3.4 Sustainable Forest Regeneration

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3.4.1 Introduction and Definition of Terms

The NFI assesses the changes and state of the forest as a basis for monitoring the forest development (BRÄNDLI 1993). A special interest here is given to the sustainability of forest influences with respect to human requirements, in other words, the permanent fulfillment of forest functions. This will only be ensured if the forest constantly regenerates itself enough or if it is regenerated by humans. Sustainable forest regeneration represents, therefore, a key measure in the evaluation of sustainable forest development.

"Sustainability" is a very complex term. Its meaning has changed considerably over time (BERNASCONI 1996; ZÜRCHER 1965). For almost all of the definitions and meanings of sustainability, the main focus is on the sustained use of the essential elements required to sustain life (BÄCHTOLD 1998). GLÜCK (1994) distinguishes between the two definitions commonly used today in forestry: first, sustainability in the sense of a multifunctional forest utilization, and second, the ecological sustainability.

Sustainability in the sense of a multifunctional forest utilization (GLÜCK refers to it as "sustainable multi-purpose forestry") emerged when the concept of sustainable timber production was extended to all forest functions. The goal of sustainable multifunctional forest utilization is to obtain regular yields that are as high as possible from timber sales and from compensations of forestry services, while at the same time fulfilling certain social, legal, operational, or ecological limitations (GLÜCK 1994).

The goal of **ecological sustainability** consists primarily in improving or preserving the ecological stability of forest ecosystems. Sustaining the ecological stability does not, therefore, represent a limitation, but is the actual goal. "Compared with the sustainable multi-purpose forestry, the conservation of the ecological stability turns from being a limitation to being the goal, and the supply of timber and forestry services turns from being the goal to being a limitation (GLÜCK 1994)". The **ecosystem management**, which grew out of this, emphasizes the natural state of ecosystems, especially the biodiversity and the ecological stability. Both should not be diminished under any circumstances, but on the contrary, should be increased whenever possible.

The **evaluation of the sustainability in the National Forest Inventory** was based for the entire forest (BRÄNDLI 1999) as well as for the forest regeneration, on the sustainability in the sense of the multifunctional forest utilization.

3.4.2 Introduction into Calculating Sustainable Forest Regeneration

According to ZÜRCHER (1965), the **examination of the sustainability** is conducted by comparing the present state of the forest with the **normal state** of the forest. The normal state is a desirable state of the forest, which constantly and at all times optimally satisfies all the demands, and which does not contradict the natural law. The **nominal state** of uniform high forests is calculated with an area based normal forest model (see also Chapter 3.4.3); the nominal state of plenterlike forests with an individual tree based plenter forest model (see Chapter 3.4.4). It is important to note that these models are very rough approximations to their complex reality. The normal state of a forest is, above all, a simple model in order to understand and to control the sustainable composition of the forest.

The **normal forest** is a model for a sustainable forest on a homogeneous site and has a constant tree species composition. Furthermore, stands are identical to the yield tables with respect to stand density and stand development, and are balanced in the representation of all age classes. The regeneration area is therefore constant every year. In a fictitious normal forest with an area of 200 hectares and a rotation period of 100 years, each year age class occupies an area of 2 hectares, so that the yearly sustainable regeneration area amounts to 2 hectares per year. Keeping this regeneration area constant ensures a yearly and consistent amount of work for harvesting, young growth tending, and thinning, as well as approximate constant timber yield and revenues.

The **normal forest model** is suitable primarily to evaluate even-aged, clear-cut high forests. The closest type of forest to this model is the uniform high forest as defined by the NFI, which is characterized by a layered structure, and which can be clearly classified as a certain stage of development. In contrast to even-aged high forests that are regenerated by clear-cuts (age-class forest), many uniform high forests in the lower elevations of Switzerland are regenerated under shelterwood, by strips, or in small gaps. In enterprises with regeneration under shelterwood, generations of trees overlap; therefore, the normal forest model is not really applicable (HOLM 1984). In the absence of a model for the shelterwood forest, the sustainable regeneration area is nonetheless calculated with the normal forest model. The use of the normal forest model is based on the following assumptions:

- Uniform high forests are continuously being regenerated in one area and are not converted into plenter high forests.
- The normal forest model provides suitable nominal value for the regeneration, even for forests that are regenerated in smaller areas.

The **plenter forest model** is a model for a selection forest, which is in a structural equilibrium, has a constant number of trees per diameter class, and has sustainable cuttings corresponding to total yield (according to SCHÜTZ 1989). The main idea behind this model is that for each diameter class a certain number of trees can be determined which does not change over time. The reason for this is because only so many stems grow into a certain class as grow into the next higher class or die off naturally during the same period of time (DUC 1991).

The plenter forest model is suitable for the evaluation of stands that have a permanent multi-storied structure and are regenerated in small patches dispersed over the whole stand. This is the case for multi-storied or clustered stands, but not for irregular stands with layered structure. The plenter forest model was, therefore, only used to evaluate plenter forests. The following assumptions were thereby made:

- The plenter forests will not be converted into uniform high forests in the near future.
- The plenter forests are in an approximate structural equilibrium or, even though certain departures exist from the equilibrium, the plenter forest model can still be used.

3.4.3 Sustainable Forest Regeneration of Uniform High Forests

Sustainable Proportion of Young Forest

The sustainable proportion of young forest is that part of the forest area occupied in the normal forest by the development stages “young growth,” “thicket,” and “thin pole wood”. These stages of development should be represented proportionally to the time it takes to grow through a particular stage, as compared to the entire rotation period (ZÜRCHER 1965). This growing time depends on the tree species, site, and length of time the stand was under shelter during the young growth and thicket stage. For this reason LEIBUNDGUT (1981) only indicates approximate values of growing time. The proportion of young forest (according to the NFI’s stages of development – young growth and thicket – with a dominant diameter at breast height that is less than 12 cm) corresponds approximately to the development stages of young growth, thicket, and thin pole wood, according to LEIBUNDGUT (1981). Relating the minimum duration of young forest development given by Leibundgut to the economically optimal rotation periods on good sites in the Swiss Plateau (BACHMANN 1990) results in minimum values for the proportion of sustainable young forest per tree species as shown in Table 1. In lower elevations, the proportion of sustainable young forest amounts to 14% to 28%. This corresponds closely with the sum of the proportions of the development stages for young growth (5% to 10%) and thicket (8% to 12%), which was considered by ZÜRCHER (1965) to be sustainable with respect to the normal forest model (i.e., in the sense of sustainable timber production).

Table 1. Standards for the period of young forest development, the rotation period, and the sustainable proportion of young forest in lower elevations (colline to submontane zone).

Tree species		Period of young forest development	Rotation period	Sustainable proportion of young forest
common	scientific	Years	Years	%
Norway Spruce	Picea abies Karst.	20–30	110–130	18–23
Silver Fir	Abies alba Mill.	30–40	120–140	25–28
Scotch Pine	Pinus silvestris L.	20–30	130–150	15–20
European Larch	Larix decidua Mill.	17–25	120–140	14–18
Common Beech	Fagus silvatica L.	30–40	130–150	23–27
English/Durmast Oak	Quercus robur L. / Quercus petraea	30–40	150–170	19–22
Common Ash	Fraxinus excelsior L.	18–25	80–100	23–25

In the higher elevations the young forest development can take considerably longer. However, since the rotation periods are also substantially longer, the sustainable proportions of young forest are similar to those of lower elevations (Table 2). Depending on the tree species and rotation period, the sustainable proportion of young forest lie approximately between 17% and 30%, which corresponds well to the expectations given by OTT *et al.* (1997). Since the young forest development depends on the site and type of regeneration system, and since the rotation period depends on the goal (especially on the target diameter), the presented values for the sustainable proportion of young forest are not constant, but instead give an approximate dimension. In the NFI a young forest proportion of 10% was considered to be too low; between 10% and 25% as sustainable; and above 25% as too large.

Table 2. Standards for the period of young forest development, the rotation period, and the sustainable proportion of young forest in higher elevations (upper montane and subalpine zone).

Tree species		Period of young forest development	Rotation period	Sustainable proportion of young forest
common	scientific	Years	Years	%
Norway Spruce	Picea abies Karst.	50–75	200–300	25
Silver Fir	Abies alba Mill.	60–90	200–300	30
European Larch	Larix decidua Mill.	40–50	200–300	17–20

Sustainable Regeneration Area

The **sustainable regeneration area** is the forest area that has to be cleared every year in order to ensure a balanced age class distribution in the normal forest enterprise. For a forested area F and a rotation period u, this corresponds to a ratio of F/u. The sustainable regeneration area was calculated in the NFI only for managed forests with regeneration in larger areas. Forest areas with regeneration on an individual tree basis and unmanaged or specifically managed forest areas were not included in the calculation.

The sustainable area of regeneration depends on the chosen or calculated rotation period. In contrast to the normal forest, work is being conducted with actual enterprises and regions with several different tree species, and at sites that have different growth potentials. Since the rotation periods are different on most of the sites for the most common tree species, the sustainable regeneration area cannot be calculated by simply using the assumed mean rotation period u. The rotation periods must be calculated for the present or the future desired proportion of the most important tree species and have to be site specific. The **rotation period** u is the planned, fixed time period between the establishment and the removal of a stand. The period depends mainly on the tree species, site quality, and thinning intensities.

The **optimal (with respect to yield) rotation periods** of a tree species on a certain site is reached when the economic yield curve of the stand reaches the site-specific production capacity during or after its culmination (BACHMANN 1990). The production capacity corresponds to the maximum value of the average economic yield on a site-specific ideal stand. Due to the model calculations carried out by BACHMANN (1990), the optimal rotation periods for the most important tree species on good sites in the Swiss Plateau are known. They are used as a basis for the chosen rotation period in the normal forest model.

As an **indicator of site quality,** Bachmann used the site index (i.e., the height of the dominant trees of a specific tree species at age 50, see Table 3). The better the site index of a tree species, the earlier the tree species reaches its yield-optimal regeneration point. An increase by four productivity classes for spruce results in a reduction of the optimal rotation period by approximately 20 years (BACHMANN 1990). Accordingly, the rotation period on mediocre good sites (site index 22 for spruce) is shorter by 20 years. On medium sites (site index 14 for spruce), the rotation period is longer by 20 years than on mediocre sites (site index 18 for spruce) (Table 4). On poor sites (site index below 14 for spruce), timber production in the lower elevations is usually not very economical. Thus, these site classes were not considered in the model. Because of their similar development and rotation period, the tree species spruce and fir, larch and pine, as well as ash and maple, were combined for the normal forest model.

Table 3a. Site index of the main tree species on similar sites.
Key: E+K: ELLENBERG and KLÖTZLI (1972) (K78): KELLER (1978) (S79): SCHÜTZ (1979) (S93): SCHMIDER (1993).

Site productivity	Forest community according to E+K (1972)	Spruce (K78)	Fir (K78)	Larch (K78)	Pine (K78)	Beech (K78)	(Oak) (S79)	Ash / Maple (S93)
Very good	7, 8, 11, 26, 29	24	20	27	24	20	22	26
Good	6, 9, 12, (18), (20)	22	18	24	22,5	18,5	20	24
Medium–good	1, 10, 13, 17, (19)	20	16	21	21	17	18	22
Medium	2, 14, 15	18	14	18	19	15,5	(14)	(20)
Poor	16, 65	8–12	4–8	6–12	8–12	8–12	6–10	6–12

Table 3b. Site index of the main tree species on similar sites in higher elevations.

Site productivity	Forest community according to E+K (1972)	Spruce (K78)	Fir (K78)	Larch (K78)	Pine (K78)	Beech (K78)
Good	18, 20	22	18	24	22,5	18,5
Medium–good	19	20	16	21	21	17
Medium	21, 49, 51	18	14	18,5	19	15,5
Mediocre–medium	50, 52	16	11	16	17	14
Mediocre	55, 57, 58	14	9	13	15	12,5
Poor	59, 67	6–10	2–6	2–10	6–10	–

The specified rotation periods are based on a mean stand development and medium high thinning. Today, **tending and thinning** the young growth stands early and severely is common practice. For these practices, shorter rotation periods should be expected. This fact was accounted for by using ten year shorter rotation periods for the calculations in one of the three model variants (see also Table 5).

Table 4. Optimally productive rotation period of the most common tree species depending on the site quality (according to BACHMANN 1990).

Site productivity	Spruce	Fir	Larch	Pine	Beech	Oak	Ash/Maple	Other broadleaves
Very good	110	120	120	130	130	150	80	60
Good	120	130	130	140	140	160	90	70
Medium–good	130	140	140	150	150	170	100	80
Medium	140	150	150	160	160	180	110	90
Mediocre–medium	150	160	160	170	170	190	120	100
Mediocre	160	170	170	180	180	200	130	110

Table 5. Variants of normal forest model for the calculation of the sustainable forest regeneration. Key: TSC: Tree species composition. PNV: Potential natural vegetation.

Model variant	Tree species composition (TSC)	Rotation periods
Current TSC	Current TSC in % of the basal area.	Optimally productive due to the customary thinning concept of the past.
Potential TSC, rich in broadleaf trees	TSC adapted to that site according to PNV, broadleaf rich variant (optimal proportion of broadleaves).	Longer by 20 years as a concession to nature conservation and the long customary regeneration periods taken into account.
Potential TSC, rich in conifers	TSC adapted to that site according to PNV, conifer rich variant (minimal proportion of conifers).	Shorter by 10 years due to current intensive thinning practice.

The **tree species composition today** is the result of site-specific factors, economical considerations, natural disturbances, and historical development. The tree species composition was calculated based on the NFI data. Since mixed stands grow on nearly half of all the assessed forest areas in the lower elevations, the proportion of the individual tree species was not calculated directly from the forest area. It was calculated on what proportion each tree species rep resented out of the entire collection of the trees that were measured. Relevant for the calculation of the proportion is, here, neither the number of stems nor the volume, but rather the basal area. The basal area is approximately proportional to the crown cover area and thus a suitable measure for the area proportion of tree species in mixed stands.

The long term **recommended tree species' composition** depends primarily on site factors and on silvicultural goals. In particular, the ecological stability of the site must be warranted. Detailed information for this is given with explanations for the description of forest communities and the site maps. An example of this is SCHMIDER *et al.* (1993) for the canton Zurich.

The calculation of the **potential tree species composition** TSC was conducted in accordance with those from OBERHOLZER (1993) for the canton Zurich. Based on a complete map of the forest communities Oberholzer calculated the potential natural tree species distribution by first assigning each forest community the proportion of tree species that was naturally expected (e.g., 60% beech for the Pulmonario-Fagetum typicum). In a second step, this was multiplied by the area of the corresponding forest community (canton Zurich: 0.6 x 1,590 ha = 954 ha). Finally, all forest communities were totalled (canton Zurich: 27,300 hectares of beech in a forest area of 49,600 hectares, i.e., 55% proportion of beech in the natural forest).

Oberholzer also conducted similar model calculations for the managed forest. Here, the basis for determining the proportion of tree species was the cantonwide description of forest communities, ecological recommendations with respect to the proportion of broadleaf trees, and economical considerations.

In the NFI the potential tree species composition was calculated in a similar manner. However, a complete map of the forest communities could not be used, since such a map was not available in many cantons of Switzerland. Thus, the distribution of forest communities over the forest area was taken from the model of potential natural vegetation (PNV) developped by BRZEZIECKI *et al.* (1993). On the basis of important site factors, the PNV-model calculates the probability that a certain forest community described by ELLENBERG&KLÖTZLI (1972) occurs at the investigated points (see Chapter 3.1).

In order to show how different tree species' compositions and different rotation periods influence the sustainable regeneration area, two model variants with the potential tree species composition and different rotation periods were calculated (Table 5) apart from the model variant, which was based on the true tree species composition.

The **model variant** with potentially high broadleaf proportion was based on the variant "recommended broadleaf proportion," and the model variant with high coniferous (potential) compositions was based on the variant "minimum broadleaf proportion" according to OBERHOLZER (1993). In contrast to Oberholzer's study, the separation into forest communities or into sub-communities did not make any sense in the NFI, because of the uncertainty of the model calculations. For example, the success rate for the forest communities with the highest probability was only 46% (Breziezcki *et al.*, 1993). The area proportion was, therefore, calculated for each phytosociological unit or subunit. These calculations amounted in the lower elevations of Switzerland to a proportion of 57% for the fastidious beech forest (Eu-Fagion). Since larger differences exist between the different communities of this type, with respect to the natural tree species composition, the most common lowland forest communities (Galio odorati-Fagetum luzuletosum, Galio odorati-Fagetum typicum, Milio-Fagetum and Cardamino-Fagetum typicum) were studied seperately. Only the forest communities Pulmonario-Fagetum typicum, Pulmonario-Fagetum melittetosum and Aro-Fagetum were combined.

Forest communities with moderate to poor yield, on which hardly any timber was used, were not compared with the normal forest model. These forest communities included, for example, mixed oak forests in the northern Alps, all pine forest communities, and rare forest communities (e.g., Salicetum albae or Carici elongatae-Alnetum glutinosae Forests on steep slopes, which for the most part have a protection function, e.g., the Cardamino-Fagetum tilietosum). For this reason, the Taxo-Fagetum were not considered. Other lowland forests today are used either primarily for timber production or timber production is not significantly hindered by other interests (e.g., recreation). The total area of the so-defined production forest is approximately 428,000 hectares (Table 6). This corresponds to a 92% proportion of the uniform high forest or 74% of the accessible forest in the lower elevations.

For these forest areas the sustainable regeneration area was calculated for each of the sites and tree species' groups seperately, with rotation periods that were similar to the optimal rotation periods given in Table 4. The determination of the rotation period for individual tree species on certain sites or for certain forest communities was carried out with the help of the corresponding site class according to KELLER (1978). These are based on the tree height measurements or estimations from phytosociological-productivity studies (e.g., BRAUN-BLANQUET *et al.* 1954; ETTER 1947; ETTER 1949; MOOR 1952; TREPP 1947), or from forest yield experiments plots (KELLER 1978). Missing values in Table 3 were complemented with values from SCHÜTZ (1979), LEIBUNDGUT (1983) and SCHMIDER (1993).

The calculation of the sustainable regeneration area is presented in four tables. In Table 7, the desired proportion of tree species per site unit (forest community or (sub) unit) is listed. Table 8 presents the forest area per tree species (group) for each site unit. They are calculated by multiplying the area per forest community with the corresponding proportion of tree species. Table 9 contains the rotation period per tree species (group) and per site unit. Table 10 shows the calculations for the sustainable regeneration area by dividing the forest area per tree species (group) and site unit from Table 8 by the mean rotation period of the corresponding table cell from Table 9. The exact procedure is illustrated using the example of the model variant 2 with high proportions of broadleaf in the tree species composition in the Jura region. In order to simplify the calculation of the area proportion per tree species, it was assumed that the tree species did not occur individually, but occurred at least mixed in clumps or groups (i.e., they occur on small-scale pure stands).

Table 6. Forest area per vegetation unit. Reference unit: Potentially managed uniform high forest in lower elevations (74.1% of the accessible forest without shrub forest).
Key: E+K: Ellenberg and Klötzli (1972)

Vegetation unit	E+K No.	Jura 1000 ha	Plateau 1000 ha	Pre-Alps 1000 ha	Alps 1000 ha	Southern Alps 1000 ha	Switzerland 1000 ha
Deer grass-Beech forest	1–4	3.3	33.8	7.9	1.8	8.5	55.3
Woodruff-Beech forest	6	1.7	37.6	1.5	1.1	0	41.9
Woodruff-Beech forest	7	19.9	17.2	1.1	1.4	0	39.6
Millet gras-Beech forest	8	2.7	52.5	12.5	1.4	0	69.1
Lungwort- Beech forest/ Arum-Mixed beech forest	9–11	32.3	24.4	4.3	2.7	0	63.7
Toothwort-Beech forest	12	28.0	8.7	3.8	3.5	0	44.0
Carex-Beech forest	14 / 15	0.4	0.4	0.7	1.5	0	3.0
Fir-Beech forest	18–20	14.3	5.8	20.5	3.6	0	44.2
Lime-Sycamore maple forest	22–25	0.0	0.0	0.4	0.7	0	1.1
Alder-Ash forest	26–32	2.2	9.5	1.7	0.4	0	13.8
Oak-Hornbeam forest	33–36	3.1	3.5	0.0	0.2	7.2	14.0
Spruce-Fir forest	46–52	0.3	0.5	7.7	18.1	8.7	35.3
Bilberry-Spruce forest	54–60	0.0	0.0	0.0	2.0	1.6	3.6
Total		108.1	193.9	62.1	38.3	26.0	428.4
Uniform high forest		116.4	197.2	67.4	58.4	27.5	466.9
Accessible forest without shrub forest		134.8	219.8	81.2	76.6	65.5	577.9

Table 7. Tree species proportion per vegetation unit.
Reference unit: Potentially managed uniform high forests in the lower elevations of the region Jura.
Model variant: Potential tree species composition, broadleaf rich variant with longer rotation periods.

		Area	Tree species in % of the basal area					
Vegetation unit	E+K No.	ha	Spruce/Fir	Pine/ Larch	Beech	Ash/ maple	Oak	Other broadleaf
Deer grass-Beech forest	1–4	3316	0	20	40	0	20	20
Woodruff-Beech forest	6	1696	10	15	35	10	20	10
Woodruff-Beech forest	7	19857	20	10	35	15	10	10
Millet grass-Beech forest	8	2700	40	0	35	10	5	10
Lungwort- Beech forest/ Arum-Mixed beech forest	9–11	32304	10	15	35	20	10	10
Toothwort-Beech forest	12	27975	10	15	35	20	0	20
Carex-Beech forest	14 / 15	413	0	20	35	20	15	10
Fir-Beech forest	18–20	14274	60	0	30	5	0	5
Lime-Sycamore maple forest	22–25	0	0	0	0	60	0	40
Alder-Ash forest	26–32	2166	0	0	0	70	10	20
Oak-Hornbeam forest	33–36	3100	0	10	0	10	50	30
Spruce-Fir forest	46–52	333	90	0	5	4	0	1
Bilberry-Spruce forest	54–60	0	98	0	0	1	0	1
Total		108134						

Table 8. Forest area per tree species and per vegetation unit.
Reference unit: Potentially managed uniform high forests in the lower elevations of the region Jura.
Model variant: Potential tree species composition, broadleaf rich variant with longer rotation periods.
Key: TSC = Tree species composition

		Area	Forest area per tree species in hectare					
Vegetation unit	E+K No.	ha	Spruce/Fir	Pine/ Larch	Beech	Ash/ maple	Oak	Other broadleaf
Deer grass-Beech forest	1–4	3316	0	663	1326	0	663	663
Woodruff-Beech forest	6	1696	170	254	594	170	339	170
Woodruff-Beech forest	7	19857	3971	1986	6950	2979	1986	1986
Millet grass-Beech forest	8	2700	1080	0	945	270	135	270
Lungwort- Beech forest/ Arum-Mixed beech forest	9–11	32304	3230	4846	11306	6461	3230	3230
Toothwort-Beech forest	12	27975	2798	4196	9791	5595	0	5595
Carex-Beech forest	14 / 15	413	0	83	145	83	62	41
Fir-Beech forest	18–20	14274	8564	0	4282	714	0	714
Lime-Sycamore maple forest	22–25	0	0	0	0	0	0	0
Alder-Ash forest	26–32	2166	0	0	0	1516	217	433
Oak-Hornbeam forest	33–36	3100	0	310	0	310	1550	930
Spruce-Fir forest	46–52	333	300	0	17	13	0	3
Bilberry-Spruce forest	54–60	0	0	0	0	0	0	0
Total		108134	20113	12338	35356	18110	8182,1	14035
Recommended TSC (%)			18.6%	11.4%	32.7%	16.7%	7.6%	13.0%
Current TSC (%)			37.5%	7.0%	36.9%	9.0%	4.8%	4.8%

Table 9. Rotation period per tree species and per vegetation unit.
Reference unit: Potentially managed uniform high forests in the lower elevations of the region Jura.
Model variant: Potential tree species composition, broadleaf rich variant with longer rotation periods.

		Area	Rotation period per tree species in years					
Vegetation unit	E+K No.	ha	Spruce/Fir	Pine/ Larch	Beech	Ash/ maple	Oak	Other broadleaf
Deer grass-Beech forest	1–4	3316	140	160	160	100	180	90
Woodruff-Beech forest	6	1696	140	160	160	100	180	90
Woodruff-Beech forest	7	19857	130	150	150	90	170	80
Millet grass-Beech forest	8	2700	130	150	150	90	170	80
Lungwort- Beech forest/ Arum-Mixed beech forest	9–11	32304	130	150	150	90	170	80
Toothwort-Beech forest	12	27975	140	160	160	100	180	90
Carex-Beech forest	14 / 15	413	150	170	170	110	190	100
Fir-Beech forest	18–20	14274	140	160	160	100	180	90
Lime-Sycamore maple forest	22–25	0	150	170	170	110	190	100
Ash-Ash forest	26–32	2166	130	150	150	90	170	80
Oak-Hornbeam forest	33–36	3100	150	170	170	110	190	100
Spruce-Fir forest	46–52	333	160	180	180	130	200	110
Bilberry-Spruce forest	54–60	0	180	200	–	150	–	140

Table 10. Sustainable regeneration area per tree species and per vegetation unit.
Reference unit: Potentially managed uniform high forests in the lower elevations of the region Jura.
Model variant: Potential tree species composition, broadleaf rich variant with longer rotation periods.

Vegetation unit	E+K No.	Area ha	Regeneration area per tree species in hectare Spruce/Fir	Pine/ Larch	Beech	Ash/ maple	Oak	Other broadleaf	Total
Deer grass-Beech forest	1–4	3316	0	4	8	0	4	7	23
Woodruff-Beech forest	6	1696	1	2	4	2	2	2	12
Woodruff-Beech forest	7	19857	31	13	46	33	12	25	160
Millet grass-Beech forest	8	2700	8	0	6	3	1	3	22
Lungwort- Beech forest/ Arum-Mixed beech forest	9–11	32304	25	32	75	72	19	40	264
Toothwort-Beech forest	12	27975	20	26	61	56	0	62	226
Carex-Beech forest	14 / 15	413	0	0	1	1	0	0	3
Fir-Beech forest	18–20	14274	61	0	27	7	0	8	103
Lime-Sycamore maple forest	22–25	0	0	0	0	0	0	0	0
Ash-Ash forest	26–32	2166	0	0	0	17	1	5	24
Oak-Hornbeam forest	33–36	3100	0	2	0	3	8	9	22
Spruce-Fir forest	46–52	333	2	0	0	0	0	0	2
Bilberry-Spruce forest	54–60	0	0	0	0	0	0	0	0
Total		108134	148	80	229	193	47	163	860

3.4.4 Sustainable Forest Regeneration in the Plenter High Forest

Plenter high forests are regenerated on an individual tree basis and not on a large scale in any given area. The control of the forest regeneration can, therefore, not be carried out using the area of regeneration, but must be accomplished by counting the number of new stems and their ingrowth into the lowest DBH class. An assessment of the natural regeneration situation is only possible with concrete ideas about the nominal state. The nominal state corresponds to a permanent structural equilibrium in which the cuttings equal the growth. Such an equilibrium, or corresponding stem number equilibrium, can be calculated with the help of the plenter forest model. The sustainability of forest regeneration is then controlled by comparing a measured and calculated minimal number of young trees of the DBH classes 2, 6, and 10, as well as by comparing effective and calculated minimal ingrowth.

The **fundamental idea** behind the plenter forest model is that for each diameter class a mean number of trees can be calculated which does not change over time. Only so many stems grow into a certain class during a time period as grow out of it, or die off due to cuttings or natural mortality. According to SCHÜTZ (1989), the following **equilibrium conditions** should be considered.

a) Constant number of stems per diameter class
For each diameter class, the ingrowth from the lower classes must compensate the loss through silvicultural operations or natural mortality and the outgrowth into the next higher class.

b) Constant timber volume
Constant number of stems per DBH class also implies a constant total timber volume. The timber volume is only constant when the sum of all the cuttings equals the growth.

c) Constant minimal necessary regeneration
The stand density (e.g., timber volume or basal area) must permit the minimal amount necessary for regeneration or the ingrowth necessary to ensure that the number of stems is kept constant.

As a **basis for the equilibrium calculation,** the proportion p (= passage) of outgrowing stems and the proportion e (=exploitation) of cut or naturally dead stems per DBH class are used.

These proportions can be calculated for certain site units with the help of a long-term time series obtained from the control method (SCHÜTZ 1975) or from yield study sites (SCHÜTZ 1981).

The **equilibrium conditions** can be expressed in an equation as follows:
Constant number of stems in the i^{th} DBH class : ingrowth = outgrowth + mortality/cuttings

$$n_i \cdot p_i = n_{i+1} \cdot p_{i+1} + n_{i+1} \cdot e_{i+1} = n_{i+1}\,(p_{i+1} + e_{i+1}) \tag{1}$$

a) Constant timber volume: total increment = total cuttings
b)

$$\sum_{i=1}^{i\,\max} n_i \cdot p_i \cdot \Delta T_i = \sum_{i=1}^{i\,\max} n_i \cdot e_i \cdot T_i \tag{2}$$

where

n_i = Number of stems in the i^{th} DBH class
p_i = Proportion of stems growing out of the i^{th} DBH class within a certain period of time
e_i = Proportion of cut stems or naturally died off stems in the i^{th} DBH class within a certain period of time
T_i = Tariff values (i.e., timber volume of a tree in the i^{th} DBH class)
ΔT_i =Tariff difference between the DBH class i and $i+ l$

The third equilibrium condition is not as easy to express in a mathematical equation. First, the stand volume should allow a sufficient regeneration; second, the conditions a) and b) must be fulfilled; and third, timber volume and increment must be within a realistic range. For this, SCHÜTZ (1997) used the assumed correlation between the ingrowth and the stand density expressed in the timber volume. Instead of the ingrowth, he used the number of stems from the lowest DBH class (8.0 to 11.9 cm DBH), which is a good indicator for regeneration.

The equilibrium position can be determined approximately with the help of a graph. The position is located at the point of intersection of the trend line of the observed values for the number of stems and timber volume. A second line connects two temporary model states. The intersection point of the two lines corresponds, on the one hand, to a possible realistic state; on the other hand, it corresponds to a possible model state. With the help of the figure, it is also possible to approximate the timber volume equilibrium as well as the number of stems in the lowest measured DBH class (initial stem number), which is necessary to sustain the structure (Figure 1).

Starting with the initial number of stems n_i in the DBH class i, the number of stems n_{i+l} in the next higher DBH class $i + l$ can be calculated by rearranging Equation (1) as follows:

$$n_{i+1} = n_i \cdot \frac{p_i}{(p_{i+1} + e_{i+1})} \tag{3}$$

Using the Equation (2), the resulting stem number curve is checked to see if the results are plausible. If the timber volume does not equal the desired timber volume, or if the calculated model increment or model cuttings results in unrealistically high or low values, the initial stem number of the first DBH class, as a deciding input variable, should be adjusted.

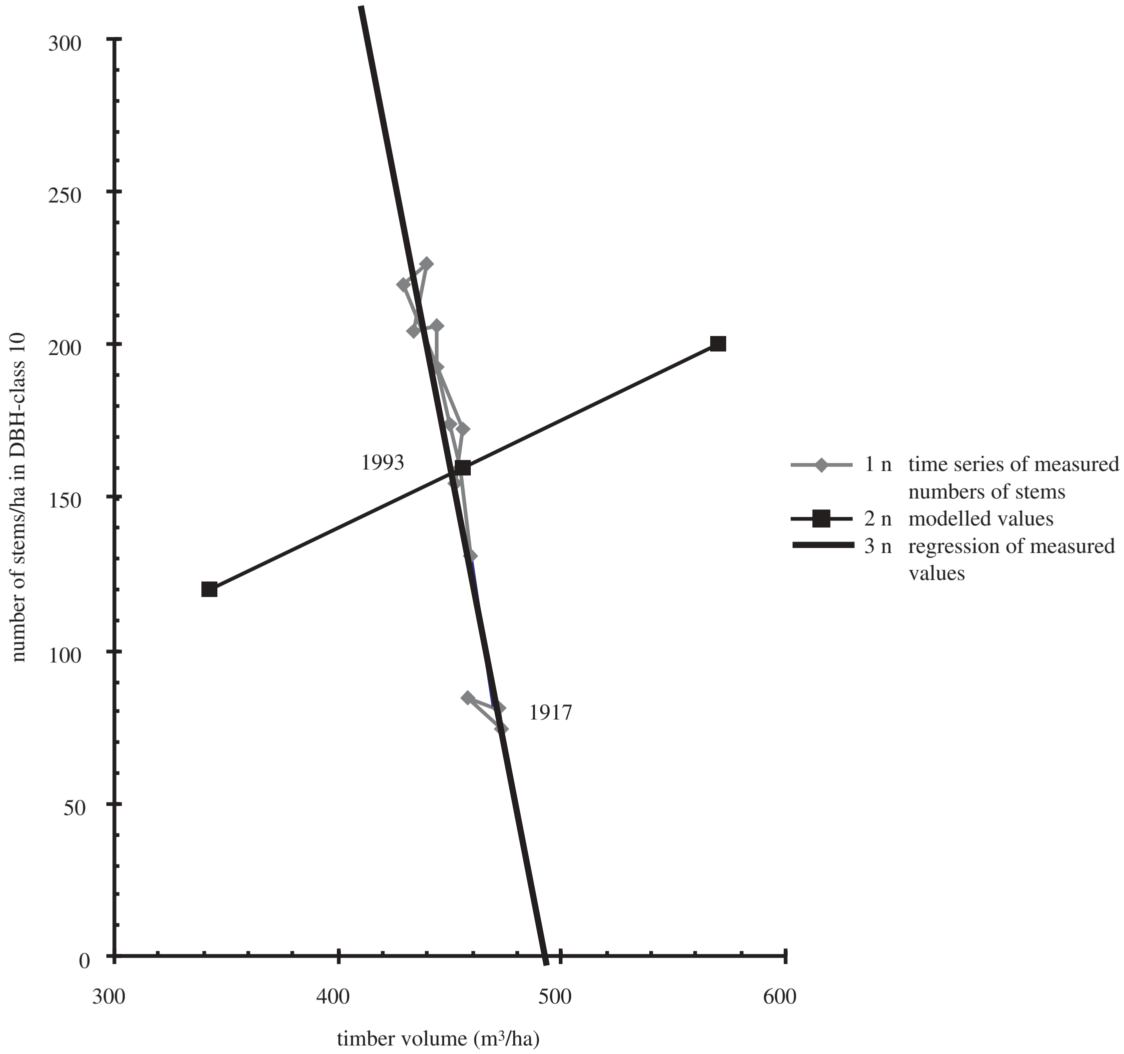

Figure 1. Determining the initial number of stems and the equilibrium timber volume. WSL experimental plot 01–15.1 (Toppwald). The Figure shows the development of the number of stems in the DBH class 10 (8–11 cm DBH) over time from 1917 to 1993 depending on the timber volume of the WSL experimental plot 01–015.1 in the Toppwald (Emmental). The stem number varies depending on the volume in a relatively wide range between approximately 70 and 230 stems per hectare. The two calculated model values that have an initial stem number of 120 and 200 stems per hectare form a line, which intersects the regression line of the observed values for a timber volume of 460 m^3 and has an initial stem number of 160 stems per hectare in the DBH class 10. This value (at the intersection) is taken as the initial number of stems for the calculation of the equilibrium curve of stem number in Table 12.

With the definite chosen initial stem number n_i in the first DBH class (in the NFI 12–15 cm) from the measured stands, the number of regeneration stems (stem number of the DBH classes 2, 6, and 10 cm) necessary to sustain the plenter equilibrium can be calculated by rearranging Equation (1) as follows:

$$n_{i-1} = n_i \cdot \frac{(p_i + e_i)}{p_{i-1}} \tag{4}$$

Stem number-equilibrium curves can be calculated for different sites (SCHÜTZ 1981) and different target diameters (SCHÜTZ 1975). Plenter high forests exist, according to the NFI data, in the montane zone of the regions Jura, Pre-alps, and Alps, as well as in the subalpine zones of the Alpine region. Since the ecological conditions and, consequently, the forest dynamics differ greatly in the two altitudinal zones, the sustainability of the forest regeneration was examined seperately for the montane and subalpine zones.

From the studies conducted by SCHÜTZ (1981), it is known that sites which are situated on limestone in the Jura region and located on molasse in the Pre-alps region remain in a very different equilibrium for the timber volume and stem number curve. Two equilibrium curves were, therefore, calculated as reference values for the plenter forest in the montane zone; specifically one curve for the region of Jura (Couvet) and one curve for the Emmental (Toppwald). For the supalpine zone, nearly all of the required parameters for increment and removal rates were completely known for one single forest in the Alps (Vals). For the purpose of comparison, two additional curves were calculated (one in the Pre-Alps (Sirgriswil), another in the central Alps (Gian d'Alva)), but are not shown.

The model parameters e_i and p_i for the calculation of the equilibrium curve in the Jura region originate from a study in Val-de-Travers (SCHÜTZ 1975). In order to be used for the NFI, the parameters had to be converted from DBH classes that had a width of 5 cm, which was normally used in the canton Neuenburg, to classes with a width of 4 cm. The parameters used for the calculation of the sustainable number of young stems originated from personal studies (DUC 2000) (Table 11).

Table 11. Equilibrium curve of stem number (n) for plenter forests with a north aspect in the Jura region (Val-de-Travers, according to SCHÜTZ 1975).

DBH class	DBH increment in mm per year	Passage p % per year	Exploitation e % per year	Number of stems n /ha	Volume v m^3	Increment i m^3/ha*year	Cuttings c m^3	WSL tariff m^3	DBH class
2	1.80	4.50	3.00	203.7					2
6	2.10	5.25	2.00	126.4					6
10	2.35	5.88	1.50	90.0	2.7	0.42	0.04	0.03	10
14	2.60	6.50	1.25	68.2	7.4	0.58	0.09	0.11	14
18	2.85	7.13	1.20	53.3	12.8	0.61	0.15	0.24	18
22	3.10	7.75	1.15	42.6	17.1	0.73	0.20	0.40	22
26	3.35	8.38	1.20	34.5	21.4	0.72	0.26	0.62	26
30	3.60	9.00	1.30	28.1	24.4	0.73	0.32	0.87	30
34	3.80	9.50	1.40	23.2	26.9	0.73	0.38	1.16	34
38	4.00	10.00	1.50	19.1	28.5	0.73	0.43	1.49	38
42	4.10	10.25	1.60	16.2	30.2	0.66	0.48	1.87	42
46	4.20	10.50	1.70	13.6	30.8	0.66	0.52	2.27	46
50	4.30	10.75	1.90	11.3	30.8	0.59	0.58	2.73	50
54	4.50	11.25	2.10	9.1	29.2	0.54	0.61	3.22	54
58	4.70	11.75	2.40	7.2	27.0	0.48	0.65	3.75	58
62	4.80	12.00	2.70	5.8	24.9	0.44	0.67	4.32	62
66	4.90	12.25	3.10	4.5	22.3	0.36	0.69	4.95	66
70	5.00	12.50	3.70	3.4	19.1	0.29	0.71	5.61	70
74	5.00	12.50	4.60	2.5	15.7	0.23	0.72	6.30	74
78	5.00	12.50	5.50	1.7	12.2	0.17	0.67	7.04	78
82	5.00	12.50	6.50	1.1	8.9	0.11	0.58	7.82	82
86	5.00	12.50	8.00	0.7	6.0	0.07	0.48	8.59	86
90	5.00	12.50	10.00	0.4	3.6	0.05	0.36	9.43	90

		∑>8 cm/ha	436.4	401.9	**9.90**	**9.60**
Ingrowth:		**∑>16 cm/ha**	**278.2**	**391.8**	8.90	9.46
DBH > 16.0	4.4 n/ha*J	∑ 16–32 cm	57.0%	19.3%	2.07	0.67
DBH > 12.0	5.3 n/ha*J	∑ 32–52 cm	25.1%	29.7%	2.71	1.87
DBH > 0.0	15.3 n/ha*J.	∑ > 52 cm	18.0%	51.0%	4.13	6.93

The equilibrium curve for the Emmental was calculated with the help of data from productivity study plots in the Toppwald of the WSL (ZINGG and DUC 1998). The sustainable stem number distribution for the regeneration is also the result of a personal study (DUC 1991) (Table 12).

Table 12. Equilibrium curve of stem number for plenter forests in Emmental (Toppwald, according to ZINGG and DUC 1998).

DBH class	DBH increment in mm per year	Passage p % per year	Exploitation e % per year	Number of stems n /ha	Volume v m^3	Increment i m3/ha*Jahr	Cuttings c m^3	WSL tariff m^3	DBH class
2	1.6	4.0	2.0	359.2					2
6	1.9	4.8	1.5	229.9					6
10	2.2	5.4	1.5	160.0	4.5	0.62	0.06	0.03	10
14	2.4	6.0	1.6	113.9	11.4	0.75	0.18	0.10	14
18	2.7	6.6	2.0	79.7	16.7	0.90	0.33	0.21	18
22	2.9	7.3	2.0	57.4	21.8	0.92	0.43	0.38	22
26	3.2	7.9	1.6	44.1	26.5	0.97	0.41	0.60	26
30	3.4	8.5	1.9	33.4	29.4	0.82	0.56	0.88	30
34	3.6	9.0	2.2	25.4	29.7	0.78	0.65	1.17	34
38	3.8	9.5	1.9	20.0	30.2	0.76	0.57	1.51	38
42	4.0	10.0	1.9	16.0	30.5	0.69	0.58	1.91	42
46	4.2	10.5	1.7	13.2	30.8	0.66	0.52	2.34	46
50	4.4	10.9	1.2	11.4	32.1	0.63	0.39	2.82	50
54	4.5	11.3	1.6	9.6	32.1	0.60	0.51	3.33	54
58	4.7	11.6	2.0	8.0	30.9	0.55	0.62	3.88	58
62	4.8	11.9	2.4	6.5	29.0	0.48	0.70	4.47	62
66	4.9	12.1	2.8	5.2	26.2	0.43	0.73	5.09	66
70	5.0	12.4	3.2	4.0	23.2	0.35	0.74	5.77	70
74	5.1	12.6	3.6	3.1	19.8	0.29	0.71	6.47	74
78	5.2	12.9	4.0	2.3	16.5	0.23	0.66	7.22	78
82	5.2	13.0	6.0	1.6	12.4	0.18	0.75	8.00	82
86	5.3	13.1	8.0	1.0	8.5	0.11	0.68	8.89	86
90	5.3	13.2	10.0	0.5	5.3	0.06	0.53	9.75	90
94	5.3	13.3	12.0	0.3	3.0	0.03	0.36	10.63	94
98	5.3	13.3	14.0	0.1	1.6	0.02	0.22	11.54	98

		∑> 8 cm/ha	616.6	472.2	**11.81**	**11.89**
Ingrowth :		**∑>16 cm/ha**	**333.9**	**456.3**	10.44	11.65
DBH > 16.0	6.8 n/ha* J	∑ 16–32 cm	64.3%	20.7%	3.61	1.72
DBH > 12.0	8.6 n/ha* J	∑ 32–52 cm	25.7%	33.6%	3.52	2.72
DBH > 0.0	21.6 n/ha*J	∑ > 52 cm	10.0%	45.7%	3.31	7.21

The parameter for the equilibrium curve in the subalpine zone originates from the work conducted by INDERMÜHLE (1978) and corresponds with his model variant B. Indermühle calculates the equilibrium curve only up to the DBH class 14 (.12–15 cm DBH). Based on the given parameters e_i and p_i, the sustainable number of trees for the DBH classes 10 and 6 were calculated, and for the DBH class 2 they were estimated based on approximate parameter values (Table 13).

Apart from the number of trees, the **ingrowth over the calliper threshold** was also used for controlling the sustainable forest regeneration. Empirical values for the minimal necessary ingrowth were known. For example, SCHAEFFER *et al.* (1930) already points out that the ingrowth over the calliper threshold of 17.5 cm DBH should be between 1.5 and 2.0 Vfm per hectare and per year. However, the empirical values depend on the calliper threshold, the class width, and the site. It is, therefore, much more precise to calculate the sustainable ingrowth from the stem number equilibrium curve. The ingrowth is equivalent to the ingrowth in the lowest calliper DBH class (i.e., in the NFI the outgrowth of plants from the DBH class 10 cm or the ingrowth in the DBH class 14 cm). The sustainable ingrowth EW_1 can be calculated as follows:

$$EW_1 = n_0 \cdot p_0 \tag{5}$$

In the plenter forest of the region Jura, the yearly sustainable ingrowth into DBH class of 14 cm (12–15 cm) amounts to 5.3 trees/ha; in the region of the Emmentale it amounts to 8.6 trees /ha; and in those regions in the subalpine zone it amounts to 3.3 trees/ha. Projected to the mean inventory interval of 10.1 years, this results in a sustainable ingrowth of approximately 50 to 90 stems in the montane zone and approximately 35 stems in the subalpine zone.

Table 13. Equilibrium curve of stem number for plenter forests of the subalpine zone, northern intermediate Alps (according to INDERMÜHLE 1978).

DBH class	DBH increment in mm per year	Passage p % per year	Exploitation e % per year	Number of stems n /ha	Volume v $m^{3.}$	Increment i m^3/ha*year	Cuttings c m^3	WSL tariff $m^{3.}$	DBH class
2	0.30	0.8	3.0	1086.8					2
6	0.45	1.1	1.0	383.6					6
10	0.65	1.6	0.5	203.1	6.1	0.26	0.03	0.03	10
14	0.80	2.0	0.5	132.0	14.4	0.24	0.07	0.11	14
18	1.00	2.5	0.5	88.0	17.6	0.31	0.09	0.20	18
22	1.15	2.9	0.5	65.2	22.2	0.30	0.11	0.34	22
26	1.35	3.4	0.5	48.4	24.2	0.31	0.12	0.50	26
30	1.50	3.8	0.6	43.1	29.7	0.37	0.18	0.69	30
34	1.65	4.1	0.6	34.2	31.5	0.39	0.19	0.92	34
38	1.70	4.3	0.7	28.5	34.2	0.41	0.24	1.20	38
42	1.65	4.1	0.8	24.6	37.9	0.44	0.30	1.54	42
46	1.60	4.0	0.9	20.7	40.8	0.37	0.37	1.97	46
50	1.55	3.9	1.1	20.4	49.3	0.36	0.54	2.42	50
54	1.52	3.8	1.3	15.5	44.5	0.28	0.58	2.87	54
58	1.50	3.8	1.5	11.2	37.6	0.21	0.56	3.35	58
62	1.48	3.7	2.5	6.8	26.2	0.13	0.65	3.86	62
66	1.45	3.6	10.0	1.8	8.1	0.04	0.81	4.39	66
70	1.40	3.5	20.0	0.3	1.4	0.01	0.28	4.95	70
			∑>8 cm/ha	743.7	425.5	**4.43**	**5.13**		
Ingrowth			**∑>16 cm/ha**	**408.6**	**405.0**	3.93	5.02		
DBH > 16.0	2.6	n/ha* J	∑ 16–32 cm	59.9%	23.1%	1.29	0.50		
DBH > 12.0	3.3	n/ha* J	∑ 32–52 cm	31.4%	47.8%	1.97	1.64		
DBH >0.0	40.8	n/ha*J	∑ > 52 cm	8.7%	29.1%	0.67	2.89		

3.4.5 Sustainable Forest Regeneration in Other Types of Forests and in the Higher Elevations

The sustainability models described above do not cover the full range of layered high forest types from the lower and higher elevations. In particular, it does not provide information about irregular forests situated in the lower elevations or about the uniform and irregular forests located in the higher elevations. Since the evaluation of the sustainability is conducted for regions or the entire country of Switzerland, the sustainable regeneration area must be calculated for these strata as well.

Because the two models discussed are not well adapted for these possibilities, a highly reduced model approach was chosen in which the rotation period was determined by an expert. It was assumed that irregular high forests in the lower elevations were regenerated over the entire area with a mean rotation period of approximately 120 years. This corresponds to the mean calculated rotation period in the lower elevations of the regions Jura, Swiss Plateau, and Pre-alps. In the uniform and irregular high forest of the higher elevations, a more continuous regeneration of the forest on smaller patches should be aimed for in the future (OTT *et al.* 1997). This should result in a groupwise, layered forest structure of tree clusters, the so-called "Rotten". An actual rotation period cannot, therefore, be determined. Due to the current one-layered structure of many mountain forests, the conversion has to be performed in gaps with minimal dimensions. This provides an opportunity to use an area-based model. As a calculatory rotation period, 200 years was set in accordance with OTT (1973).

3.4.6 Discussion of the Employed Models

Normal Forest Model

The normal forest model is suitable only for the planning and controlling of clear-cut high forests. This is not always the case despite the limitation to the potentially managed, uniform high forests in the lower elevations since, for example, uniform high forests can be converted into multi-layered forests. Employing the normal forest model assumes that the intention of the forest owner, with respect to future forest management, is known. However, this intention was not questioned during the enquiry at the forest service.

The model employed by the NFI differentiates between tree species and site units. It is based for the most part on the assumption that the potential vegetation can correctly be determined using the PNV-model. This model is, however, not very reliable with respect to the forest communities. Furthermore, the scientific research to determine the site class per tree species and forest community (e.g., for the tree species oak and ash/maple), as well as the optimal time of regeneration (e.g., for the tree species pine and maple, and on medium and good sites for spruce, larch, and beech), is missing. Finally, scientific research is also missing that could determine the proportion of minimal and optimal broadleaf species, which is used as a basis for the variant with high broadleaf and high coniferous proportions.

It is therefore clear that the calculation for the sustainable regeneration area, with the help of the normal forest model, is only an approximation. The calculated values of approximately 62,000 ha in 10 years corresponds, at least relatively well, with the 64,000 ha that were calculated 25 years ago by OTT (1973) as the sustainable regeneration area in the clear-cut high forests. However, the analysis shows for the estimated stand age that this area was not close to being achieved in any of the decades. This in turn could mean that not enough forest is regenerated, or perhaps that the model is based on false assumptions or tries to achieve unrealistic goals. A prerequisite for a conclusive evaluation of the sustainable forest regeneration is, therefore, apart from the information about the forest structure today and the created regeneration area, knowledge about the future treatment of the forest. Of these three variables, future treatment is unknown and the forest structure as well as the created regeneration area can only be derived approximately.

- The **determination of the forest (structure) type** depends strongly on whether a stand is classified as a certain stage of development (stage of development young growth/thicket, pole wood, young, medium, or old timber) or not classified as such (stage of development mixed). Even though the inventory manual was not changed between the first and second NFI, the proportion of the plenter high forests was reduced by approximately half. An existing plenter structure could not be lost in such a short period of time, even if all silvicultural operations would have been completely abandoned. Thus, the decline had to be largely the result of how the instructors taught the material in the inventory manual. As a consequence, the inventory manual was applied in the field in a different manner as compared to ten years earlier. The definition of the forest type as a basis for separating regeneration forest areas based on individual trees and area is, therefore, uncertain.

- The **calculation of the regeneration area** that has been newly created in the last ten years represents not only a problem for the NFI, but as a general problem as soon as smaller areas are regenerated or regeneration is conducted under shelter. In such cases it is often not clear whether an area is still in the process of being regenerated (regeneration under shelterwood), or when it can be assumed to be regenerated and can thus be called young growth. The effective regeneration area can be calculated in different ways. None of the possible calculations are precise, but they all have approximately the same results. Nonetheless, a certain amount of uncertainty with respect to the size of the effective regeneration area remains.
- The enquiry at the forest service did not provide any information about the future treatment of the forests. The assumption that today's layered stand will still be treated with clear-cuts in the future is questionable, given the situation of today's forestry practices. Due to economical pressures, forest enterprises are starting to manage their forests according to the plenter principles and slowly convert their forests into plenter high forests. For such enterprises, the success of the regeneration efforts cannot be measured by the cleared areas per period, but on the stem number distribution in the DBH class and on the ingrowth (see Chapter 3.4.4).

For all of these reasons, the normal forest model in the NFI is limited in its reliability, especially in the higher elevations. The model is relatively reliable in the lower elevations of the Jura, Swiss Plateau, and Pre-Alps' regions.

Plenter Forest Model

The plenter forest model according to SCHÜTZ (1975) represents an interesting method by which to calculate the stem number equilibrium curve of plenter forests. For this reason it has already been applied several times in calculating (INDERMÜHLE 1978; SCHÜTZ 1981; DUC 1991;) or in evaluating the equilibrium state of plenter forests (ZINGG and DUC 1998), as well as in evaluating their structure and growth changes (BACHOFEN 1996). However, the model in its current format still has some weaknesses. The following questions in particular must be clarified:

- SCHÜTZ (1975) proves that the stand density, expressed by the cumulative basal area of the thickest trees, has an influence on the diameter increment of the trees in the DBH classes 45 to 70 cm. However, according to BACHOFEN (1996), this relationship does not exist on the long-term WSL study areas in Rougemont (canton Vaud). If such a relationship between stand density and DBH increments exists, it must be considered in the model. The stem number curve in this case can only be calculated by starting with the number of stems in the largest DBH class. This results in some practical problems: If the number of stems in the largest DBH class is set to one, then this usually results in a model timber volume and increment that is too large. For this reason, the stem number in the lowest DBH class was used as a starting point for the calculations of the stem number curve. It is also true that the stem count of lowest class could not be exactly determined, but could be approximated with the values determined up to that point (see Chapter 3.4.1).
- Even if the relationship between timber volume and number of regeneration stems seems plausible, this cannot be used as described to determine the number of stems in the DBH class 10 STZ_{10}. We believe that there exists, in principle, a relationship between timber volume and the number of regeneration stems. Nonetheless, the change in the timber volume has a time-delayed effect on the number of stem STZ_{10}. The analysis of several WSL study sites shows that the relationship between timber volume and STZ_{10} is relatively low (ZINGG and DUC 1998), and that some individual values strongly influence the regression line.
- There exists a linear relationship between the stem number in the DBH class 10 STZ_{10}, which is used as a starting point for the calculation and the equilibrium timber volume. The reason is that for the calculation of the equilibrium curve, the same estimated, constant relative values pi and ei are used. An increased number of stems STZ_{10} results in a correspondingly higher equilibrium timber volume. In reality this should be reversed; however, at

least for homogeneous site conditions, the larger the timber volume, the smaller the number of stems STZ_{10}. Thus, the model misses a negative feedback between the timber volume and the number of regeneration stems.

- The decrease of the stem number in the lowest DBH classes (0.1–3.9 cm DBH) is probably not caused by thinning (DUC 2000), but by natural mortality. There is, however, no information available about the amount of natural mortality in regularly managed forests with layered structures. Therefore, the mortality rate e_i had to be determined ocularly while considering the cutting rate. In the future, more knowledge is necessary about the natural mortality of the regeneration in managed forest.
- The main tree species of plenter forests (fir, spruce, and beech) have different rates per DBH class for the increments and cuttings in the regeneration (DUC 2000) as well as in the measured stands. In addition, the tariff for the tree species is different, which affects the timber calculation of the volume and increments. The model presented here did not take into consideration the different proportions of tree species and their effect on the equilibrium curve.

For all of these reasons, equilibrium curves known today should be seen as being temporary. The goal of the research in this field should be to establish equilibrium models for all important site units.

3.4.7 Literature

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