer-quality sites. For example, Sitka spruce produced only 16 m^3/ha/y on a SI 38 site, while Norway spruce produced 17.1 m^3/ha/y on a SI 30 site at a higher elevation with a higher timber yield. Based on existing literature, mean annual increments of up to 26 m^3/ha/y were expected from Sitka spruce (Øyen, 2009). For this reason, the stand growth simulations carried out in the coastal zone at elevations between 0 and 250 m.a.s.l. were not used in portfolio optimization. Another problem encountered n Heureka was that, with the Norwegian harvesting and forwarding costs, thinnings were hardly ever profitable — some treatment programs generated positive cash flows, but their discounted values were either very low or negative). In the simulations, optimistic hourly harvesting and forwarding rates of 1600 NOK and 1200 NOK, respectively, were adopted, resulting in harvesting costs around 90-110 NOK/m^3 and thinning costs up to 200 NOK/m^3, which appears realistic as the sites were easily accessible and relatively flat. All stands were cleaned in years 5 to 15, but only few were subsequently thinned and still no significant mortality was observed. The deterministic and stochastic mortality models implemented in Heureka may need further study and adjustment if applied outside Sweden.

The simulated treatment programs did not include harvesting of stumps, branches and treetops for bioenergy. Judging by the estimated sawlog/pulpwood fractions, harvesting residues may account for 10 to 30% of the total harvested volume, especially in mixed stands of conifers and broadleaves and in pure stands of larch and lodgepole pine at higher elevations. Including the harvesting residues might improve the financial performance of such stands, but it was chosen not to do so considering that the market for biomass for conversion to bioenergy is relatively limited in Norway. It should be noted here that some mixed stands performed very well: for example, mixtures of Norway spruce and Scots pine with birch has generated annuities comparable with pure spruce stands (NOK 429 and 314 vs. 494, respectively) and left behind pure pine stands (NOK 185) at elevations between 200 and 450 m. A mixture of spruce and pine was found to be the most valuable stand type at 200-450 m (NOK 710). At higher elevations, spruce was the only species to offer a positive annuity (NOK 196) while the other conifers grew unexpectedly slowly and had negative annuities. Larch demonstrated surprisingly disappointing net present values and annuities in all simulations, though performance at least on par with Scots pine was expected (Øyen, 2009); a higher share of harvesting residues might be an explanation (.20% vs. 10% in pine). Lodgepole pine showed an impressive performance at mid-elevations (NOK 315), second only to spruce and mixed stands. However, at higher elevations, where it is often recommended for planting (Nygaard, Nyeggen, & Støtvig, 2015), lodgepole pine had a negative annuity of NOK -83.

The first portfolio optimization method offers a straightforward way to compare the performance of multiple stand types. It is illustrates the beneficial effects of diversification consisting in lower volatility of a forest asset's returns for a given level of annuity. For example, planting mixed stands of pine and birch instead of mixed stands of spruce and birch or the latter instead of pine monocultures reduces volatility by NOK 5 to 10 while the annuity remains practically unchanged at NOK 400 (Fig. 11). The deciduous species birch and aspen were found to be the most secure, yet low-return investments (volatility NOK 30, annuity NOK 200 or lower) — the forestry 'counterpart' of treasury bonds. This behavior, as well as the good performance of mixed conifer and broadleaf stands, is explained by the correlation pattern discovered in the timber prices. Pulpwood (including hardwood) prices have much lower volatility (by a factor of 2) than sawlog prices, therefore the pulpwood species aspen and birch and mixed stands with higher pulpwood yields have an expressed stabilizing effect on investment returns. The first method has, however, a methodological weakness — it calculates annuities only once for a given price list using Heureka's built-in financial functions. The effect of price volatility is thus ignored and the output is static.

The second optimization method overcomes this problem by integrating historical price volatility and recalculating annuities for each price level that has been observed. This method allows to find the efficient (tangent) portfolio, which is the best one in the market according to the modern portfolio theory — it is characterized by the highest increase in return per an additional unit of volatility. Due to the limited number of forest stands analyzed with this method, diversification effects are less visible in the efficient frontier plot (Fig. 12), but still it shows that conversion from larch to pine might bring a higher annuity with a smaller increase in volatility, supports the earlier finding that broadleaves reduce volatility when mixed with conifers, and indicates that lodgepole pine is a high-risk high-return investment. Generally, since all stand types forming the portfolio are found below the efficient frontier, the conclusion is that investing in a diversified species mix — be it the tangent mix (30% birch, 39% Norway spruce, 11% Scots pine, 21% lodgepole pine) or some other of the suggested tree species mixes — can be expected to generate a higher return for a given level of risk compared to any monoculture or tree species mix that lies below the efficient frontier.

Conclusion

In this study, the spatial extent of potential forest expansion due to agricultural land abandonment was estimated in the Norwegian county of Trøndelag. It was found that 7923 ha of former farmland can be potentially used in a large-scale afforestation program. A major share of this area is found along the coast at elevations up to 200 m.a.s.l. (nearly 3000 ha), the rest is distributed more or less evenly between low elevations in non-coastal areas, mid (200-450 m.a.s.l.) and higher (450-750 m.a.s.l.) elevations and around the tree line area or higher (750-1150 m.a.s.l.). Typical expected growing conditions were described and 26 stand types were modeled in the Swedish forest planning software suite Heureka. The modern portfolio theory was applied to the simulated stand growth and yield data to compare the financial performance of the stands, demonstrate diversification benefits, and identify the best-performing (efficient, or tangent) portfolio). It was found that the efficient portfolio in the elevation range of 200 to 450 m.a.s.l. would be composed of 30% birch, 39% Norway spruce, 11% Scots pine, 21% lodgepole pine. It is the tree species mix offering the highest increase in return on investment for an additional unit of risk.

It was observed that Heureka needs adjustment and calibration to model tree and stand growth in conditions not typically found in Sweden. Apart from that, Heureka proved to be a very powerful and useful planning tool for forest management and operations. A very limited share of its functionality was employed in this study and further experiments with Heureka might be of relevance for the Norwegian forest industry. Further research is also required into spatially-explicit identification in Norway of areas with potential for forest expansion. One potential approach to this knowledge gap might be the use of machine learning technology and supervised classification of remotely sensed data.

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