

## 3 Derived Variables and Models

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### 3.1 Site

Site conditions influence the processes and interactions in the ecosystems, and therewith the state and the changes of the forest. Therefore, the second NFI collected not only data about the forest, but about the site (see Chapter 2.3 and appendix STIERLIN *et al.* 1994) and gathered site information from other sources as well (see Chapter 2.7). These site factors allowed the arrangement of the sample plots into classes with ecologically similar conditions and, thereby, the assessment of other influences within these classes. Furthermore, site factors are the foundation for the study of cause and effect relationships between the environment and the forest.

Depending on the source of the data, the site factors were available for the sample plots of the 0.5 km, 1.0 km, or the 1.4 km grid.

Several different **individual factors** were collected or determined. These were usually secondary factors (DUC and STROBEL 1999) or “proxies”, which do not directly affect the trees, but influence the directly acting (primary) factors. In addition, certain **factor combinations** were determined.

#### 3.1.1 Individual Factors

Table 1 gives an overview of the employed individual factors, the grid in which they are available, the sources which they were derived from, and the primary factors which they influence. All factors are assumed to be consistent throughout time.

##### 3.1.1.1 Primary Factors

**Rockfall, snow movement, landslides, erosion and forest fires** (mechanical factors according to WALTER, 1979) were assessed as primary factors. Since these factors could not directly be assessed on the ground and no other data were available with complete coverage, they were assessed based on marks on the trees (e.g., sweep of the bole, tilted tree, damage) as well as on the ground (e.g., stretches without trees, wash outs/undercuts).

##### 3.1.1.2 Secondary Factors

###### Orographic Factors

**Elevation, relief, and exposition** were measured terrestrially and, if necessary, supplemented by the digital elevation model RIMINI (Chapter 2.7, BFS 1992), which has a 250 m resolution.

The **slope** was interpolated with the help of RIMINI for the entire 500 m grid. Due to the low resolution of RIMINI, the resulting estimate was relatively unrefined. This estimate is sufficient as an approximation for processes acting over larger distances, such as avalanches and water runoff. As an approximation for local factors that are influenced by the slope, the application of interpolated slope is problematic, since it smoothes out the relief. Because of this, the local slope of the sample plot was also measured in the field.

###### Edaphic Factors

Information about the soil factors: **soil depth, percentage of rocks, soil water capacity, water-logged soil, and nutrient-holding capacity of the soil**, originate from the digitized Soil Capability Map of Switzerland (Chapter 2.7, FREI *et al.* 1980). This map was produced by first dividing Switzerland into “physiographical units” based on aerial photographs, topographical and geological maps. In a second step, soil samples were taken in a subset of these physio-

graphical units and their properties were analyzed. This resulted in an empirical model, which was applied to the entire area. Due to the coarse resolution of the Soil Capability Map, only certain spatially detailed interpretations are possible. Merging the map information with the NFI grid nonetheless compensates possible position errors in simple summarizing analyses, such as determining the forest area with a certain soil property. From the geotechnical map (Chapter 2.7, GEO7 1990), details about the **geology** and the **acidity of the bedrock** were obtained.

The **pH-value of the topsoil**, which is used in the derivation of the potential natural forest vegetation (PNV, see below), was measured in the first NFI.

### Climatic Factors

The **average annual temperature** was interpolated using the data from the Swiss Meteorological Institute (SMI), (SMA, 1990, BRZEZIECKI *et al.* 1993). First, the measurements of the SMI stations were adjusted with the help of the empirical temperature-elevation relationship to the elevation independent temperature at sea level. Second, these adjusted values were interpolated onto the 500 m grid. The temperature at the actual elevation was predicted with the help of the digital terrain model RIMINI and the empirical temperature-elevation relationship. The **annual precipitation** was determined from digital precipitation maps.

Table 1. Individual factors and the source these factors originate from, and the priority they are used. RIMINI: digital elevation model (BFS 1992) (Chapter 2.7, External data sources) with a 250 meter resolution. SMA: long-term climatic average values (SMA 1901–1990).

Secondary factors	Grid	Source 1	Source 2	Source 3	Influenced primary factor
<b>Geographic</b>					
Region	0.5 km				Heat, water, nutrients
<b>Orographic</b>					
Elevation	0.5 km	Aerial photograph NFI2	Terrestrial NFI2	RIMINI	Heat, water, light
Relief	1.4 km	Terrestrial NFI2	Terrestrial NFI1	Derived from slope	Light, heat, water
Slope	0.5 km	Terrestrial NFI2	Aerial photograph NFI2	RIMINI	Water, nutrients, light, heat
Exposition	0.5 km	Terrestrial NFI2	RIMINI		Light, heat
<b>Edaphic</b>					
Soil depth	0.5 km	Soil capability map			Nutrients
Percentage of rocks	0.5 km	Soil capability map			Water, nutrients
Soil water capacity	0.5 km	Soil capability map			Water
Water permeability	0.5 km	Soil capability map			Water
Water-logged soil	0.5 km	Soil capability map			Water
Acidity of the bedrock	0.5 km	Geotechnical map			Nutrients
pH-value of the topsoil	1 km	Terrestrial NFI1			Nutrients
Geology	0.5 km	Geotechnical map			Nutrients, water
<b>Climatic</b>					
Average annual temperature	0.5 km	SMI stations	Interpolated using RIMINI		Heat, water, nutrients
Annual precipitation	0.5 km	Rainfall map			Water
<b>Primary factors</b>					
<b>Mechanical factors and fire</b>					
Rockfall	1; 1.4 km	Terrestrial NFI2	Terrestrial NFI1		
Snow movement	1; 1.4 km	Terrestrial NFI2	Terrestrial NFI1		
Landslides	1; 1.4 km	Terrestrial NFI2	Terrestrial NFI1		
Erosion	1; 1.4 km	Terrestrial NFI2	Terrestrial NFI1		Heat, nutrients, water
Fire	1;1.4 km	Terrestrial NFI2	Terrestrial NFI1		Light, nutrients

### Region

The data from the second NFI were analyzed according to different regions (Figure 1), which were the results of political, economical (**economic regions, production regions, and protective forest regions**, BRÄNDLI 1999) or ecological criteria (**growth regions** according to KELLER, 1978; 1979, **ecological regions** according to ELLENBERG and KLÖTZLI 1972). All regions are, to a certain degree, also proxies for edaphic factors like acidity, water permeability, and climatic factors, like the north-south temperature gradient and the continental climate in the heart of the Alps (e.g., Wallis).

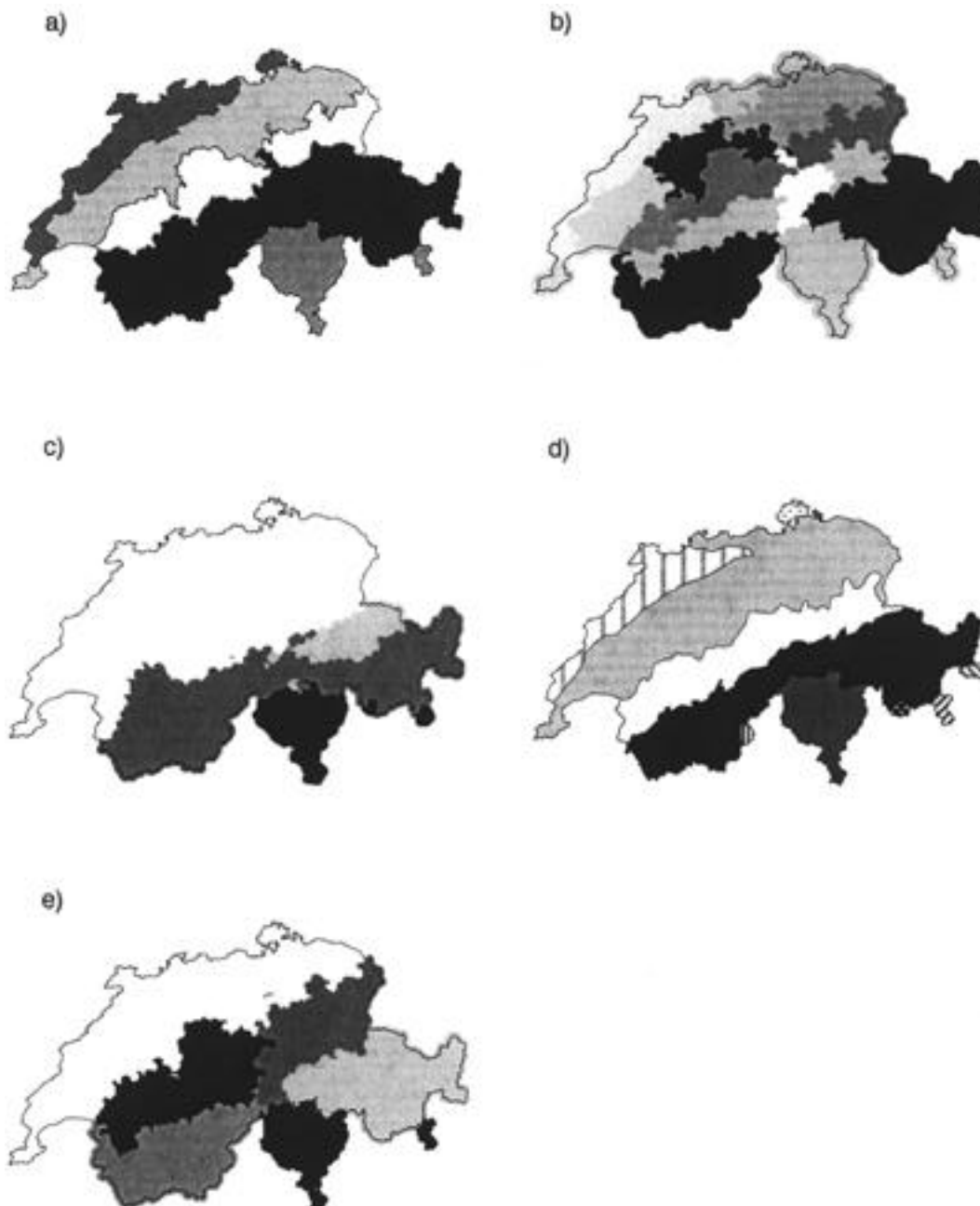


Figure 1. Dividing Switzerland by a) production regions b) economic regions c) growth regions (KELLER 1978; 1979), d) climatic zones (ELLENBERG and KLÖTZLI 1972) and e) protection forest regions.

### 3.1.2 Factor Combinations

The forest is not only influenced by individual environmental factors, but by several concurrent environmental factors as well. For a simple and ecologically meaningful summary of the sample plots in analyses, several factors were joined to one indicator – the “site property”. Relevant factors were selected and the relationships between them and a quantity describing the forest (e.g., species composition, site index) were derived (e.g., with a statistical procedure) (Figure 2).

Important bases for the derivation of the three indicators used in the second NFI were the phytosociological assessments, which were classified into 71 forest communities according to ELLENBERG and KLÖTZLI (1972). Additional data were taken from forest yield assessments.

The phytosociological assessments comprise, apart from phytosociological information, such secondary site factors as elevation, exposition, or slope. Further factors can be derived, if necessary, by means of interpolation from other sources of data.

These types of data allowed forest communities or site indexes (determined from phytosociological or forest yield data) to be classified into an ecological scheme that was defined by site factors. This scheme is called the ecogram. Since potentially not all relevant site factors were available, the analysis was conducted separately for all of the different regions (see above). This procedure covered other site factors which were not assessed, such as the different continentality of the climate in the North and Central Alps.

The following procedures used in the NFI (Figure 2) differ in the manner in which the forest communities are arranged in the ecological space, and in the indicators that were derived from the forest communities or directly from the site factors.

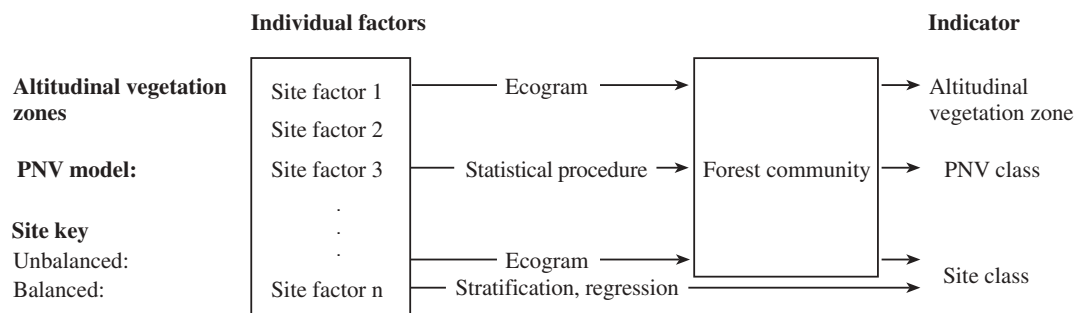


Figure 2. Principle of the indicators used in the NFI for the site properties. The models assign a certain combination of individual factors to one indicator. For the altitudinal vegetation model by BRÄNDLI and KELLER (1985) and for the unbalanced site key by KELLER (1978; 1979) this is carried out by classifying the forest community into an ecogram. This makes it possible for the unbalanced site key to link the site class within the forest communities with the site conditions. The balance site key by KELLER (1978; 1979) estimates indirectly the relationship between the site factors and site class using a height dependent regression with different classes of site factors. The PNV model (BRZEZIECKI *et al.* 1993; KIENAST *et al.* 1994) determines the relationship between the forest community and the site factors by a statistical procedure.

#### 3.1.2.1 Total Increment

The model by KELLER (1978; 1979) in its original form (“unbalanced key”) estimated, with the help of the forest communities, the site quality (site index) from the site factors in Table 2. The site index was either presented as the maximum of the Total Mean Increment (TMI) since establishing the stand – called here “Total Increment” (TI) – or as the mean height of the 100 thickest trees per hectare of a 50 year old stand (productivity index of stand). TI was measured in kilogram dry weight per year and hectare.

Table 2. Secondary site factors in the site class model by KELLER (1978; 1979).

Secondary site factor	Class/unit
Region	Jura + Plateau + Pre-Alps, Intermediate Alps, High Alps, Southern Alps
Relief and slope	Syncline, hill, hilltop, steep hill
Aspect	North, South
Acidity of the bedrock	Base-rich, base-deficient, extreme base-deficient
Geology	Lias limestone, Triassic (for the Southern Alps)
Elevation	Meters above sea level

The model used the stand characteristics “stand age”, “stand height”, and the “mean stem diameter” to assess the site index within a forest community. The stand characteristics were partially taken from the phytosociological assessments and partially from the forest yield research plots. Site index and site factors were linked together by the position of the forest community in the ecological scheme.

The forest communities by themselves, and the site index within the forest communities, depend on the elevation  $h$ . For this dependency, a model (Equation 1) was developed which took into account that growth is positively influenced by precipitation (which increases with elevation) and temperature (which decreases with elevation).

$$TI = k/(h - c) + m + p \cdot h \quad (1)$$

This model was fitted separately for each factor combination (region, acidity of the bedrock, geology, exposition, and type of relief – Table 3) to the site indexes, which were estimated by using the phytosociological and forest yield assessments. The resulting model, which was used in the second NFI, was a site index key that was adjusted for the elevation, called the “adjusted site index key”. The estimated parameters  $k$ ,  $c$ ,  $m$ , and  $p$  can be found in Table 4. The TI values calculated with Equation 1 are arranged in Table 5 in the site quality classes.

Table 3. Site class dependency on secondary site factors: factor combination according to KELLER (1978; 1979). No information, undetermined:

Region	Acidity	Geology	Expo- sition	Plain	Factor combination in relief type...			
					Base of hill	Middle hillside	Steep hill	Hilltop
Jura	Acidic	–	–	7	7	7		8
Plateau			North	7	7	7	7	8
Pre-Alps			South	7	8	8	8	8
	Alkaline	–	–	2	1	2		6
			North	2	1	2	3	6
			South	2	4	5	6	6
Intermediate Alps	Acidic	–	–	9	9	9		
			North	9	9	9	9	10
			South	9	10	10	10	10
High Alps	Acidic	–	–	11	11	11		
			North	11	11	11	11	12
			South	11	12	12	12	12
Southern Alps	Acidic	–	–	13	13	13		14
			North	13	13	13	13	14
			South	13	13	13	13	14
	Alkaline	Lias limestone	–	17		17		
			North	17	15	17	17	
			South	17		17		19
		Triassic	–	18		18		
			North	18		18	18	
			South	18		18	18	

Table 4. Parameter values for the elevation dependency of the total increment (Equation 1). (KELLER 1978; 1979). To each factor combination from Table 3, a combination of parameter values  $k$ ,  $c$ ,  $m$ , and  $p$  belongs.

Factor combination	$k$	$M$	$p$	$c$	Lower elevation limit (m)	Upper elevation limit (m)	TI maximum (kg/ha year)
1	2.0423E+06	5074.689	1.4886	1873.9	0	1600	4376.94
2	8.1723E+05	6859.791	-1.1286	1761.7	0	1600	6395.90
3	0.0672	6148.48	-3.8008	1600.001	0	1600	6148.48
4	3.9686E+16	2.4050E+10	14590.3106	1650100.1	118	1600	4856.83
5	1.8717E+07	9705.374	3.562	2815.001	0	1600	3402.26
6	7.4488E+14	1.2410E+09	2075.2869	600210.1	610	1600	848.88
7	1.1192E+06	5733.256	-0.3396	2018.5	0	1800	5178.80
8	6.2504E+08	7.3369E+04	6.561	9137.95	0	1800	4968.77
9	1.1581E+07	5341.356	3.6909	2984.6	0	2100	3281.18
10	2.4209E+15	2.2509E+09	2096.7442	1075560	0	2100	2250.99
11	5.0676E+15	3.0666E+09	1857.367	1652500	0	2300	2826.21
12	1.3026E+16	8.2738E+09	5264.7993	1574400.2	561	2300	2530.88
13	8.0530E+05	4830.524	-0.8411	2362.8	0	2100	4489.70
14	8.9986E+05	3291.198	0.1372	2351.4	0	2100	2908.51
15	6.1994E+06	9294.71	-0.1314	2484.4	0	1800	6799.36
16	5.1664E+05	5256.728	-0.0926	1901.5	0	1800	4985.03
17	3.1501E+05	4210.304	-0.4911	1894.7	0	1800	4044.05
18	3.0106E+04	3432.097	-0.4397	1811.4	0	1800	3415.48
19	1.9521E+04	2997.1	-0.6702	1810.9	0	1800	2986.32

Table 5. Classification of the site classes in the NFI.

Site quality	TI (kg/ha year)	Site height at age 50			
		Spruce	Fir	Larch	Beech
Poor	Up to 1500	8		6	8
Medium	1500–3000	15	9	14	13
Good	3000–4500	20	14	21	17
Very good	Over 4500	23	18	26	19

### 3.1.2.2 Altitudinal Vegetation Zones

This model related the site factors with the altitudinal vegetation zones. The basis of this model (BRÄNDLI and KELLER 1985) was the classification of the forest communities in an ecological scheme of elevation, exposition, acidity of the bedrock, and growth regions (Table 2).

Based on the literature (ELLENBERG and KLÖTZLI 1972; HESS *et al.* 1967; KUOCH 1954; KUOCH and AMIET 1970; LANDOLT 1983), the forest communities were then linked to the altitudinal vegetation zones (Figure 3). The delimitation of the forest area at the timber line was based on the work of BROCKMANN-JEROSCH (1919).

### 3.1.2.3 Potential Natural Forest Vegetation

The model for the potential natural forest vegetation (PNV) (BRZEZIECKI *et al.* 1993; KIENAST *et al.* 1994) was also based on numerous (7,500) phytosociological assessments that were classified into 71 forest communities according to ELLENBERG and KLÖTZLI (1972). This approach differed from the ones previously discussed. Here, a statistical method was used to determine the probability of the occurrence  $V_i$  of each individual plant community  $i$ , depending on several abiotic factors  $F_1, F_2, \dots, F_n$  (Table 6).

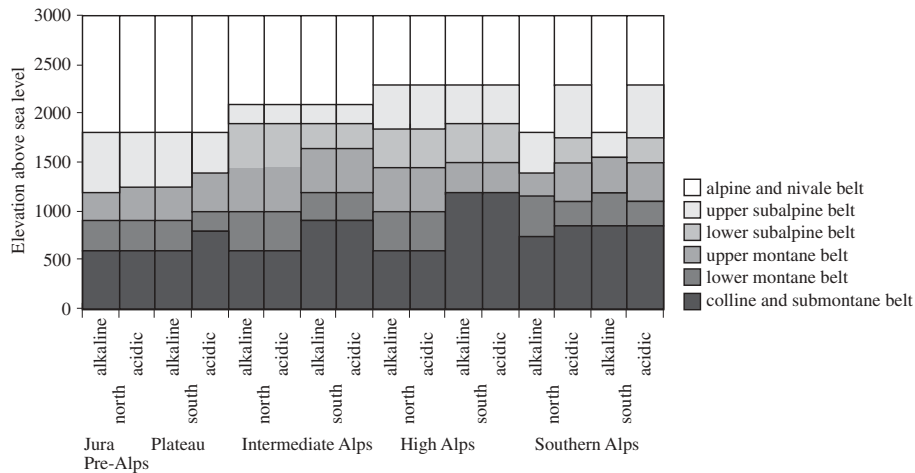


Figure 3. Altitudinal vegetation zones (BRÄNDLI and KELLER 1985).

**Procedure:** Figure 4 illustrates the procedure with a (non-realistic) example of two forest communities and two continuous factors (average annual temperature and sum of annual precipitation) as well as one discrete site factor (soil depth).

- Based on the phytosociological data and the factors at the corresponding sites, the frequency of occurrence for each forest community was assessed, depending on the value of the factors.
- These frequency distributions were fit to a normal distribution. The factors were hereby assumed to be independent. For discrete factors it was only ascertained whether the forest community occurred or not.
- For the factors, the resulting probability density functions  $P(F_1 = f_1, F_2 = f_2, \dots, F_n = f_n | V_i)$  (for all possible combinations of factors  $F_k$ , and each forest community  $i$ ) make up the PNV model.
- In order to determine the probability  $P(V_i | F_1 = f_1, F_2 = f_2, \dots, F_n = f_n)$  that forest community  $i$  occurred for a given factor combination  $F_1=f_1, F_2=f_2, \dots, F_n=f_n$ , the Bayes theorem was used.

$$P(V_i | F_1 = f_1, F_2 = f_2, \dots, F_n = f_n) = \frac{P(V_i) \cdot P(F_1 = f_1, F_2 = f_2, \dots, F_n = f_n | V_i)}{\sum_j P(V_j) \cdot P(F_1 = f_1, F_2 = f_2, \dots, F_n = f_n | V_j)}$$

$$= \frac{P(F_1 = f_1, F_2 = f_2, \dots, F_n = f_n | V_i)}{\sum_j P(F_1 = f_1, F_2 = f_2, \dots, F_n = f_n | V_j)}$$

The a-priori probability was assumed to be  $P(V_i)=1$ . This means that all forest communities occurred when all factors were optimal.

The result was the frequency of occurrence of the forest community  $i$  for a certain factor combination. This was relative to the frequency of occurrence of all forest communities for this factor combination.

The model was applied to the 500 m grid of the second NFI. As a result, the model determined the three most probable forest communities as well as their probability of occurrence at each NFI plot, depending on the values of the site factors (Table 6) at the plot. The 71 forest communities were combined into 6 classes for the analysis (Table 7).

From the results of the model, theoretical nominal conditions of the forest composition could be determined, such as the theoretical conifer proportion compared to the assessed conifer proportion, which was used as an indicator for the closeness to nature (Chapter 3.8, Natural Protection Function).

Table 6. Site factors in the PNV model by BRZEZIECKI et al. (1993)

Site factor	Class/unit
Ecological regions according to Ellenberg and Klötzli	Jura with north aspect, Jura with south aspect, Plateau, northern Pre-Alps, western Central Alps, eastern Central Alps, Southern Alps
Slope	°
Aspect	°
Average annual temperature	°C
Annual precipitation	cm
Soil-pH	
Soil depth	
Soil water capacity	
Nutrient-holding capacity of the soil	
Water permeability	
Water-logged soil	
Elevation	Meter above sea level

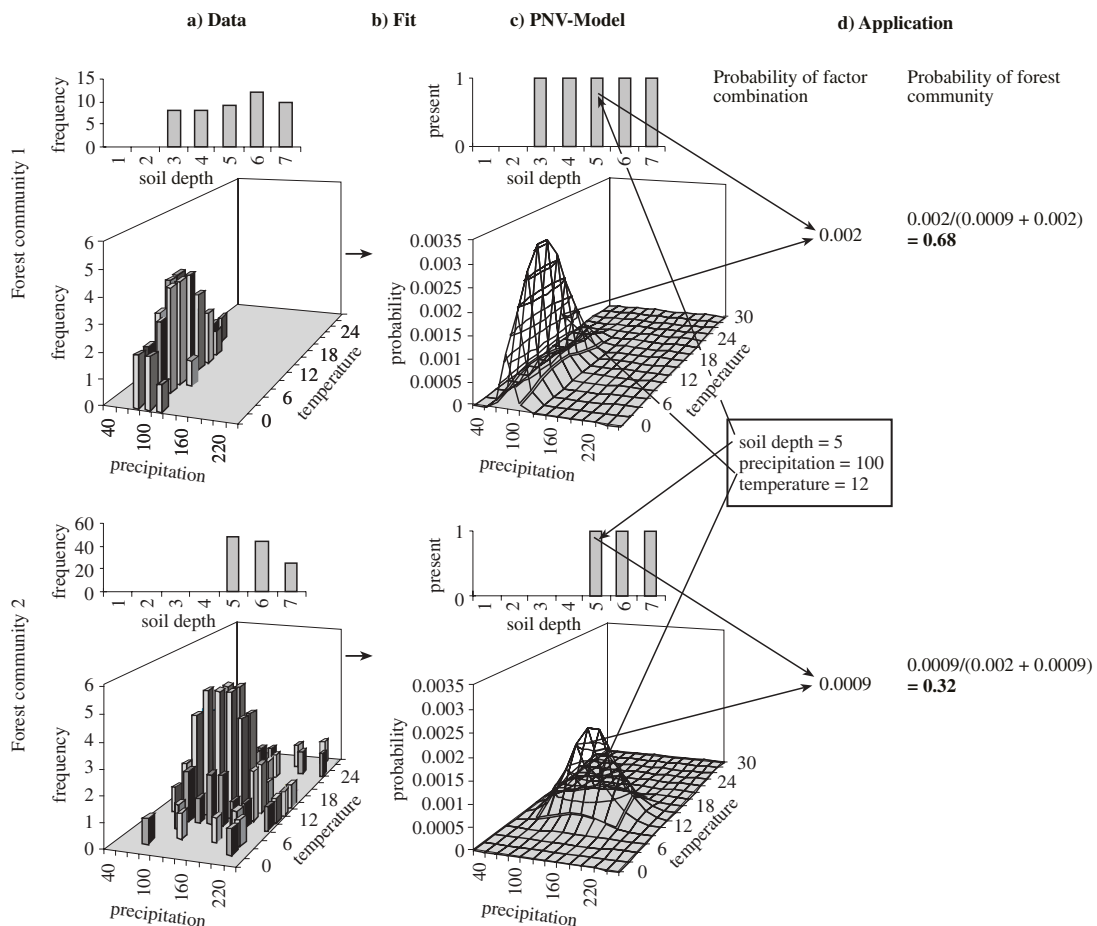


Figure 4. Principle of the PNV model (BRZEZIECKI et al. 1993; KIENAST et al. 1994). From the occurrence frequency of the forest community for certain factor combinations (a), the probability distributions are estimated (c). By using the Bayes theorem, the probability is determined that this forest community occurs for a certain factor combination (d).

Table 7. Classification of the forest communities according to ELLENBERG and KLÖTZLI (1972) in 6 PNV-classes when the PNV models of BRZEZIECKI *et al.* (1993) were used in the NFI.

Forest community in the NFI2	Forest community according to Ellenberg and Klötzli
Beech forests	1–17
Beech-fir forests	18–21
Other broadleaf forests	22–45
Spruce-fir forests	46–52
Spruce forest and larch- Cembran pine forest	53–60
Scotch-pine forest	61–71

### 3.1.3 Discussion, Outlook

Instead of using primary factors that were difficult to assess, easier to assess secondary factors were employed to a large degree. For example, the elevation was used to approximate temperature, which in turn was an indicator for the primary factor "heat". Nonetheless, the sole utilization of such secondary factors involves certain problems.

The relationship between the primary and a certain secondary factor is, strictly speaking, only valid for those regions and dates where and when they were assessed. The relationship can not be assumed to be constant in time and space.

It is possible, for example, to use on a certain date and in a certain region, the elevation as an approximation for the temperature. However, the temperature characteristic for a certain elevation increases with decreasing latitude; also, the temperature increases due to other influences such as climate change. It is also possible that the anthropogenic nitrogen input changes the nutrient supply (primary factor). The acidity of the bedrock, which is used as an approximation of the nutrient supply, however, does not change.

It is therefore increasingly desirable to determine primary factors or factors that could be used to calculate primary factors with the help of the laws of physics. An example is the daily sum of heat which can be interpolated using the daily average temperature and the daily temperature amplitude of the closest climate stations and be further modified with the local exposition and slope.

Since forests can react with sensitivity to factors that change over time (e.g., the climate) (BENISTON and INNES 1998; GROTE *et al.* 1998; LASCH *et al.* 1998), information regarding the variability and changes throughout time should be provided.

The Soil Capability Map of Switzerland represents, for the moment, the only information with complete coverage of the soil properties within Switzerland. Small-scale variations of the soil properties are not reflected in the map because of its coarse resolution. In addition, it neglects completely the influence of biological processes, such as the decomposition of organic material in the soil. Supplemented by measurements of numerous soil samples within Switzerland, the map should provide more exact information in the future. Measurements that could also provide information about the small-scale variability would also be desirable.

The approaches that were chosen for the second NFI that determined relevant factor combinations have the advantage that they are: 1) easy to implement, 2) based on extensive data, and 3) do not require any previous knowledge about the processes in the ecosystem.

They are partly based on the concept of forest communities. From the assessed composition of the herbaceous layer, the potential natural vegetation (PNV) was inferred with this model. That is the vegetation that would be present in an equilibrium (climax) without any human influence (since the last ice age) and with constant environmental conditions (e.g., without climate change) (according to TÜXEN 1956). Nevertheless, the herbaceous layer is in a strict sense only a reliable indicator for the tree layer composition in natural forest which is in an equilibrium state (see also WILDI and KRÜSI 1992). The reason for this is because the herbaceous layer composition is influenced, just as the tree layer, by the site conditions, but the tree layer composition also influences the herbaceous layer (p. 139, ELLENBERG 1986). The tree layer composition, however, changes during the succession and because of human interference.

This problem was avoided by using, for the most part, only phytosociological assessments from near-natural, mature forests for the analysis of the site index model, the altitudinal vegetation zone model, and the PNV model.

A new method could consist of using ecosystem process models to select certain forest relevant factor combinations from several individual factors (e.g., temperature and precipitation). Some of these could be, for example, bioclimatic variables, including the drought stress, which can be determined from climate and soil factors with dynamic forest models (BUGMANN 1996; KRÄUCHI and KIENAST 1993; LISCHKE *et al.* 1998) and which influence the growth, mortality, and establishment of trees. With such bioclimatic indicators, it would be possible to stratify the NFI data in an ecologically appropriate way, which would allow the comparison of data with forest development simulations (LISCHKE 1998; LÖFFLER and LISCHKE 2001). Ecosystem process models could also be used to determine, from a multitude of sources, the most important factors by conducting a sensitivity analysis. These approaches could also help to assess how discrete the factor space needs to be.

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