3 DEFINITIONS, TERMINOLOGY

Undoubtedly, more attempts have been made to define timberline than other vegetation limits, in particular for correlating the location of this prominent vegetation- and landscape-limit to certain isotherms or other altitudinal limits, such as snow line, for example (e.g., Hermes, 1955). Most definitions refer to a certain minimum tree height or minimum forest cover. Aas (1964) and Mork (1968b), for example, consider a forest to be a closed forest if the average distance between the trees does not exceed 30 m. The critical minimum heights range from 2 to 8 m (Table 1), the minimum cover from 30% to 40% (Jenic and Locvenc, 1962; Ellenberg and Muller-Dombois, 1967; Ellenberg, 1978).

Table 1. Minimum height as criterion for identifying upper treeline

Author	**Tree height (m)**
Brockmann-Jerosch (1919)	5
Schröter (1926)	4–5
Leibundgut (1938)	5
Vincent (1938)	8
Rubner (1953)	6–8
Hermes (1955)	5
Plesnik (1959)	8
Jenic and Locvenc (1962)	5
Ellenberg (1963)	2
Wardle (1964, 1965a)	1
Holtmeier (1965)	>average depth of winter snowpack
Hustich (1966)	5
Müller-Dombois and Ellenberg (1974)	2
Wardle (1974, 1981a)	2
Bernadzki (1976)	2
Braathe (1977)	2.5 (at timberline 3)
Kullman (1979 onwards)	2
Little (1979)	4
Piussi and Schneider (1985)	2
Timoney et al. (1992)	3–4
Hofgaard (1997a)	2
Paulsen et al. (2000)	3

Minimum tree height as criterion is also differently used as far as different tree species are concerned. For example, Aas and Faarlund (1996) require a minimum height of 2.5 m to consider a birch (*Betula tortuosa*) growing at the upper timberline in northern Scandinavia a tree, while the

F.-K. Holtmeier, *Mountain Timberlines: Ecology, Patchiness, and Dynamics,*
Advances in Global Change Research 36, 11–28.

critical height of a pine (*Pinus sylvestris*) should be at least 5 m. Kullman (1987), on the other hand, included birch and spruce higher than 2 m when monitoring tree line in the southern Swedish Scandes, while the corresponding stem height of pine was only 1 m. In the temperate mountains a minimum height of 2 m appears to be adequate to the particular climatic and ecological situation, as a birch or any other tree species growing taller will be exposed to the harsh climatic influence above the winter snow cover, whereas smaller individuals are fairly well protected. However, particularly for this reason and with respect to the varying thickness of the snow cover in the forest-alpine tundra ecotone, the present author (Holtmeier, 1965, 1974) has objected to an absolute minimum height as criterion. Thus, a pine or birch should be considered a tree as soon as it projects beyond the average snow cover typical of the specific site (Table 1; see also Däniker, 1923). At tropical mountain timberline, however, this does not work, because a long-lasting seasonal snow cover is lacking. Yet, also a certain minimum tree height as criterion for defining tree line might make sense in so far as, for example, a 2 m high 'tree' would be more decoupled from the climate near the soil surface and thus would be growing in a different environment than the lower vegetation. Kessler (1995), on the other hand, holds the view that a tree may be smaller than 2 m provided that it shows typical tree habitus (one or several stems and a crown). However, where tall growing forests, such as 9 m high *Erica* stands on Moun. Kenya, grade into 'low' and 'dwarf forest' and finally into shrub, defining forest limit and tree line turns out to be rather difficult and remains arbitrary (Coe, 1967; Miehe and Miehe, 1994). For further differentiation of the upper forest belt Miehe and Miehe (1994, 1996), for example, make a difference between 'low forests' (>5 to 10 m) and 'dwarf forests' (<5 m). Salomons (1986), on the other hand, calls the 3 to 8 m high stands of *Gynoxis*, *Hesperomeles* and some attributed species occurring above the closed forest belt in the Páramo in central Columbia 'Andean dwarf forest'.

To be sure, defining the upper limit of mountain forests by a minimum tree height will result in a 'line' that can easily be correlated to any average temperature or temperature sums, growing degree days, etc. supposed to be controlling factors. However, studying the response of this 'line' will not provide any deeper insight into the ecological situation and spatial and temporal structures (Holtmeier, 1965, 1974; Stugren and Popovici, 1991).

This becomes particularly clear in view of the dynamics in the forest-alpine tundra ecotone. There has been a long discussion as to whether a natural climatic forest limit would be sharper than a transition zone (ecotone) at all. The existence of a transition zone is explained by unfavourable edaphic conditions and/or human impact (Scharfetter, 1938; Ellenberg, 1963, 1966, 1978; Schiechtl, 1967; Nägeli, 1969; Mayer, 1970; Köstler and Mayer, 1970; Kral, 1971). This concept has been taken over in textbooks on plant geography (Ellenberg, 1978; Klink and Mayer, 1983). From his own experience in mountain areas in and out of Europe and in the Subarctic the present author does not agree with this opinion, since the mountain and polar timberline are so heterogeneous that they should not be generalised to such an extent (Holtmeier, 1985b). In fact, in various high mountains that have not, or only randomly, been influenced by humans, the closed forest ends abruptly at its upper climatic limit. However, in many other high-mountain areas as well as in the Subarctic, the climatic timberline forms a more or less wide ecotone, extending from the closed forest to isolated stunted trees within the lower alpine belt or tundra. On gently sloping fjelds in central and northern Finnish Lapland, for example, broad Savannah-like mountain birch forests (*Betula tortuosa*) with sporadic several metres high trees (Photo 16) form the timberline ecotone. Thus, the position of the tree limit depends on how a tree is defined. There is much evidence that also the original upper birch forests were once open woodland (e.g., Oksanen et al., 1995; Kankaanpää, 1999; Holtmeier and Broll, 2006). Dead wood, for example, partly found in densely spaced peat hummocks (10–30 cm high) above the present timberline support this hypothesis (Holtmeier and Broll, 2006). The hummocks developed from organic matter accumulated around the stem base of the birches as can be observed below the present timberline.

The existence of these ecotones cannot be primarily and everywhere attributed to human interference and/or unfavourable pedological conditions, but must be explained as the result of the complex influences of the actual and previous climate, fire, biotic factors and site history on tree growth and ecological conditions. In many cases the existence of a timberline ecotone is the result of oscillations of the climate, persistence of tall (mature) trees and regeneration under changing conditions. A general warming may be followed by advance of the forest to greater altitude and northern latitude (Chapter 5), while cooling will cause decay and retreat of the forest in the long-term, followed by change of the site conditions in the former forested area.

Moreover, mountain timberlines are formed by tree species with different ecological properties and requirements. Spruce, for example, is more shade-tolerant than pine or larch and thus forms comparatively dense forests while light-demanding pine or larch forests are usually more open. Some species, such as fir and spruce, are able to reproduce and propagate by layering (formation of adventitious roots) under conditions that would prevent sexual regeneration completely. In this respect most timberline forming pines, for example, are at a clear disadvantage compared to spruce or fir (Holtmeier, 1985b, 1986a, 1993a, Section 4.3.10). Moreover, due to the local and regional history of climate, vegetation and, not least, human impact, tree stands at timberline may be different as to successional stage, age classes, composition and ecological dynamics.

In view of the great physiognomic variety and heterogeneity of mountain timberlines and with respect to the many possible scientific approaches to timberline, it is not surprising that a general precise and practicable definition, meeting all aspects, is hardly possible. Nevertheless, from a global view at least four different types of timberlines can be distinguished (Figure 3).

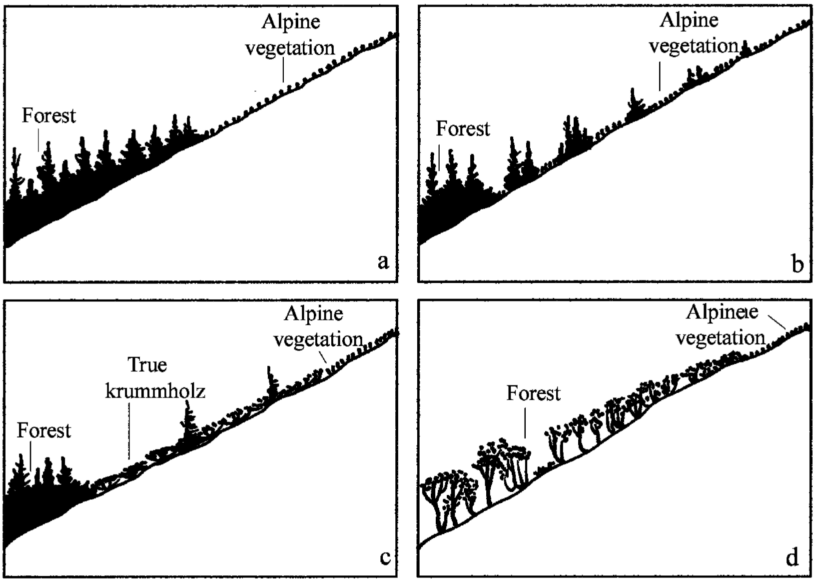


Figure 3. Main types of timberline. **a** – abrupt forest limit bordering alpine vegetation, **b** – transition zone (ecotone), **c** – true krummholz belt (e.g., *Pinus mugo, Pinus pumila*) above the upright growing forest, **d** – gradual transition from high-stemmed forest to crippled trees of the same species bordering alpine vegetation (e.g., *Nothofagus solandri* var. *cliffortioides*). Modified from Norton and Schönenberger (1984).

Timberline may occur as a line (e.g., Photos 1, 3, 4, 55, 111), or as a more or less wide ecotone (e.g., Photos 2, 32, 38, 51–53, 61, 67, 76, 88, 94, 95, 122; see Table 4 for synonyms). Different types may occur in close proximity to each other, even on a single mountainside (Photos 1 and 2). In other areas the forest gradually merges into alpine scrub formed by wooden species other than the tree species in the forest. Occasionally, high-stemmed forest stands border the alpine vegetation (Figure 3a, Photo 3) while in some areas tree height decreases approaching the upper limit of tree growth, and the most advanced individuals are more or less stunted (Figure 3a; Photo 4).

These climatically shaped individuals (e.g., Photos 24, 29, 38, 58, 59, 64, 66–77, 84, 87, 90, 91, 104) of the normally upright-growing tree species are usually called 'krummholz' in English. This popular term has been introduced from the German language. Originally it meant contorted, gnarled, twisted

Photo 1. Abrupt forest limit (*Picea engelmannii*, *Abies lasiocarpa*) on the WNW-exposed slope of Goliath Mountain (Mt. Evans area, Colorado) at about 3.500 m (view SW). F.-K. Holtmeier, 19 July 1994.

Photo 2. The same slope as above (view N). In this section, which provides higher soil moisture (being reflected in the distribution of willow shrubs), the timberline occurs as an ecotone located at about 3.500 to 3.540 m. F.-K. Holtmeier, 17 July 1997.

Photo 3. Abrupt limit of *Nothofagus solandri* var. *cliffortioides*-forest (evergreen) in the Craigieburn Range (New Zealand, South Island) at about 1.350 m. F.-K. Holtmeier, 24 November 1979.

Photo 4. Abrupt upper limit of *Nothofagus pumilio*-forest (deciduous) on an east-facing slope (550 to 580 m) on Isla Navarina (Tierra del Fuego). The uppermost trees exhibit dwarfed growth forms. A. Vogel, 3 March 1990.

and prostrate growing species such as *Pinus mugo*, *Pinus pumila*, *Alnus viridis*, *Alnus sinuata*, and *Alnus maximowiczii* (Figure 3c, Photos 5, 6; see also Photos 12, 18, 114, 115) the growth form of which is genetically predetermined. Thus, it should not be confused with climatically stunted 'krummholz'. Although krummholz in the proper sense (Holtmeier, 1973, 1981a) does not display tree habitus, Masuzawa (1985, see also Saiko and Masuzawa, 1987) calls the *Alnus maximoviczii*-belt above the larch forest on Mt. Fuji 'dwarf forest'.

Photo 5. Prostrate mountain pine belt (*Pinus mugo*) above Swiss stone pine forest (*Pinus cembra*) in the High Tatra near Strbske Pleso (Slovakia). F.-K. Holtmeier, August 1970.

In the following (see also Holtmeier, 1965, 1974), timberline is understood to be the transition zone between closed forest, the density of which depends on tree species represented and site conditions, and the most advanced individuals of the forest-forming tree species (see also Däniker, 1923; Pfister et al., 1977; Slatyer and Noble, 1992; Heikkinen et al., 1995; Smith et al., 2003). Ecotonal timberlines are characterized by a mosaic of tree clumps, scattered groves, isolated, more or less deformed tree individuals and treeless patches covered by low shrubs, herbs, and grasses. Here, it should be stressed again that, at close sight, abrupt timberlines usually reveal themselves as narrow ecotones. In the temperate and northern mountains, these outliers of tree growth are usually deformed, only a few decametres high and mostly but not everywhere protected by the snow cover from adverse climatic influences in the winter ('scrub line' in the sense of Arno, 1984, dwarf tree or cripple limit in the sense of Schröter, 1926).

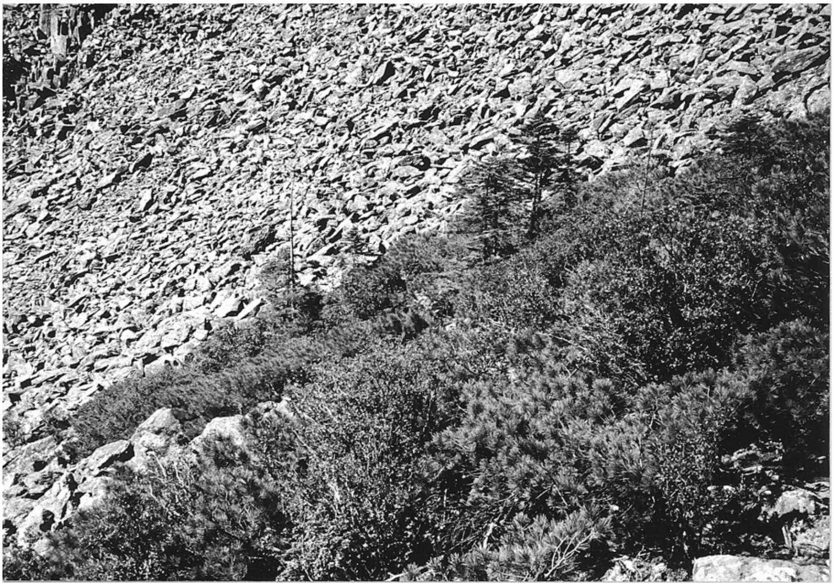


Photo 6. Dwarf Siberian stone pine (*Pinus pumila*) overtopped by several *Abies nephrolepis* on Lisaja Shg (Sikote Aline, Russia) at about 1.200 m. H. Mattes, 25 August 1997.

Though these climatically stunted spruces, firs and pines will usually not meet the minimum height of a 'tree' the genetic disposition for becoming a tree is inherent, as is evidenced by prostrate-growing individuals having assumed or re-assumed tree-like features (single- or multi-stemmed, crown) or in the event of improved climatic conditions (Photos 72–75, Figure 58). This makes them different from shrubs, which thrive from the base (basitony) and show a sympodial ramification (Strasburger et al., 1991). This is one reason to distinguish genetically predetermined from climatically shaped 'krummholz' (Table 2; Holtmeier, 1973, 1974, 1981a). When the latter is considered in the following chapters it is put in quotation marks. Variation of growth form of tree individuals caused by the effects of oscillating climate is typical of the ecotone (Scott et al., 1997). Consequently, upright stems thriving from a mat-like growing 'tree' above 2 m height should not be lumped together with advance of timberline as it has been usual for several authors (e.g., Kullman, 1986a, 2000b, 2002; Lavoie and Payette, 1992; Lescop-Sinclair and Payette, 1995; see also Section 5.1).

As to the ecological situation, timberline ecotones are completely different from the closed forest and from the treeless alpine belt. While in the treeless alpine belt the microclimatic pattern is a function of the influence of microtopographical structure (convex, concave) on solar radiation and windflow near the soil surface, in the ecotone these climatic elements are influenced also by the scattered stands of trees, an aspect that has hardly

Table 2. Krummholz-terminology and its practical use

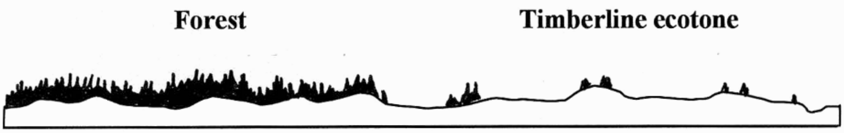
	True krummholz (genotype)	Environmentally induced krummholz (phenotype)
Growth form	Shrub, scrub	Environmentally shaped growth forms of the forest tree species
Example	*Pinus mugo* *Pinus pumila* *Alnus viridis* *Alnus sitchensis* *Podocarpus nivalis*	Flagged trees Table and flagged table trees, Mat-like growth etc., Identical or similar growth in different tree species at same external influences
Distribution	Usually more or less wide altitudinal belt above the forest, which is formed by other species also common in avalanche chutes	Controlled by the locally varying site conditions (e.g. wind-exposure, snow depth etc.) in the ecotone
English terms	Krummholz[1] Scrub[2] Subalpine scrub[3] Elfin wood[4] Dwarf forest[5]	Krummholz[6] Dwarfed krummholz[7] Wind-timber[8] Dwarf forest[9] Dwarf/matted trees[10] Crippled trees[11] Stunted trees[12] Brushwood[13]
German terms	Krummholz[14] Knieholz[15] Latschenbuschwald[16] Grünerlenbuschwald[17] Legföhrengebüsch[18] Alpenerlengebüsch[19] Krummholzwald[20]	Krüppelholz[21] Baumkrüppel[22] Krüppelbäume[23] Krummholz[24]

References: [1]Klikoff (1965); [2]Wardle (1973, 1977); [3]Wardle (1973, 1977); [4]Hansen-Bristow (1986); [5]Masuzawa (1985), Saiko and Masuzawa (1987); [6]Wardle (1968, 1973, 1974, 1993), Lamarche and Mooney (1972), Ives (1973b), Troll (1973b), Pfister et al. (1977), Komarkova (1976, 1979), Peet (1981), MacMahon and Andersen (1982), Arno (1984), Arno and Hoff (1989), Crawford (1989); [7]Habeck (1969), MacMahon and Andersen (1982); [8]Löve (1970); [9]Coe (1967), Salomons (1986), Miehe and Miehe (1994), Miehe and Miehe (1996); [10]Griggs (1938), Bliss (1963); [11]Arno (1984); [12]Arno (1984); [13]Cuevas (2002); [14]Schröter (1926), Hegi (1958), Braun-Blanquet (1964), Schmidt (1969), Ellenberg (1978), Franz (1979), Klink and Mayer (1983), Strasburger et al. (1991); [15]Hueck (1962), Klink (1973), Kuoch and Schweingruber (1975), Ellenberg (1978); [16]Ozenda (1988); [17]Ozenda (1988); [18]Rübel (1912); [19]Rübel (1912); [20]Ellenberg (1978); [21]Braun-Blanquet (1964); [22]Ellenberg (1978); [23]Geiger (1901), Ozenda (1988); [24]Marek (1910), Piussi and Schneider (1985).

been considered so far in timberline literature (Section 4.3.12). In the extremely wind-exposed forest-alpine tundra ecotone of the Rocky Mountains, for example, even the prostrate crippled trees cause by their effects on the wind-mediated relocation of snow a locally varying mosaic of snow-covered and snow-free patches which in turn influence site conditions (cf. Photo 87). The less broken the terrain, the more the wind, snow cover, radiation exchange and thus site conditions are influenced by the distribution pattern of stands of trees and openings. The influence of the mosaic of tree clumps and open areas on snow accumulation, for example, may result in a longer duration of snow cover in the ecotone (cf. Photo 32) compared to the forest (high interception) and the treeless alpine zone (deflation). The finely differentiated local site pattern that appears is partly cause and partly result of the way in which the tree stands are distributed. These ecological conditions are peculiar to the ecotone (Figure 4). In the closed forest, however, the influence of microtopography on solar radiation, wind velocity and direction is by far less important. Altogether, these effects of microtopography and trees on the patchiness of site conditions are by far more important for tree growth, regeneration and survival than altitudinal gradients of air temperature.

Consequently, a better understanding of the ecological situation and spatial and temporal dynamics in the ecotone requires extensive local and regional studies on microsite conditions and microsite patterns specific to the ecotone and cannot be achieved only by investigating physiological responses of mature tree growth to thermal conditions (Holtmeier, 1994b, 1999a). This also holds true for the tropical mountain timberlines. These appear to be as diverse and heterogeneous as the timberlines outside the tropics and obviously more different from each other than can be assumed in view of the tropical type of timberline, which Troll (1959, 1973) compared in a schematic sketch to the ‘general’ type of timberline in the temperate zones. This generalisation might have been useful for teaching differences in the effects of temperate and tropical climates on timberlines. Thus, it was not by chance that this sketch was adopted by many authors in their textbooks on geography or geobotany (e.g., Price, 1981; Klink and Mayer, 1983; Leser et al., 1991). However, from the landscape ecological view, this generalisation disguised the diversity that is typical of timberlines in the worlds’ mountains, and it is this diversity that should be explored (Chapter 1).

Bader et al. (2007), for example, describe timberlines in the tropical Andes and on Haleakala volcano (Hawaii) as being mostly abrupt. However, their physiognomy varies locally. Most of these timberlines are fringed by tall shrubs, ferns or tall grasses (Photo 7). In other places, patchy timberlines occur with sharply-contoured dense tree stands alternating with Páramo vegetation (cf. Photo 113), thus forming a more or less wide ecotone. Moreover, ‘gradual’ timberlines occur where forest decreasing in height with altitude passes almost seamlessly into the Páramo, although this situation is rather rare. Richter et al. (2008) report considerable variation in the physiognomy of neo-tropical timberline in the Cordillera Real (Ecuador).



Forest	Timberline ecotone
Radiation transfer in the upper canopy surface	Radiation transfer at the surface of the ground vegetation, tree clumps, scattered trees and at the soil surface
Almost no influence of microtopography on solar radiation	Strong influence of microtopography, tree clumps and scattered trees on solar radiation
Relatively low temperatures	Locally varying temperature (High temperatures at sun-exposed and wind-protected sites)
Almost no effect of microtopography on wind velocities and directions	Wind velocities and directions modified by microtopography, tree clumps and scattered trees
Low wind velocities	High wind velocities
High interception of precipitation by the forest canopy	Low interception of precipitation by tree clumps, scattered trees and ground vegetation
Relatively even depth and length of the snow cover	Irregular depth and length of the snow cover due to the effects of microtopography and scattered trees on wind velocities and directions
Relatively high humidity	Locally varying humidity
Relatively even distribution of soil moisture	Locally varying soil moisture
'Forest soils' (in conifer forests mainly Podzols)	Mosaic of different soils related to microtopography and plant cover

Figure 4. Ecological conditions in the forest and in the forest-alpine tundra ecotone. Modified from Holtmeier (1979).

Thus, in tropical high mountains it may be hard to distinguish timberline and tree line in their proper sense, particularly if high-stemmed forests, such as the 9 m high *Erica* forest on Mt. Kenya for example, gradually merges into ‘low forest’, ‘dwarf forest’ and shrub without any change of tree species (Section 4.3.11). In this case a demarcation between tall and lower forest is arbitrary (Coe, 1967; Miehe and Miehe, 1994).

Photo 7. Abrupt timberline (at about 3.400 m) in the eastern cordillera of southern Ecuador. This timberline has not been influenced by fire for more than 10 years. M. Y. Bader, October 2002.

The great physiognomic and ecological variety and heterogeneity of mountain timberlines is reflected in timberline terminology (Table 3, see also Holtmeier, 1974, 2000). Some terms refer to the location of the timberline only (upper, lower timberline); others refer to the controlling factor or complex of factors (climatic, orographic, anthropogenic timberline) or to both location and causes (alpine, polar/subarctic/arctic, continental, maritime timberline). Thus, for example the alpine, the polar (subarctic, arctic, northern) and maritime timberlines are climatic timberlines. While the upper and northern timberlines are caused by heat deficiency, the maritime timberline is caused by strong winds and salt spray that adversely affect tree growth at the seashore (Brockmann-Jerosch, 1928). The maritime timberline also is a lower timberline (see also continental timberline). Consequently, the term 'maritime timberline' should not be confused with the comparatively low altitudinal timberline in mountains with a maritime climate, as did Pott (1993) for example. Also, the continental timberline is a lower timberline (Brockmann-Jerosch, 1919) that borders the steppe (Photo 8). Since the continental timberline is caused by insufficient moisture, it is also called dry timberline or drought-caused timberline. In arid and semiarid zones, mountains that are high enough to catch sufficient moisture from the air currents, an upper and a lower climatic timberline ('double timberlines' in the sense of Arno, 1984) occur: the upper timberline caused mainly by heat deficiency, the lower timberline by lack of moisture. The less moisture is available to the forest the higher is the dry timberline located (Schweinfurth, 1957; Troll, 1972; Arno, 1984; Jacobsen and Schickhoff, 1995).

Table 3. Terms related to causes and position of timberline

Terms (tl = timberline)	**Synonyms**	**German terms** (Wgr = Waldgrenze)	**Position**	**Causes**
Climatic tl	Alpine tl Alpine treeline ecotone Mountain tl	Obere Wgr Alpine Wgr	Altitudinal limit	Heat deficiency, short growing season (outside the tropics)
Polar tl	Subarctic tl Arctic tl Northern tl Northern cold tl Subantarctic tl Antarctic tl Southern tl Southern cold tl	Subarktische Wgr Arktische Wgr Nördliche Wgr Subantarkt. Wgr Antarktische Wgr Südliche Wgr	Horizontal tl, bordering the tundra	Heat deficiency, short growing season
Inverted tl	Valley tl Valley bottom tl Bottom tl	Inversions-Wgr Inverse Wgr	Lower tl in mountain valleys	Inversions with frequent early and late frost, waterlogged soil
Continental tl	Lower tl Drought-caused tl Dry tl	Kontinentale Wgr Trockengrenze Desertische Wgr	Lower tl in mountain, tl bordering the steppe	Moisture deficiency
Maritime tl	Coastal tl	Maritime Wgr	Lower/horizontal tl at the ocean coast	Influences adverse to tree growth at the coast (e.g. salt spray)
Historic tl	Max. postglac. tl Hypsithermal tl	Historische Wgr. Wärmezeitliche Wgr	Altitudinal tl	Heat deficiency, short growing season (outside the tropics)
Potential tl	Hypothetical tl	Potentielle Wgr	Altitudinal tl	Heat deficiency, short growing season (outside the tropics)
Orographic tl		Orographische Wgr	altitudinal tl, always below the climatic tl	Steep topography, rock walls, talus cones, boulder fans
Edaphic tl		Edaphische Wgr	Mostly altitudinal tl, always below climatic tl	Missing soil, waterlogged soils
Anthropogenic tl	Man-caused tl Artificial tl	Anthropogene Wgr	Mostly altitudinal tl, below climatic tl	Pastoral use, mining, salt works, firewood, incendiarism
Actual tl	Present tl	Akltuelle Wgr	Altitudinal tl, below climatic tl	Different causes

Photo 8. View from Montgomery Pass (Hwy 6) of the lower timberline (*Pinus monophylla* and *Juniperus osteosperma*) at the foot of the White-Inyo Range (California). The timberline is caused by lack of moisture. F.-K. Holtmeier, 25 July 1994.

Occasionally, in poorly ventilated mountain valleys with frequent stagnant cold air on the valley bottom, another type of lower timberline can be observed, the so-called inverted timberline (Photo 9). It is (mostly) caused by frost occurring within the cold air layers (Wardle, 1965b, 1971, 1973, 1974, 1980, 1985b, 1993, 2007; Moore and Williams, 1976; Costin, 1981; Paton, 1988; Slatyer, 1988; Banks and Paton, 1993). Also, the existence of inverted timberlines in tropical high mountain valleys is ascribed to frost (e.g., Fries and Fries, 1948; Hedberg, 1964; Wardle, 1971, 1974; Davidson and Reid, 1985) and/or to water-saturated soils (Smith, 1980; Davidson and Reid, 1987; Gilfedder, 1988; Young, 1993). Löffler (1979), however, referring to his studies in high mountains of New Guinea, rejects the frost hypothesis and considers water logging to be the controlling factor (Photo 10). An inverted timberline caused by water-saturated soils would be considered an edaphic rather than a climatic timberline. In addition, fire, mainly caused by humans for different purposes (Young, 1993; see Section 4.3.14), probably is an important agent preventing the valley bottoms in many tropical high mountains from being invaded by forest.

The northern (polar, subarctic, arctic) timberline caused by heat deficiency, borders the tundra or the subarctic dwarf shrub-lichen heath (Northern Europe). The ecotone is snaking its way for more than 13.000 km at varying width across northern Eurasia and northern North America. The farther north

Photo 9. Inverted timberline (*Picea engelmannii*, *Abies lasiocarpa*) in the Cache la Poudre Valley (Rocky Mountain National Park, Colorado) at about 3.170 m. Frequent stagnant cold air and frost very likely prevent the conifer forest from colonizing the valley bottom. F.-K. Holtmeier, September 1994.

Photo 10. Inverted timberline in the Mt. Wilhelm area (New Guinea). Grassland covers the valley bottom. Accumulation of cold air with frequent frost temperatures, waterlogging or human-caused fires are possible factors keeping the valley bottom treeless. E. Löffler.

the more the trees disappear from exposed interfluves and similar convex topography and are restricted to sheltered lowland and river valleys (Atkinson, 1981; Larsen, 1989). Thus, the northern timberline often occurs as an altitudinal boundary at comparatively low elevations. The varying width of the forest-tundra ecotone in Canada, for example, is partly ascribed to this effect of regional topography (Larsen, 1989; Timoney et al., 1992). Where high mountains are located precisely where the northern forest-tundra ecotone would otherwise exist, they eliminate the gradual transition zone and create an abrupt northern timberline as on the southern slope of the Brooks Range, for example (Larsen, 1989; Hobbie and Chapin III, 1998).

In contrast to the northern timberline, a southern (subantarctic, antarctic) timberline can be observed only on a few islands in high southern latitudes (Tuhkanen, 1993, 1999).

Besides climate many other factors such as steep rocky trough walls, talus cones, slope debris and avalanche chutes may prevent the forest from reaching its upper climatic limit. This is the orographic timberline (Photo 11, see also Figures 38–40 and Photo 43). Orographic timberlines, as is also true for the man-caused (anthropogenic) and edaphic timberlines, are always located more or less far below the elevation to which the forest would advance at the given climatic conditions (cf. Table 3).

Man has influenced mountain forests and timberline in many ways, such as forest pasture, clearing high-elevation forests to create alpine pastures, mining, burning, charcoal production, salt works, timber harvesting for construction wood, fuel and others (see Section 4.3.14.1). Anthropogenic timberlines may be abrupt, as can be particularly observed, for example, in many tropical mountains, where the high-elevation grasslands and forests are regularly burned (cf. Photo 113, see also Section 5.4). In other regions, the uppermost forests became open and over-aged due to over-utilization as in the European Alps, for example. However, a general characteristic that would be common to all anthropogenic timberlines does not exist.

By many authors the upper climatic timberline is also called alpine timberline (Jenic and Locvenc, 1962; Wardle, 1974;Tranquillini, 1979a; Leuschner and Schulte, 1991; Körner, 1998a, b; Bader, 2007; Bader et al., 2007; Wieser and Tausz, 2007). The present author, however, prefers the terms ‘upper timberline’ or ‘altitudinal timberline’ to ‘alpine timberline’, because the word ‘alpine’ does not meet the environmental conditions in the tropical high mountains. The same holds true for the treeless zone above the upper timberline in the tropics, which is often called ‘alpine zone’ (e.g., Klötzli, 1958; Young, 1993). Troll (1959) already explicitly referred to this problem. Thus, it seems less inappropriate to restrict the term alpine timberline, if inevitable, to the temperate mountains characterized by climates with cold and long winters, avalanches, strong influence of snow cover (distribution

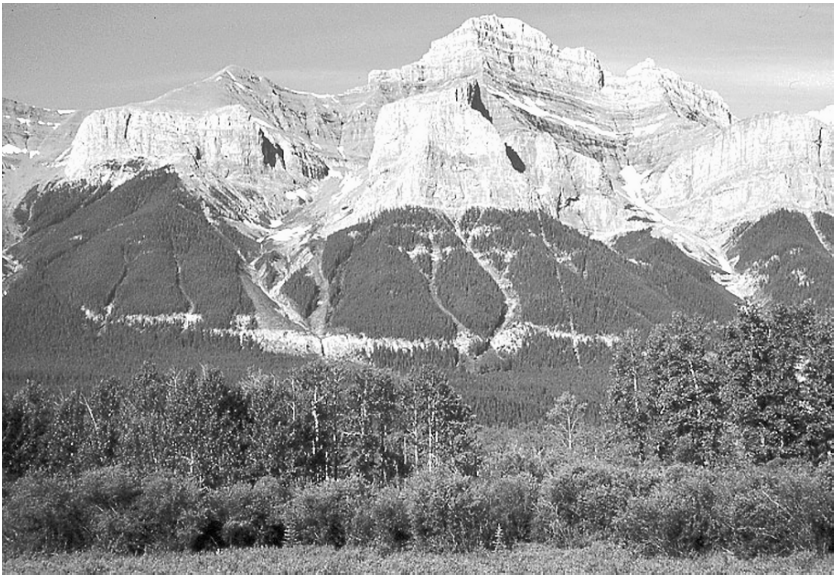


Photo 11. Orographic timberline near Banff in the Canadian Rocky Mountains). F.-K. Holtmeier, 21 July 1994.

Table 4. Terms and synonyms concerning the transition zone between the closed forest and the upper limit of crippled trees

English terms	**German terms**
Timberline[1]	Kampfzone[14]
Timberline region[2]	Kampfgürtel[15]
Timberline zone[3]	Kampfwald[16]
Timberline ecotone[4]	Waldgrenzökoton[17]
Forest-tundra ecotone[5]	Subalpines Ökoton[18]
Forest-alpine tundra ecotone[6]	
Alpine timberline ecotone[7]	
Subalpine parkland[8]	
Subalpine forest[9]	
Subalpine belt[10]	
Patch forest[11]	
Meadow tree clump parkland[12]	
Treelimit region[13]	

References: [1]Wardle (1974), Price (1981), Heikkinen et al. (1995); [2]Franklin and Dyrness (1973); [3]Daly (1984); [4]Tranquillini (1979a), Holtmeier (1994b); [5]Clements (1936), Marr (1948); Marr and Marr (1973); [6]Wardle (1973); [7]Arno (1984); [8]Rochefort et al. (1994), Miller and Halpern (1998); [9]MacMahon and Andersen (1982); [10]Löve (1970); [11]Weisberg and Baker (1995); [12]MacMahon and Andersen (1982); [13]Marr (1967); [14]Schröter (1926), Holtmeier (1965, 1974), Mayer (1974), Tranquillini (1979a), Ozenda (1988), Piussi and Schneider (1985); [15]Geiger (1901), Schröter (1926), Scharfetter (1938), Schmidt (1969), Troll (1973), Tranquillini (1979a); [16]Strasburger et al. (1991); [17]Walter (1973), Holtmeier (1993a, 1995a); [18]Walter (1973).

pattern, thickness, duration) on site conditions (soil temperature, soil moisture, length of the growing season, etc.) and tree growth (Section 4.3.7). The upper climatic timberline in the tropics could be called ‘tropical cold timberline’. If necessary, this term might be specified by using ‘African cold timberline’ (instead of ‘Afroalpine timberline’, Wesche, 2002) or ‘Andean cold timberline’, for example, instead of ‘tropical alpine treeline’ (Bader, 2007; Bader et al., 2007; Wesche et al., 2008).

The upper timberline at its maximum altitudinal position (postglacial optimum) is called historic timberline. It had advanced to considerably higher elevation and northern position than the present climatic timberline. Potential timberline means the altitudinal position forest could achieve at the present climate without being disturbed by human impact.

In general, the use of the terms timberline, tree line, forest limit etc. is rather ambiguous. Thus, in many cases it does not become clear whether the author refers to the upper limit of closed forest, to the entire ecotone or to the upper tree line. The last term, for example, may refer to the ecotone or to tree line in the proper sense as well (Table 4). Occasionally, however, clear differences are made. Habeck and Hartley (1968), for example, consider the upper limit of closed forest as ‘forest line’, the upper limit of upright growing trees (arborescent growth) as ‘tree line’ (see also Rochefort et al., 1994; Price, 1981) and the altitudinal limit of crippled tree individuals as ‘scrub line’ (see also Arno, 1984). By Rochefort et al. (1994) again ‘scrub line’ is called ‘tree limit’ (in contrast to ‘tree line’), ‘krummholz limit’ (e.g., MacMahon and Andersen, 1982) or ‘tree species limit’ (e.g., Heikkinen, 1984). Griggs (1938) instead uses the term ‘cripple line’. All these terms refer to climatically caused altitudinal limits of forest or trees. In case of controlling factors other than climate, adjectives such as ‘anthropogenic’ or ‘orographic’ are added.