

Appendix A – Constants

Table A1. The initial states of the old stands – state parameters before regeneration harvest.

Site index SIH(100) ^{a)}	Age from seed	Stem number	Basal area	Dominant height	Volume on bark	Volume under bark	Diameter of basal area mean stem (Dg)
m	Years	Stems ha ⁻¹	m ² ha ⁻¹	m	m ³ sk ha ⁻¹	m ³ fub ha ⁻¹	cm
T28	90	686	39.25	27	469	395	27
T26	95	651	37.25	26	421	354	27
T24	105	669	35.5	24	385	323	26
T22	115	677	33.25	23	345	288	25
T20	125	702	31.75	22	314	262	24
T18	135	722	30	21	282	234	23
T16	140	765	26.5	20	233	191	21

a) Site index denotes the dominant height at age 100 yrs.

Table A2. Seedlings removed in pre-commercial thinning.

Site index (stand's dominant height at age 100 yrs.)	Planting		Natural	
	SIH < 18	SIH ≥ 18	SIH < 18	SIH ≥ 18
Birch seedlings in Humus (seedlings ha ⁻¹)	0	400	0	400
Birch seedlings in scarified patches (seedling per patch)	1	1	1	1
Spruce seedlings (seedlings ha ⁻¹)	1450	1450	1450	1450
Pine seedlings in Humus (seedlings ha ⁻¹)	250	250	800	650
Pine seedlings in scarified patches, (seedlings ha ⁻¹)	350	350	Variable ^{a)}	Variable ^{a)}
Advanced growth of pine seedlings (seedlings ha ⁻¹)	1800	150	1800	150

a) Estimated using Hagner's (1962) functions of natural regeneration. One seedling per patch is kept at pre-commercial thinning (Eqs. 2 and 3 Appendix B).

Appendix B – Optimisation engine and functions

Solver optimisation engine

The optimisation tool embedded in Excel is developed by Frontline systems Inc. The algorithm used is the Generalized Reduced Gradient (GRG2) for nonlinear optimization (Frontline systems Inc. 2013; Fylstra et al 1998). Following settings were used:

Engine description: = "GRG Nonlinear"; Search Option: = Newton search method; Estimates: = Quadratic; Convergence: = 0.0001; Derivatives: = Central differencing; Assume Non Negative decision variables: = True; Scaling: = True; Max Time: = 1000 seconds; Max Iterations: = 1000; Precision: = 0.0001

The programming was written in Visual Basic for Applications.

Seedling survival

The function modelling the annual survival rate of seedlings was based on a function for mortality by Eriksson et al. (1980):

$$M_{20\text{yr}} = 0.14635 * \text{lat} * \text{alt} / 100 + 0.04364 * \text{lat}^2 - 157.21$$

where $M_{20\text{yr}}$ is the % mortality rate for a period of 20 years, lat is the latitude in °N, and alt is the altitude in meters above sea level. Based on this a function for annual survival was constructed. It was assumed that the annual survival rate (AS) was of the same magnitude over years:

$$AS = (1 - M_{20\text{yr}} / 100)^{1/20} \quad (\text{b1})$$

Seedlings in natural regenerated stands

Number of seedlings in scarified patches

The functions for natural pine seedlings on the scarified area take the following forms (adapted from Hagner (1962), function 1 and 2a):

$$S_f = N_{\text{patch}} * (810.8 + 1.39309 * b * N * W * L - 1.174 * A - 7.23 * N + 13.13 * W + 960.8 * W * L - 8.77 * W^2 * L) * 10^{-3} \quad (\text{b2})$$

$$S_d = N_{\text{patch}} * (-2.3066 - 0.004182 * N + 0.03878 * W + 2.2553 * W * L - 0.0487 * W^2 * L + (4.077 + 5.286 * W * L) * \exp(-300/(700 - A))) \quad (\text{b3})$$

where S is the number of seedlings per ha, f denotes fresh sites, d denotes dry sites, N_{patch} is the number of scarified patches per hectare, A is the altitude in meters above sea level, N is the number of seed trees per ha, W and L are the width and the length of the patch respectively in meters. b is a variable of sowing effectiveness. Note that this equation is illogical with respect to N. Based on the data presented in Hagner (1962), b was estimated to a function of altitude and latitude:

$$b = -1.59375 * \varphi^2 + 193.72 * \varphi - 0.039 * A - 5847.8 \quad (\text{b4})$$

where φ is the latitude in degrees north.

Number of seedlings in undisturbed humus cover

The functions for natural pine seedling in the undisturbed humus cover take the following forms (adapted from Hagner (1962), function 7 and 8):

$$SH_f = (23.578 - 32.464 * (t/5) + 14.556 * (t/5)^2) * 100 \quad (\text{b5})$$

$$SH_d = (62.539 - 10.781 * N/100 - 83.98 * (t/5) + 2.502 * (N/100)^2 + 34.612 * (t/5)^2) * 100 \quad (\text{b6})$$

where SH is the number of seedlings in the undisturbed humus cover per ha, f denotes fresh sites, d denotes dry sites, N is the number of seed trees per ha, t is the number of vegetation periods after regeneration harvest. In the model the number of vegetation periods was set equal to the number of years after regeneration harvest.

Height of highest seedlings in natural regenerated stands

Functions calculating the height of the highest seedling after a time period of 1 to 6 years (from Hagner (1962), function 12 and 13):

$$SH_f = (-3.1634 + 13.5039 * t/5 + 0.5727 * (N/100)^2 - 4.6764 * N/100 * t/5) * 0.01 \quad (b7)$$

$$SH_d = (-3.3387 + 9.6644 * t/5 + 1.2442 * (N/100)^2 - 4.0339 * N/100 * t/5) * 0.01 \quad (b8)$$

where SH is the seedling height, t is the time in years, N is the number of seed trees, f denotes fresh sites, d denotes dry sites. Together with the function for height development the functions were used to calculate the time for natural regenerated seedlings to germinate and reach the same height as the planted seedling were when planted.

Height development

Hdom is the dominant height as a function of site index and stand age (Elfving and Kiviste 1997):

$$H_{dom} = a / (2 + b / c) \quad (b9)$$

where

$$a = r + SIH100 + 23.8$$

$$c = r + SIH100 - 23.8$$

$$r = ((SIH100 - 23.8)^2 + 29582 * SIH100 / 100^{1.7829})^{0.5}$$

$$b = 29582 / age^{1.7829}$$

SIH100 is the average height of the 100 largest trees per ha at a total stand age of 100 years, age is the stand age.

Initial basal area

Function for the initial basal area of young pine stands (Elfving 2007).

$$BA_{initial} = PL * (\exp(-1.8171 + 0.4902 * \ln(H_{dom}) + 0.6867 * \ln(H_{dom} * N_0 / 100)) - 1) \quad (b10)$$

where PL is the production level which is set to a constant of 1, N₀ is the initial stem number, H_{dom} is the dominant height.

Stand development

The functions for the stand development take the following forms (Elfving 2007):

Notations

PL = 1, the production level is set to a constant of 1

t₁ = stand age in years in the beginning of a time period

t₂ = stand age in years at the end of a time period

H_{dom1} = dominant height at the beginning of a period

H_{dom2} = dominant height at the end of a period

BA_{ant} = self-thinning (mortality) in basal area during a period

N_{nt} = self-thinning (mortality) in stem number during a period

N₀ = initial stem number

BA_{ath1} = basal area after thinning in beginning of a period

N_{ath1} = stem number after thinning in the beginning of a period

BA_{th%1} = in % removal of basal area in the thinning in the beginning of the period

S_{di} = Nath₁ * (BA_{ath1} / Nath₁)^{0.8} + 1.5 * (H_{dom2} - H_{dom1})

Igred = $1 - 0.0118 * (47 - sdi)$ for $sdi < 47$, Igred = 1 for $sdi \geq 47$
 FH = Form height, Volume on bark/Basal area
 Vob = per hectare timber volume on bark

Basal area increment

$$BA_{\text{increment}} = (PL * 2.5 * Igred * (N0 / 1800)^{0.3} * (Hdom_2 - Hdom_1)) - BAnt \quad (b11)$$

Self-thinning (mortality) of basal area

$$BAnt = 0.008 * (sdi / 100)^2 * (t_2 - t_1) * BAath_1 \\ + 1 / (1 + \exp(9 - 8.2 * BAth\%_1 - 0.121 * Hdom_1)) * BAath_1 \quad (b12)$$

Self-thinning (mortality) of stem number

$$Nnt = 0.008 * (sdi / 100)^2 * (t_2 - t_1) / (1.315 - 0.757 * sdi / 100) * Nath_1 \\ + 1 / (1 + \exp(9 - 8.2 * BAth\%_1 - 0.121 * Hdom_1)) * Nath_1 \quad (b13)$$

Volume over bark

$$Vob = FH * BA \quad (b14)$$

$$FH = (-4.2 + 0.4315 * Hdom + 4.26 * Hdom / (Hdom - 1.3))$$

Volume under bark

The function for converting volume over bark to volume under bark was based on yield tables for Scots pine in northern and central Sweden (Cernold 1981 a and b):

$$Vub = (0.8596 * Vob) - (0.0119 * N) \quad (b15)$$

where Vub is the per hectare volume under bark, Vob is the per hectare volume on bark, N is the per hectare stem number.

Maximum basal area

Function determining the maximum basal area of dense or unthinned stands (Elfving 2010):

$$BA_{\text{max}} = -89.7 + 2.47 * Hdom - 0.0212 * (Hdom)^3 / SIH + 0.834 * SIH + 0.0035 * N0 \\ + 0.89 * lat \quad (b16)$$

where BA_{max} is the maximum basal area attainable $\text{m}^2 \text{ha}^{-1}$, Hdom is the dominant height, SIH is the site index, N0 is the initial number of seedlings and lat is the latitude in meters above sea level.

Basal area diameter (dg)

$$dg = 2 * (BA * 10000 / N / \pi)^{0.5} \quad (b17)$$

where dg is the basal area diameter in cm, BA is the basal area in $\text{m}^2 \text{ha}^{-1}$, N is the stem number per ha.

Appendix C – Prices and costs

Table C1. Average of three timber price lists and pulpwood for the districts: Skellefteå, Umeå and Örnsköldsvik first quarter 2009 (Norra 2009).

Quality class	Diameter at top-end of the log, cm										
	12	13	14	16	18	20	22	24	26	28	30
€ m ⁻³ to ^{a)}											
Class 1	39.4	47.4	52.2	58.9	64.7	70.4	74.0	76.9	79.7	82.4	82.4
Class 2	36.9	43.9	47.5	55.0	55.0	55.3					
Class 3	29.4	34.8	38.3	41.1	46.0	48.6	50.0	50.5	50.8	51.6	51.7
Class 4	25.0	27.6	32.5	32.9	32.9	33.4	33.5	33.5	33.5	33.9	33.9

a) m³to denotes the largest cylinder of wood that can be sawn from a conical log. The volume is calculated as the product of the length of the log and the circular area ten cm from the log's top end, under bark.

Average pulpwood price and the cost of transport to industry

Pulpwood (€ m ⁻³ fub) ^{b)}	26.5
Costs for transporting pulpwood to industry (cent m ⁻³ fub km ⁻¹)	1.8
Pulpwood including cost for transport ^{c)} (€ m ⁻³ fub)	24.3

b) m³fub denotes log volume under bark.

c) The average distance of transporting pulpwood in northern Sweden was assumed to be 100 km (Thor and Johansson 1999).

Table C2. Statistics from the Swedish Forest Agency (2009) and the consumer price index were used to calculate adjustment factors for pulpwood and timber prices.

Average timber and pulpwood price for northern Sweden	Average real ^{a)} price for the period: 1996–2009 (€ m ⁻³ fub)	Real ^{a)} price first quarter 2009 (€ m ⁻³ fub)	Adjustment factor ^{b)}
Timber	42.5	43.0	0.93
Pulpwood	21.9	27.3	0.80

a) In the price level of 2009 (deflated with CPI).

b) Adjustment factor multiplied by timber price list and price of pulpwood yield the adjusted prices.

Table C3. Costs for regeneration, silviculture and harvest.

Costs for regeneration and silviculture		
Soil treatment Planting (€ ha ⁻¹) ^{a)}		123.8
Soil treatment natural regeneration (€ ha ⁻¹) ^{a)}		137.6
Planting incl. cost for normal seedlings (cent per seedling) ^{b)}		18.4
Planting incl. cost for genetically enhanced seedlings (cent per seedling) ^{b,d)}		19.3
Pre-commercial thinning (€ per man-hour) ^{c)}		26.6
Constants used in cost functions	Thinning	Final harvest
Movement (cent m ⁻³ fub) ^{d)}	36.7	13.8
Harvester (€ per G15-hour) ^{d)}	74.3	84.4
Forwarder (€ per G15-hour) ^{d)}	55.0	64.2
Forwarding distance (meters) ^{d)}	300	300

a) Brunberg (2007); Westerberg and von Hofsten (1996)

b) Simonsen et al. (2010)

c) Bergstrand et al. (1986); Lantz Skogsvård (2009)

d) Kraftsamling skog (2009)

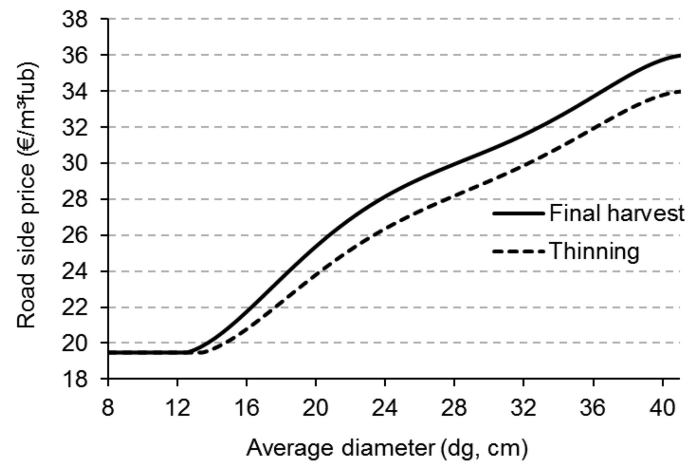


Fig. C1. Road side price as function of average diameter (dg) for extracted trees.