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THE SENSITIVITY OF THE AUSTRIAN FORESTS TO SCENARIOS OF CLIMATIC CHANGE

A Large-scale Risk Assessment

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Summary

In the present study a large-scale climate change impact assessment for Austrian forests is presented. Due to ongoing discussions on a possible global climate change the study aimed at (i) identifying areas which are sensitive to changing climatic conditions, and (ii) indicating the magnitude of potential impacts of a changing climate on currently existing forests. Further key issues of the present study were to integrate available data of the Austrian Forest Inventory, the Austrian Forest Soil Survey and an extensive network of weather stations (Zentralanstalt für Meteorologie und Geodynamik, Hydrographischer Dienst) with ecological models.

A recently developed 3D-patch model was initialised at a representative subset of sample points of the Austrian Forest Inventory (AFI) with ground-true spatially explicit site and stand data. Current climatic conditions at the inventory points were represented by the period 1961-1995. Monthly temperature and precipitation data of that period were interpolated to the inventory plots from an extensive network of more than 600 weather stations of the Austrian weather services. The construction of climate change scenarios was based on regionalized output of the global circulation model (GCM) ECHAM4. In an attempt to regionalize scenario output of the global circulation model statistical downscaling techniques were employed. Principal component analysis (PCA) was used to condense the information content of temperature, relative humidity and geopotential height fields at three pressure levels at the coarse grid scale of global circulation models for a window extending from Central Europe west across the Atlantic ocean. Principal components of the meteorological variables at the coarse scale were then used as predictors in multiple linear regression models of temperature and precipitation respectively at each inventory plot at the local scale. The regression models were calibrated with the NCEP/NCAR data set. The regression models calibrated with the NCEP/NCAR data were used to regionalize the climate data as simulated by ECHAM4 under both, a control run with a trace gas concentration of the atmosphere according to 1990, and the “business as usual” greenhouse gas emission scenario IS92a of the Intergovernmental Panel on Climate Change (IPCC) (“disturbed run”) from the coarse grid scale to the inventory plots at the local scale for the period 2000-2065. The time series of monthly temperature and precipitation from 2000 to 2050 was used to simulate the transient response of currently existing forests to a changing climate. From 2050 on the climate was considered as being stable and was represented by the regionalized climate scenario data of the period 2035-2065. Monthly values for temperature and precipitation were stochastically sampled from a normal distribution fitted to data from that period in case of temperature, and from a 2-parameter gamma distribution in case of precipitation.

This attempt to regionalize transient climate data from GCM experiments under the "business as usual" scenario IS92a of the IPCC yielded spatial heterogeneous results for both temperature and precipitation. While temperature showed a generally increasing trend with a mean increase for the represented forest area of appr. +0.8 °C by the year 2050 compared to the average of the period 1961-1995, the pattern of regionalized precipitation anomalies comprised both increases and decreases of up to +/–7%. To complete the envelope of possible future climatic conditions two additional climate change scenarios were constructed based on the regionalized scenario (scA). Scenario scB with a temperature increase of +2 °C by the year 2050 and precipitation as under scenario scA, and scenario scC with the same temperature assumptions as in scenario scB but with an additional decrease in summer precipitation of -15 % by the year 2050 compared to scenario scA.

Vegetation development at each investigated sample point was simulated under current climate (baseline scenario) as well as under the three climate change scenarios without management interventions. Under baseline conditions as well as under scenario scA a total of 2830 sample points were simulated, under scenarios scB and scC the sample size was reduced to 708 inventory points. Similarity measures between simulated vegetation under baseline and under climate change conditions were used to evaluate the impact of a chang-

ing climate for (1) the transient phase 2000 to 2050, and (2) the equilibrium state (i.e., potential natural vegetation (PNV)). Prior to the risk assessment the plausibility of simulated equilibrium species composition was compared to expert reconstructions of PNV available for the forest inventory plots. Based on this model evaluation it was concluded that the employed forest model PICUS v1.2 was capable of reproducing the expected spatial pattern of equilibrium species composition in the Eastern Alps reasonably well.

Major findings of the risk assessment were:

(1) Severe short-/midterm impact of the moderate warming scenario scA on existing forests with substantial tree mortality was simulated for appr. 3% of the inventory plots included in the study. However, stands not well adapted to site conditions showed substantial periodic tree mortality even under the baseline scenario. The latter result is corroborated by statistics on salvage cuttings in Austrian forests. Under conditions of scenarios scB (strong warming) the proportion of sample points showing severe impacts due to the changing climate increased to 12%, while under scenario scC (strong warming , additional decrease of precipitation) just a slight additional increase of such severe impact stands to 14% occurred. Particularly Norway spruce stands at low elevations in the eastern and partly in the southern parts of Austria responded rather sensitive to small variations in soil moisture supply.

(2) Short-/midterm impact indices representing the transient response of currently existing forests as recorded by the Austrian Forest Inventory from 2000 to 2050 differed strongly from long-term indices derived from PNV. At lower elevations (today's colline and submontane vegetation belt below 900 m a.s.l.) with frequently occurring secondary Norway spruce forests at sites naturally supporting broad-leaved species mixtures increased tree mortality compared to current climatic conditions was simulated due to increased frequency of drought periods and subsequent bark beetle infestations. While this was an expected response of current forests which are known to suffer from periodical mortality events even under current climatic conditions, the simulated potential natural vegetation at such sites in general showed only minor indications of climate change impacts. The opposite holds true for high altitude sites. At these sites the substantial increase of temperature under scenarios scB and scC resulted in a major shift of the simulated PNV species pool towards broad-leaved species. Thus, despite no indications for immediate adverse effects of a changing climate (as indicated by low impact categories of short-/midterm indices), the long-term implications of the applied climate change scenarios for the competitive interrelationships of tree species might be substantial.

(3) Under the marked warming conditions of scenarios scB and scC (+2 °C by 2050) the potential impact derived from short-/midterm (2000-2050) as well as from long-term indices (derived from simulated shifts in PNV) was significantly larger compared to the moderate warming conditions of scenario scA. According to a sensitivity index based on both, short-/midterm and long-term measures, the share of sample points with low expected climate change impacts decreased from 67.3 % under conditions of scenario scA (moderate warming) to 18 % under scenario scB (strong warming), and finally to 15.5 % under scenario scC (strong warming, reduced precipitation). From these simulation results it might be concluded that climate change conditions as represented by scenario scA seemed to characterise some kind of threshold beyond which the severity of potential climate change impacts might increase substantiall.

Kurzfassung

Hintergrund und Problemstellung

Szenarien einer anthropogen bedingten Klimaänderung werfen die Frage nach möglichen Auswirkungen auf heimische Waldökosysteme auf. Prognosen über das Ausmaß sowie die zeitliche Entwicklung einer solchen Klimaänderung sind nach wie vor hochgradig mit Unsicherheit verbunden. Im wesentlichen deuten alle verfügbaren globalen Klimamodelle (GCM; global circulation models) denselben Entwicklungstrend für den Bereich Mitteleuropa an: Eine mehr oder weniger starke Erhöhung der Jahresmitteltemperatur im Ausmaß von etwa +1 bis +2.5 °C bis zum Jahr 2050. Hinweise deuten darauf hin, dass die Temperaturen im Winter stärker ansteigen werden als im Sommer, die Temperaturminima wiederum stärker als die Maxima. Die Aussagen in bezug auf den Niederschlag variieren zwischen den Klimamodellen sowohl in bezug auf die Richtung der Veränderung als auch in bezug auf Größenordnung und saisonale Differenzierung.

Aufgrund der Bedeutung von Waldökosystemen für den Kohlenstoffhaushalt, die Erhaltung der Biodiversität, den Schutz vor Naturgefahren, die Sicherung der Trinkwasserressourcen und die nachhaltige Produktion des Rohstoffes Holz beschäftigten sich weltweit bereits viele Klimafolgenabschätzungen mit Wäldern. Neben der generellen Komplexität von Waldökosystemen erschwert die Langlebigkeit von Baumpopulationen diese Studien. In Form von Szenarioanalysen ("Was wäre, wenn ...?") wird dabei versucht, mit Simulationsmodellen die Wirkung von Klimaänderungsszenarien auf Ökosysteme abzuschätzen, um so die Bandbreite möglicher Systemreaktionen zu identifizieren. Die Relevanz einer möglichen tiefgreifenden Veränderung in den ökologischen Rahmenbedingungen für die Waldbewirtschaftung ist offensichtlich, hängt doch der Bewirtschaftungserfolg weitgehend von der Angepasstheit der Waldbestände an die jeweiligen Standortsbedingungen ab.

Für Österreich liegen bis dato keine quantitativen flächendeckenden Studien der möglichen Auswirkungen einer Klimaänderung auf heimische Waldökosysteme vor.

Angewendete Methoden

In der vorliegenden Studie wurden Daten der Österreichischen Waldinventur (FBVA 1995), der Österreichischen Waldbodenzustandsinventur (Englisch et al. 1991), der Zentralanstalt für Meteorologie und Geodynamik sowie des Hydrographischen Dienstes mit ökologischen Simulationsmodellen integriert. Um den österreichischen Wald (Witschaftswald, Schutzwald im Ertrag) repräsentativ zu erfassen, wurden 2830 Erhebungspunkte der Waldinventur ausgewählt. Auf diesen Inventurpunkten wurde das Waldsukzessionsmodell PICUS v1.2, welches am Institut für Waldbau an der Universität für Bodenkultur entwickelt wurde, gemäß den von der Waldinventur bzw. der Waldbodenzustandsinventur erhobenen Standorts- und Bestandesmerkmalen initialisiert. Simuliert wird von PICUS Wachstum, Verjüngung sowie Mortalität von Einzelbäumen auf vielen jeweils 100 m^2 großen Kleinflächen, die in Summe die Entwicklung eines Waldbestandes charakterisieren. Da der Effekt von Temperatur, Wasser- und Nährstoffversorgung an einem simulierten Standort dabei explizit berücksichtigt wird, können mit PICUS die Auswirkungen einer Klimaänderung auf die Waldentwicklung abgeschätzt werden.

Um das Waldmodell anwenden zu können, werden monatliche Temperatur- und Niederschlagsdaten zu dessen Betrieb benötigt. Um das gegenwärtige Klima zu repräsentieren, wurden Temperatur- und Niederschlagsdaten der Periode 1961-1995 von über 600 Messstationen der Zentralanstalt für Meteorologie und Geodynamik und des Hydrographischen Dienstes an die Waldinventurpunkte extrapoliert. Zur Konstruktion von Klimaänderungsszenarios wurde erstmals flächendeckend für Österreich versucht, ein durch ein globales Klimamodell berechnetes Klimaänderungsszenario zu regionalisieren. Globale Klimamodelle berechnen Klimaänderungsszenarien auf sehr grober Auflösung auf einem Gitternetz von etwa 100 x 100 km^2. Die direkte Verwendung der auf diesen Gitterpunkten simulierten Klimaszenarien auf lokaler Ebene kann zu groben Fehlinterpretationen führen und entspricht heute nicht mehr dem Stand des Wissens.

Um Ergebnisse des Klimamodells ECHAM4 des Deutschen Klimarechenzentrums (DKRZ) für Inventurpunkte zu "regionalisieren", wurde folgende Methode angewendet. Ein vom National Centre of Atmospheric Research in Boulder, Colorado (NCEP/NCAR) zur Verfügung gestellter Datensatz (Temperatur, relative Feuchte, geopotentielle Höhe auf Monatsbasis) liegt auf einem dem Modelloutput von ECHAM4 vergleichbaren Gitternetz vor. Die Daten eines geographischen "Fensters", welches von Zentraleuropa bis in den Nordatlantik reichte und das für das Wettergeschehen in Mitteleuropa entscheidend ist, wurde dazu verwendet, um einen statistischen Zusammenhang zwischen den Klimadaten auf dem groben Gitternetz (Makrovariable) und den Klimadaten auf den Inventurpunkten (Mikrovariable) herzuleiten. Um die Datenmenge (429 Gitterpunkte x 420 Monate der Periode 1961-1995) zu reduzieren, wurde eine Hauptkomponentenanalyse durchgeführt. Die resultierenden Hauptkomponenten der Klimavariablen auf dem groben Gitternetz wurden in multiplen linearen Regressionsmodellen als Prediktoren der lokalen Temperatur- bzw. Niederschlagsdaten verwendet. Dabei erklärten die Modelle für monatliche Temperaturmittel im Mittel 86% der Variabilität, die Modelle für den Monatsniederschlag im Mittel 55%.

Im Allgemeinen bestätigte sich, dass Niederschlagsdaten für stark gegliedertes Gelände wie den Alpenraum jedoch schwierig zu regionalisieren sind. Nachdem die Modelle mit den NCEP/NCAR-Daten parametrisiert wurden, wurden die Temperatur- bzw. Niederschlagsanomalien von zwei durch das Klimamodell ECHAM4 gerechnete Klimaszenarien an die Waldinventurpunkte „transferiert“. Bei den zwei Szenarien handelte es sich um (a) den sogenannten "control run" unter den Treibhausgasbedingungen des Jahres 1990, und (b) um den sogenannten "disturbed run" der dem "business as usual" – Szenario IS92a des Intergovernmental Panel on Climate Change (IPCC) entspricht (historische Treibhausgaskonzentration von 1860 bis 1990, danach bis 2099 eine jährliche Zunahme der Treibhausgase um 1%). Beide Szenarien lagen für die Periode 2000 bis 2065 vor. Die regionalisierte Periode 2000-2050 wurde verwendet, um die transiente Übergangsphase einer Klimaänderung zu charakterisieren. Ab dem Jahr 2050 wurde das Klima wiederum als stabil angenommen.

Das veränderte Klima ab dem Jahr 2050 wurde durch die Periode 2035-2065 repräsentiert. Dieses regionalisierte Klimaänderungsszenario wurde als Szenario scA bezeichnet. Bezogen auf das Jahr 2050 betrug die Temperaturerhöhung im Mittel über Österreich etwa +0.8 °C. Die relativ stärkste Erwärmung entfiel auf (a) die Sommermonate, und (b) die nördlichen und westlichen Landesteile. Die Niederschlagsveränderungen des regionalisierten Szenarios scA wiesen eine höhere räumliche Heterogenität auf als die Temperaturveränderungen (Abb. 4-3a-d) und betrugen bis +/-7% bezogen auf die Jahresniederschlagssumme. Am stärksten reduzierten sich die Niederschläge in den nördlichen Randalpen. Winterniederschlagsveränderungen wiesen eine höhere räumliche Heterogenität auf als die Veränderungen der Sommerniederschläge. Die sommerlichen positiven Anomalien (Zunahmen) des Niederschlags waren relativ klein und auf einige kleinere Regionen im Süden Österreichs beschränkt (Abb. 4-5a-d).

Um die Bandbreite möglicher zukünftiger Klimabedingungen für die Risikoanalyse zu vergrößern, wurden zwei weitere Klimaänderungsszenarien konstruiert. Szenario scB ging von einer Temperaturzunahme bezogen auf das Jahr 2050 von +2 °C aus. Dabei wurde die Variabilität der Temperaturzeitreihe des Szenarios scA beibehalten (Abb. 4-6). Der Niederschlag wurde wie im Szenario scA verwendet. Das Szenario scC schließlich kombinierte die stärkere Temperaturzunahme des Szenarios scB mit einer zusätzlichen Niederschlagsreduktion während des Sommerhalbjahres (April-September) von 15% bezogen auf die Niederschlagsverhältnisse im Szenario scA (vgl. Tab. 4-1).

Die Waldentwicklung auf jedem der ausgewählten Inventurpunkte wurde nun beginnend mit dem "heutigen" Bestandeszustand laut Waldinventur simuliert. Unter gegenwärtigem Klima (baseline scenario) und unter dem Klimaänderungsszenario scA wurden alle ausgewählten Waldinventurpunkte verwendet, unter den Szenarien scB und scC jeweils ein reduzierter Datensatz von etwa 700 Punkten. In den Simulationen wurde keine Bestandesbehandlung berücksichtigt ("natürliche Waldentwicklung"). Dieses Vorgehen wurde gewählt, da (a) die Festlegung auf ein bestimmtes Bestandesbehandlungsprogramm in plausibler Weise wegen der vielen variierenden Merkmale (Ausgangsbestand, Standort, Klimaänderung, Besitzstruktur, Bewirtschaftungsziele) nicht möglich war und ein Szenario im Szenario dargestellt hätte, und (b) eine simulierte waldbauliche Behandlung es erschwert bis unmöglich gemacht hätte, den Effekt des Klimaänderungsszenarios auf die aktuell bestehenden Wälder isoliert zu betrachten. Für die Simulationsperiode 2000-2050 konnten sich laut Szenariodefinition neben Pionierbaumarten nur solche Baumarten potentiell im Modell verjüngen, die im Ausgangsbestand laut Waldinventur vertreten waren. Danach waren alle Baumarten potentiell verfügbar und es von der jeweiligen Konkurrenz- und Umweltsituation abhängig, ob und welche Arten sich verjüngen konnten. Für die Simulationsperiode 2000-2050 wurde die Zeitreihe des jeweiligen Klimaänderungsszenarios zum Betrieb des Modells verwendet. Ab dem Simulationsjahr 2050 wurde das Klima mit dem Wettergenerator in PICUS auf der Grundlage der Periode 2035-2065 des jeweiligen Klimaänderungsszenarios stochastisch erzeugt. Insgesamt wurden je Inventurpunkt und Szenario 1400 Simulationsjahre absolviert. Diese Simulationsdauer ist für PICUS notwendig, um eine im Gleichgewicht mit dem jeweiligen Standort befindliche Baumartenzusammensetzung zu simulieren (entspricht der potentiellen natürlichen Vegetation (PNV) im Sinne Tüxens (1956)).

Um den Effekt eines Klimaänderungsszenarios auf aktuell bestehende Wälder abzubilden, wurde wie folgt vorgegangen (Abb. 3-2).

(1) Um die Reaktion des Ausgangsbestandes auf den simulierten Inventurpunkten in der transienten Phase 2000-2050 zu erfassen, wurde alle zehn Jahre (Simulationsjahre 2010, 2020, 2030, 2040, 2050) die simulierte Vegetation unter dem gegenwärtigen Klima (baseline scenario) jeweils mit der simulierten Vegetation unter einem der drei Klimaänderungsszenarien (scA, scB, scC) verglichen und der Unterschied mittels eines Ähnlichkeitsmaßes quantifiziert.

(2) Um die potentielle langfristige Auswirkung eines Klimaänderungsszenarios auf einen bestehenden Waldbestand abzuschätzen, wurden zwei Analysekriterien abgeleitet, die auf dem Konzept der potentiellen natürlichen Vegetation (PNV) basieren. Um eine mögliche Veränderung des ökologischen Standortspotentiales zu erfassen, wurde die simulierte PNV unter aktuellem Klima (baseline scenario) mit der simulierten PNV unter einem Klimaänderungsszenario verglichen. Schließlich wurde noch geprüft, ob sich die Abweichung der Baumartenzusammensetzung des aktuell existierenden Waldbestandes auf einem Inventurpunkt von der simulierten PNV unter einem Klimaänderungsszenario vergrößert im Vergleich zur simulierten PNV unter aktuellem Klima.

Die so ermittelten Analysekriterien wurden im Hinblick auf mögliche Effekte bewertet (Abb. 3-3) und in einem hierarchischen Ansatz sowohl zu einem Indikator für das Kurz-/Mittelfristverhalten von Wäldern unter Klimaänderungsbedingungen (SMS) als auch zu einem Indikator für potentielle Langfristwirkungen einer Klimaänderung (LI) aggregiert. SMS und LI wurden schließlich zu einem allgemeinen Klimafolgenindex (CCI) verbunden.

Ergebnisse

Bevor PICUS v1.2 zur Abschätzung der potentiellen Auswirkung von Klimaänderungsszenarios auf bestehende Wälder eingesetzt wurde, erfolgte eine Überprüfung, inwieweit das Modell unter den für diese Studie gegebenen Rahmenbedingungen (Einsatz auf Inventurpunkten, extrapolierte Klimadaten) imstande ist, plausible potentielle natürliche Vegetationszusammensetzungen auf 2830 Erhebungspunkten der Österreichischen Waldinventur unter aktuellem Klima zu simulieren. Die simulierte potentielle natürliche Vegetationszusammensetzung wurde mit den für sämtliche Inventurpunkte vorliegenden Expertenansprachen der PNV verglichen. Wurden nur solche simulierten Baumartenzusammensetzungen als korrekt bezeichnet, die sämtliche Bedingungen in bezug auf Basis der Vegetationskunde für jeden PNV-Typ definierte maximal mögliche bzw. minimal erforderliche Artenanteile erfüllten, stimmten in 40.2% aller Fälle Simulation und Expertenansprache überein (Tab. 5-4). Dies stimmt gut mit den Resultaten anderer Modellevaluierungen in der Literatur überein. Bedenkt man zusätzlich, dass (a) natürlich eine simulierte Baumartenkombination nicht als unplausibel zu bezeichnen ist, sollten Schwellenwerte für einzelne Arten geringfügig über- oder unterschritten worden sein, und (b) die Expertenansprache natürlich ebenfalls nur ein (allerdings nicht formalisiertes) Modell darstellt, wurde gefolgert, dass PICUS imstande ist, für den Ostalpenraum überaus plausible Vegetationszusammensetzungen zu generieren.

Wesentliche Ergebnisse der Risikoanalyse waren:

(1) Unter den Bedingungen des Klimaänderungsszenarios scA (moderate Erwärmung) zeigten sich für ca. 3% aller betrachteten Inventurpunkte starke Auswirkungen durch das veränderte Klima (Wirkungsklassen 4 und 5 von insgesamt 5 Klassen für den Kurz-/Mittelfristindikator SMS). Dieser Anteil erhöhte sich unter den Bedingungen des Szenarios scB (starke Erwärmung) auf ca. 13%, im Falle des Szenarios scC (starke Erwärmung, zusätzliche Abnahme des Niederschlages im Sommerhalbjahr von 15%) auf ca. 14%. Für einen Großteil der in diesen Kategorien erfassten Bestände bedeutet dies, dass in der Periode 2000-2050 starke Baummortalität (Nettobiomassenverlust innerhalb einer Dekade >20%) simuliert wurde. Der Anteil von Inventurpunkten, auf denen PICUS v1.2 schon unter gegenwärtigem Klima (baseline scenario) periodische Mortalität dieser Größenordnung simulierte, betrug 1.3%. Hauptsächlich betroffen waren davon Fichtenbestände (Picea abies (L.) karst.), die gemäß den Modellannahmen sehr sensitiv auf Veränderungen des Wasserhaushalts reagierten. Die Klassen 4 und 5 des Kurz-/Mittelfristindikators SMS beschränkten sich unter den Bedingungen der Szenarien scA und scB auf die heutige kolline, submontane und tiefmontane Höhenstufe. Unter Szenario scC erstreckte sich der Vorkommensbereich solcher starken Klimaänderungseffekte bis in die heutige mittelmontane Höhenstufe. Der Anteil der Inventurpunkte, auf denen die simulierten Bestände kaum oder nur sehr schwache Wirkung erkennen ließen, reduzierte sich von knapp 71% unter Szenario scA (moderate Erwärmung) auf ca. 53% unter den Szenariobedingungen von scB (starke Erwärmung) und scC (starke Erwärmung, zusätzliche Reduktion des Niederschlags im Sommerhalbjahr um 15%).

(2) Der von Veränderungen der simulierten potentiellen natürlichen Vegetation (PNV) und Vergleichen der Baumartenzusammensetzung in aktuell bestehenden Beständen mit simulierter PNV abgeleitete Langfristindikator LI zeigt ein deutliches Ansteigen des Anteiles von Inventurpunkten, für die die Modellergebnisse starke bis sehr starke Auswirkungen von klimatischen Veränderungen anzeigen (Kategorien 4 und 5 des Indikators LI), von 1.2% unter Bedingungen des Szenarios scA, über 25.8% unter Szenario scB bis 43.4% unter den Bedingungen des Szenarios scC. Gleichzeitig reduziert sich der Anteil derjenigen Punkte, für die nur sehr schwache langfristige Auswirkungen erwartet wurden, von ca. 42% unter Szenario scA, auf knapp 1% unter Szenario scC (Tab. 5-10). Der Anteil von Inventurpunkten, die den LI-Kategorien 4 und 5 zugeordnet wurden, konzentrierte sich auf höhergelegene Standorte. Unter Szenario scA auf die heutige subalpine Höhenzone beschränkt, erweitert sich der Vorkommensbereich solcher Punkte unter Szenario scB jedoch bis in die heutige mittelmontane, unter Szenario scC bis in die tiefmontane Höhenstufe.

(3) Werden Kurz-/Mittelfristindikator SMS und Langfristindikator LI zu einem Index für die allgemeine Wirkung einer Klimaänderung auf bestehende Wälder kombiniert (CCI), zeigt sich wiederum deutlich das Ansteigen von starker und sehr starker simulierter Klimafolgenwirkung (CCI-Kategorien 3 und 4) unter den Szenarien scB (24.4%) und scC (39.9%) im Vergleich zu den Bedingungen unter dem Szenario scA (6.7%) (Tab. 5-11 und Abb. 5-28). Verglichen nach heutigen Höhenzonen erwies sich die Zunahme der Klimaänderungsfolgen unter Szenario scB (starke Erwärmung) im Vergleich zu Szenario scA (moderate Erwärmung) mit Ausnahme der kollinen Stufe immer als signifikant ($\alpha = 0.05$). Unter Szenario scC (starke Erwärmung, zusätzliche Reduktion der Niederschläge im Sommerhalbjahr um 15%) erfolgte eine weitere signifikante Zunahme des Indikators CCI

verglichen mit dem Szenario scB nur mehr in der mittel- und hochmontanen Höhenstufe. Werden die Ergebnisse getrennt nach Hauptwuchsgebieten betrachtet, ist die Zunahme der CCI-Kategorie 4 (sehr starke Auswirkung einer Klimaänderung) in den Hauptwuchsgebieten 4 (Nördliche Randalpen), 5 (Östliche Randalpen), 6 (Südliche Randalpen), 7 (Nördliches Alpenvorland), und 9 (Mühl- und Waldviertel) am stärksten. Nur relativ gering ist die CCI-Kategorie 4 im Hauptwuchsgebiet 8 (Sommerwarmer Osten) vertreten. Dies ist allerdings primär darauf zurückzuführen, dass die Indikatoren den Effekt einer Klimaänderung charakterisieren und viele aktuelle Bestände bereits unter dem gegenwärtigen Klima (baseline scenario) nur mangelhaft an die jeweiligen Standortsverhältnisse angepasst erscheinen. Der zusätzliche negative Effekt einer klimatischen Veränderung fällt dann oft nur mehr geringfügig aus. Mag somit der Anteil der Punkte in Wirkungskategorie 4 (starke Auswirkung einer Klimaänderung) aus diesem Grund oft als niedrig erscheinen, ist aber im Gegensatz dazu der Anteil der CCI-Kategorie 1 (schwache Auswirkung einer Klimaänderung) im Sommerwarmen Osten am niedrigsten (Tab. 5-13). Als besonders anfällig für Klimaänderungsfolgen erweisen sich wie erwartet fichtenreiche Bestände in Tieflagen. Unter den Bedingungen des Klimaänderungsszenarios scC wurden in der heutigen kollinen Höhenstufe über 66% aller Bestände mit mindestens 50% Biomassenanteil der Fichte der CCI-Kategorie 4 zugeordnet, 54% in der submontanen Zone und immerhin noch knapp 44% in der tiefmontanen Höhenstufe (Abb. 5-31).

(4) Alle Inventurpunkte, für die eine Ansprache der Verjüngungssituation durch die Österreichische Waldinventur vorlag, wurden daraufhin analysiert, inwieweit die vorhandene Verjüngung mit der Artenzusammensetzung der unter den drei Klimaänderungsszenarien (scA, scB, scC) simulierten potentiellen natürlichen Vegetation (PNV) übereinstimmt. In einem solchen Fall kann das natürliche Adaptionspotential von heute bestehenden Waldbeständen als günstig eingestuft werden. Betrug der Anteil solcher Inventurpunkte unter gegenwärtigem Klima (baseline scenario) über 76% und unter Szenario scA (moderate Erwärmung) immerhin knapp über 75%, reduzierte sich dieser Anteil unter Szenario scB (starke Erwärmung) auf 66%, unter Szenario scC (starke Erwärmung, zusätzliche Reduktion des Niederschlags im Sommerhalbjahr um 15%) auf ca. 45% (Tab. 5-14).

Folgerungen

Anhand der Ergebnisse kann gefolgert werden, dass eine Temperaturerhöhung von etwa +1 °C (Jahresmittel) bezogen auf die Periode 1961-1995 bei im wesentlichen unveränderten Niederschlägen einen Schwellenwert darzustellen scheint, ab dem es zu starkem Ansteigen der Auswirkungen auf bestehende Wälder kommen dürfte. Zusätzlich reduzierte Niederschläge während der Vegetationsperiode verschärfen diese Situation zusätzlich. Bereits unter gegenwärtigem Klima (repräsentiert durch die Periode 1961-1995) treten in Tieflagen insbesondere in fichtendominierten Waldbeständen klimainduzierte Schäden auf. Auffallend das stark kontrastierende Verhalten von Kurz-/Mittelfristindikator SMS und Langfristindex LI. Während der Indikator SMS vor allem konzentriert in tieferen Lagen erhebliche Probleme im Falle von klimatischen Veränderungen wie sie durch die drei Klimaänderungsszenarien (scA, scB, scC) repräsentiert wurden anzeigt, deutet der auf dem PNV-Konzept beruhende Langfristindikator LI auf deutliche subtiler wirkende Folgen einer Klimaveränderung in höheren Lagen hin. In diesen Lagen stellen die Temperaturverhältnisse für viele Laubbaumarten einen limitierenden Faktor dar, was im Falle einer Erwärmung zu einer drastischen Veränderung der Konkurrenzverhältnisse zwischen den Baumarten führen dürfte. In den heute schon trockenen und warmen Regionen (Sommerwarmer Osten, Alpenvorland, Niederösterreichischer Alpenostrand, Klagenfurter Becken) nimmt den Modellresultaten zufolge der Anteil von trockentoleranteren Eichenarten (Quercus petraea, Quercus cerris, teilw. Quercus pubescens) und teilweise Weißkiefer (Pinus sylvestris) auf heutigen Eichenstandorten zwar zu, jedoch deutet unter den analysierten Klimaänderungsszenarien nichts auf eine Tendenz zur Versteppung hin. Es muss jedoch angemerkt werden, dass die in dieser Studie involvierten Waldinventurpunkte eventuell nicht die extremsten Standorte der östlichen Regionen Österreichs repräsentieren. Für heutige potentielle natürliche Buchenwaldstandorte wird auch in den meisten Fällen unter den Klimaänderungsszenarien eine buchendominierte PNV simuliert. Der Buchenanteil in den montanen Höhenstufen nimmt unter den wärmeren Bedingungen der Szenarien scA, scB und scC deutlich zu. Es sollte jedoch Klarheit darüber bestehen, dass die Interpretation von ausgewiesenen Klimafolgenkategorien, die in einem indirekten Ansatz von der potentiellen natürlichen Vegetation abgeleitet wurden (z.B., Indikator LI), natürlich entsprechend limitiert ist und der Berücksichtigung der jeweiligen Standortsverhältnisse bedarf. So ist es offensichtlich, dass beispielsweise ein berechnetes Ähnlichkeitsmaß von PS = 0.5 zwischen der simulierten PNV unter gegenwärtigem Klima und unter einem Klimaänderungsszenario auf einem Eichenstandort im Sommerwarmen Osten anders zu interpretieren ist, als ein entsprechendes Ergebnis auf einem heutigen hochmontanen Fichtenstandort.

Was bedeuten die Ergebnisse im Hinblick auf die Waldbewirtschaftung? In höhergelegenen Lagen (heutige montane bis subalpine Höhenstufe) wären die grundsätzlichen Konsequenzen einer klimatischen Veränderung wie sie in den Klimaänderungsszenarien scA, scB und scC abgebildet wurden, ein vergrößerter waldbaulicher Entscheidungsraum sowohl in Fragen von Baumartenwahl als auch in Fragen geeigneter Naturverjüngungsverfahren. Dies würde den Anspruch an den waldbaulichen Planungsprozess in diesen Höhenlagen deutlich steigern. Die Modellergebnisse zeigen auch, dass unter den Bedingungen der Klimaänderungsszenarien scB und scC mit Temperaturerhöhungen von jeweils +2 °C davon ausgegangen werden kann, dass eine geregelte nachhaltige Bewirtschaftung von Fichtenwäldern in der heutigen kollinen, submontanen und teilweise in der tiefmontanen Höhenstufe weitestgehend ausgeschlossen werden kann. In Tieflagen ließe in Fragen der Baumartenwahl eine Orientierung an der potentiellen natürlichen Vegetation (PNV) eine Milderung der laut Modellberechnungen erwarteten Klimaänderungsfolgen erwarten. Dies ist hauptsächlich darauf zurückzuführen, dass ein großer Anteil der heutigen Waldbestände schon unter den gegenwärtigen Klimaverhältnissen eindeutig als schlecht an die jeweiligen Standortsverhältnisse angepasst bezeichnet werden muss. Worauf jedoch ebenfalls hingewiesen werden soll, ist der Umstand, dass die potentielle natürliche Vegetation zwar indirekt die Eignung der in der PNV vertretenen Baumarten anzeigt, in Mischung nachhaltig quasi “natürlich” koexistieren zu können ohne die Standortsqualität negativ zu beeinträchtigen, jedoch keine fundierten Aussagen zur ökophysiologischen Eignung (d.h. zur physiologischen Amplitude) der einzelnen Arten per se zulässt. Der Vollständigkeit halber sei noch angemerkt, dass eine Baumartenzusammensetzung die aus der “Orientierung” an der PNV resultiert, keinesfalls den Zielsetzungen der Waldbewirtschaftung entsprechen muss. Angesichts der in der Praxis naturgemäß eingeschränkten Detailliertheit bei der Rekonstruktion von potentiellen natürlichen Vegetationseinheiten und der damit verbundenen Unsicherheiten ist eine stärkere Berücksichtigung autökologischer Arteigenschaften anzuraten.

Schließlich muss angemerkt werden, dass die Ergebnisse der vorliegenden Studie nicht als Prognosen aufgefasst werden dürfen. Ausschlaggebend dafür sind sowohl die Unsicherheiten in bezug auf die zukünftige Klimaentwicklung als auch in bezug auf das vorhandene Wissen zu physiologischen Ansprüchen und synökologischem Verhalten der heimischen Baumarten. Schließlich muss berücksichtigt werden, dass neben den ökologischen Rahmenbedingungen die gesellschaftliche und sozioökonomische Entwicklung wesentliche Determinanten der zukünftigen Entwicklung unserer Wälder sein werden. Der präsentierte methodische Ansatz erwies sich als gut geeignet, um Regionen und ökologische Bedingungen, unter denen heute bestehende Wälder besonders sensitiv auf klimatische Veränderungen reagieren könnten, zu identifizieren. Für besonders sensible Regionen empfehlen sich zusätzliche Detailanalysen zur Identifizierung von Risikopotentialen mit detaillierteren Modellansätzen. Solche detaillierteren Modellansätze würden einen bei weitem höheren Datenaufwand bedeuten (Klima, Boden) und könnten in einem großräumigen Maßstab wie in der vorliegenden Studie nur mit erheblichem Mehraufwand durchgeführt werden. Schließlich bedarf die modellgestützte Entwicklung und Analyse von optimierten Waldbehandlungsstrategien im Rahmen einer Mehrzweckforstwirtschaft unter Berücksichtigung veränderlicher Umweltbedingungen vermehrter Aufmerksamkeit.

1 INTRODUCTION

Scenarios of a global climate change gave rise to questions on the possible effects of a changing climate. Although mechanisms and magnitudes of possible changes in the earth's climate are still unclear it is common scientific understanding that anthropogenic activities such as burning of fossil fuels and various land use practices are significantly altering the composition of the earth's atmosphere. Under such conditions essentially all available global circulation models (GCMs) indicate a general trend of increasing mean temperatures regardless of the underlying greenhouse gas emission scenario. However, the range of climate model projections includes increases from +1.5 °C to as much as +4 °C for the year 2100 depending on the model used and on the underlying emission scenario (Houghton et al. 1990, 1996). With regard to precipitation substantial differences among the models occur regarding to the spatial pattern of precipitation anomalies as well as to the direction of change.

Due to the potential long-term consequences of a changing climate much attention has been paid to climate change impact studies. Particular attention has focused on the likely impacts of climatic change on forest ecosystems due to several reasons. Forests cover substantial parts of the globe, they are closely coupled to the earth's climate system due to their key role in the global carbon and water cycles, and they maintain a major portion of the earth's biodiversity. Furthermore, forests are particularly vulnerable to changing environmental conditions due to the longevity of most tree species. The key role of forests becomes directly apparent in mountain areas. For instance, in Central Europe forests serve a multitude of functions and play an irreplaceable role in maintaining alpine landscapes. Beyond supporting industries by producing timber these forests protect settlements and infrastructure from natural hazards such as avalanches and rockfall, they prevent soil erosion and play a key role in maintaining biodiversity in landscapes that have been cultivated since thousands of years (Scheiring 1999). Recently the importance of forests in providing sustainable water resources has been underlined (Kohm and Franklin 1997). As a consequence the importance of functional sustainable forests has been pinpointed by a number of international co-operations and resolutions (CIPRA 1997, Ministerial Conference for the Protection of European Forests 1998).

Possible direct effects of climatic change on forests include as a worst case scenario rapid forest dieback events triggered by drought. However, climate change impacts my be more subtle. For instance, in low-elevation forests at the foothills of the Alps secondary coniferous forests mainly consisting of Norway spruce (*Picea abies (L.) Karst.*) may suffer from increased drought which may increase susceptibility to infestations by insects and disease organisms which in turn might be favoured by a warmer climate. This increased vulnerability of forests may result in an imbalance in harvesting operations due to salvage cuttings, thus increasing management costs and causing perturbations of timber markets by imbalancing demand and supply. Changing environmental conditions may alter physiological processes (Kräuchi 1993, Ceulemans and Mousseau 1994, Mohren et al. 1997, Jarvis 1998) which in turn may result in altered volume increment (Spiecker et al. 1996) or in changing competitive status of tree species. In the light of these considerations it is highly recommended to re-evaluate risks of management and to search for optimised management strategies (e.g., Müller 1997, Lindner 1998).

There are several methodological approaches available for the analysis of climate change impacts, essentially each one finding its advantages counterbalanced by several shortcomings.

i. Short-term experimental studies of physiological processes on small individual saplings provide cause-effect based explanations for what might happen under altered environmental conditions (e.g., Jarvis 1998) but are rather limited with regard to temporal and spatial extrapolation, and thus are not directly applicable to support decision making in forest management.

ii. Simplistic conceptual models of altitudinal shifts of vegetation belts with increasing temperatures (e.g., Peters and Darling 1985) were among the first tools to project potential consequences of a climate change. Although such approaches can provide an idea of what might be the potential effect of climate change, they are not sufficient to support site-specific silvicultural decision making. Similar objections hold true for other approaches where today's vegetation in warmer and drier regions is used as an analogue for future vegetation under a changing climate. There are reasons to assume that "no analogue" - situations might occur which are not represented by the climate-vegetation pattern of the past. A further disadvantage of such static approaches is, that the transient response of today's forests to a changing climate is neglected.

iii. A promising approach to integrate available knowledge on vegetation-site interactions and to investigate the possible transient responses of forest ecosystems to changing climatic conditions are dynamic forest models (Shugart et al. 1992). A variety of forest models which are considered useful for forest management decision support under changing environmental conditions have been developed during the recent years. However, it must be recognised that there are knowledge gaps involved with models of forest vegetation development. Physiologically based process models utilise findings from ecophysiological studies and try to mathematically describe the key mechanisms of fundamental growth processes. However, despite the potential merits most existing models of these type are either unable to represent real forest structure and composition in multi-species systems or are unsuitable for projection periods of several decades to centuries. Among existing modelling approaches gap models (patch models sensu Shugart 1998) are considered to be particularly useful for simulating forest development under changing climatic conditions. For European forests such models have been constructed by Kienast (1987), Kellomäki et al. (1992), Prentice et al. (1993), Kräuchi (1994) and Bugmann (1994). Though early applications of patch models to study the response of forests to a changing climate have been criticised for either too simplistic or even misleading representations of key ecosystem processes (e.g., Schenk 1996, Loehle and LeBlanc 1996), recent model versions have been improved and try to avoid such limitations (e.g., Lasch et al. 1998, Bugmann and Solomon 2000, Lexer and Hönninger 2000).

Investigations of future forest composition and structure rely on some kind of model projection. Numerous model based studies have been conducted to explore the potential response of forest ecosystems to changing environmental conditions (e.g., Kienast 1991, Bugmann 1994, Lindner et al. 1997, Lasch et al. 1999, Solomon 1986, Bartlein and Solomon 1996). Most model applications have been confined to a very limited number of scattered sites with more or less synthetic site characteristics (e.g., Kienast and Kuhn 1989, Bugmann 1994, Solomon, 1986). This approach might include the problem of models primarily tuned to the few sites under investigation. Another shortcoming is, that for natural resource planning assessment results are required at regional to national scales. Lindner et al. (1997) employed two gap models in a regional climate change impact assessment for the State of Brandenburg (Germany) where the site and climate data necessary to initialise the model runs were lumped at a spatial resolution of 10 x 10 km^2. However, this lumping procedure might lead to synthetic "average" site conditions within each grid cell, thus blurring the effect of site conditions on forest response to a changing climate. In most large-scale model applications so far, the simulations were started from bare ground (i.e., "clear cut conditions") aiming at the steady state species composition as the only assessment endpoint (e.g., Lindner et al. 1997). Despite the obvious relevance of today's forest composition for future forest development very few model-based climate change impact studies considered current forest's composition and structure. Examples include Lindner (1998) and Lasch et al. (1999) for the State of Brandenburg, and Kienast et al. (1996) who applied a static climate-sensitive equilibrium model at sample plots of the national forest inventory of Switzerland. Recently Talkkari and Hypen (1996) presented an outline of the application of gap models based on spatially explicit data for boreal conditions.

Regional climate change impact studies require climate change scenarios at a comparable scale (Lasch et al. 1999). The direct use of scenario output of global circulation models (GCM) operating at a spatial resolution of approximately 100 x 100 km^2 is no appropriate means to characterise climate at the regional scale. To bridge the gap between the coarse scale of global circulation models and the regional to local scale required for most impact studies a standard technique until recently was to use average temperature and precipitation anomalies from GCM grid points in the vicinity of the study area (e.g., Kienast 1991) and apply them to current local climate data. Three additional methods have been and still are being developed: (1) simulation of regional climate by regional climate models (RCM) which are nested within GCM grid cells (e.g. Wild et al. 1996), (2) relating large-scale meteorological patterns at the GCM grid scale to local-scale weather data by means of statistical techniques ("statistical downscaling", e.g., Gyalistras et al. 1993), and (3) the relation of local climate data with expected changes in the frequencies of large-scale weather pattern (e.g., Werner and Gerstengarbe 1997). The construction of climate change scenarios for regional applications still involves substantial difficulties and techniques are still progressing.

From the preceding sections it follows that substantial uncertainties are involved with climate change impact analyses. It is important to recognise the reasons for this uncertainty. Several sources can be identified: (1) the underlying mechanisms of the earth's climate system are yet not fully understood, thus leading to uncertainty in global climate modelling; (2) global circulation models (GCM) operate at a spatial resolution of appr. 10^5 km^2 which is a substantial mismatch for local to regional impact analyses; (3) the "unknowable" knowledge (cf. Hulme and Carter 1999) on future societal and socio-economic development which will determine greenhouse gas emissions and land use practices; (4) incomplete knowledge with regard to the response of ecosystems to changing environmental conditions.

Thus, it is important to recognise that we are apparently not able to predict the future of our forests. Rather we apply scenario analyses techniques aiming to answer "What ... if ...?" questions in a consistent and rational manner.

Nevertheless, despite the remaining uncertainties we are convinced that by strictly following the principles of ecological risk assessments (Suter 1993, Molak 1997) climate change impact analysis can provide valuable insights to a highly complex and challenging decision making situation.

2 OBJECTIVES

The general objective of the present study is to analyse the sensitivity of Austrian forests to scenarios of climatic change. In particular we aim at (i) identifying areas which are sensitive to changing climatic conditions, and (ii) indicating the magnitude of potential climate change impacts on today's forests.

Further key issues of the present study were to link available data sources such as the Austrian Forest Inventory, the Austrian Forest Soil Survey and an extensive network of weather stations on one hand, and ecological simulation models on the other hand.

3 METHODS

3.1 Risk assessment procedures

By definition risk is the chance that an unfavourable event which is related to some kind of damage will occur (Holloway 1979). In case of forests the functioning of forest ecosystems under changing climatic conditions, in other words, the ability of forests to sustainable secure societal needs, is at risk. Due to the involved complex system interactions (climate, forest vegetation, disturbances, societal needs and demands) it is essentially impossible to quantify the conditional probability of a particular impact event to occur (v.Gadow 2000). Rather qualitative risk assessments with aggregated more general risk descriptors are appropriate means (Hunsaker et al. 1990). Such risk assessments provide the expected responses of a system under an envelope of boundary conditions.

A crucial step in risk assessments is the definition of appropriate assessment endpoints (Suter 1993). According to Suter (1993) and Hunsaker et al. (1990) risk assessment endpoints have to meet the requirements of societal and biological relevance, unambiguous operational definition, accessibility to prediction and measurement as well as susceptibility to the hazardous agent. In case of forests ecosystem-level characteristics such as species composition or accumulated biomass are considered useful parameters in evaluating the functioning of forests (Gordon 1994, Ott and Schönbächler 1986, Gundermann 1974, Grottenthaler and Laatsch 1973).

Beyond defining the entity which is at risk (i.e., a forest stand), ecological risk assessment procedures have to devise methods to define the current state and quantify the expected changes of the assessment entities (Suter 1993). Models of forest vegetation development which are responsive to the disturbance agent (i.e., changing climatic conditions) are appropriate means to project ecosystem changes. Figure 3-1 represents this risk assessment scheme.

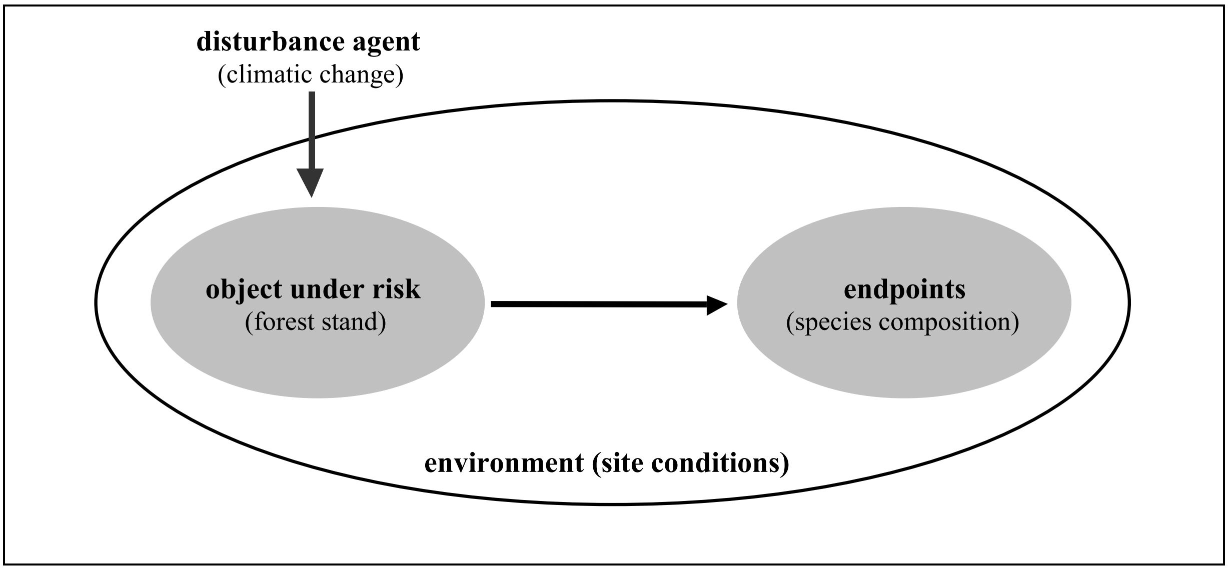


Figure 3-1. Schematic frame for an ecological risk assessment.

Abb. 3-1: Schema für eine ökologische Risikoanalyse.

However, it is important to recognise that the fate of a particular forest stand under a changing climate will be hardly ever directly predictable for several reasons:

a) Major portions of European forests have been and are subject to intensive forest management. There is no reason to assume that this will change. Thus, knowledge on future forest management would be an inevitable prerequisite for such a task. Due to the heterogeneous ownership structure (which may include strongly contrasting sets of management objectives) as well as to the variety of forest site conditions in Austria it is neither realistic to assume a single treatment program per stand type nor to differentiate between all possible stand treatment paradigms. Another reason which renders the consideration of long-term forest management scenarios unsuitable is the fact that stand treatment is not primarily a matter of ecological considerations but substantially affected by socio-economic conditions which in turn are in a feed back loop linked to the response of forests to a changing climate (i.e., supply of timber). Such integrated assessments aim at coupling ecological and socio-economic systems but currently are at an early stage of development (Picket et al. 1994).

b) Disturbance such as wind throw strongly determine stand development. Such natural disturbances are stochastic events and quite frequent but usually are not included explicitly in forest models.

3.1.1 Defining assessment endpoints

There are substantial difficulties involved in quantifying the inherent potential of current forests to adapt to changing climatic conditions. It was concluded that a set of indicators extended over short- to long-term temporal scales can provide a reasonable basis for the evaluation of possible climate change impacts. One approach very common in "classical" Central European forestry is to utilise the divergence of the actual forest composition to the species composition of the potential natural vegetation (PNV sensu Tüxen 1956) as a proxy for the suitability of forest vegetation (i.e., the adaptedness of tree species to given site conditions). According to Tüxen (1956) PNV is the equilibrium species composition of the expected forest climax community at a particular site considering today's site conditions. No direct anthropogenic influences are assumed. The rationale for the use of PNV in forest resource planning is, that PNV characterises the ecological potential of forest sites, and thus indicates which species mixture is well adapted to the prevailing site conditions (e.g. Kienast et al. 1996). Moreover, minimising the divergence of PNV to the actual forest composition is expected to minimise the input of effort and energy (i.e. silvicultural treatments) required to sustain ecosystem function (Mayer 1984, Leibundgut 1981). The latter point derives from the fact, that PNV integrates information on the competitive relationships between tree species. PNV for a given site is usually inferred from rather coarse-scale descriptions of regional climax forest communities (e.g., Kilian et al. 1994) or reconstructed in the field by experts. It is important to note, that recently the use of PNV in forest resource planning has been criticised (e.g., Zerbe 1997). One major limitation surely is the consistent definition of site-specific PNV. Even more serious objections exist regarding the ad hoc projection of future PNV for altered climatic conditions based on expert judgements. These major limitations can be circumvented by the application of formal models suitable to objectively simulate PNV for a given site. Patch models are a class of dynamic forest models considered capable of generating PNV (Shugart et al. 1992). Moreover, these models can also be used to characterise the transient behaviour of forests to changing environmental conditions.

The newly developed patch model PICUS v1.2 (Lexer and Hönninger 2000) was employed to simulate vegetation development under current and future climate starting from current forest composition until the site-specific equilibrium species composition (which is equivalent to PNV sensu Tüxen) was reached. As a prerequisite for projecting future PNV it is essential to assume stable climatic conditions at some point in time. To reach an equilibrium species composition under altered climatic conditions the hypothetical future climate was assumed to correspond to the average conditions of the period 2035 to 2065 of the underlying transient climate change scenario.

Two different kinds of criteria can be deduced from simulated PNV: (i) Utilising the simulation run under current climate as a baseline scenario we calculated the similarity of simulated PNV under current climate to PNV as simulated under a climate change scenario and used this measure as an indicator for shifts in ecological site potential (ac_6), and (ii) observed forest composition at a particular site can be matched with the species composition of the simulated PNV and suitability of the current species mixture for given site conditions can be inferred. Differences in similarity between observed vegetation composition and simulated PNV, both under current climate and under a climate change scenario, represent the impact of climatic change on the adaptedness of a given forest to the prevailing site conditions (ac_7). Kienast et al. (1996) employed a similar approach to evaluate what they called the adaptation potential of actual forest vegetation at the sample plots of the Swiss forest inventory to climatic change.

Beyond this indirect long-term measures for the impact of climate change vegetation development was evaluated on a decenial scale during the period 2000 to 2050 to capture the short- to midterm sensitivity of currently existing forests to a changing climate directly ($ac_{1\text{-}5}$). No management interventions are assumed. The rationale for this approach is, that an eventually occurring divergence of vegetation as simulated under baseline conditions to vegetation as simulated under climate change conditions (expressed as the degree of similarity) during the transient phase indicates, that the changing climate affects the potential successional pathway of current forest vegetation. This quasi "natural" behaviour would be blurred by the inclusion of management operations. For the first 50 simulation years (2000-2050) no external seed input to the simulated forest is provided. For this period only locally produced seed (compare model description in section 3.2) as well as actually existing regeneration as recorded by the Austrian Forest Inventory is the source for the recruitment of new trees within the forest model. Figure 3-2 schematically characterises the concept for the quantification of climate change impacts on existing forest vegetation.

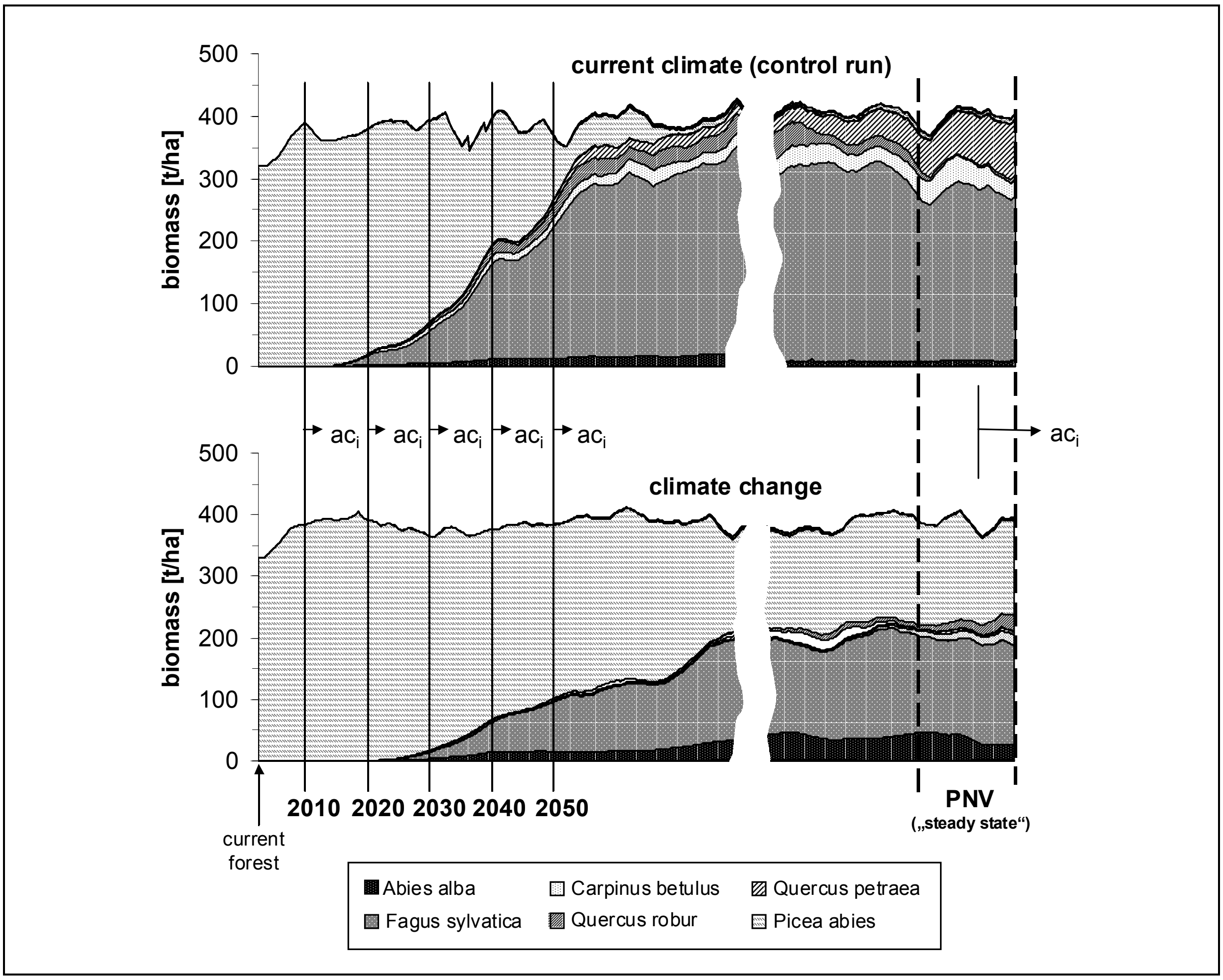


Figure 3-2. Scheme for the quantification of climate change impacts on existing forest vegetation at sample points of the Austrian Forest Inventory.

Abb. 3-2: Ansatz zur Quantifizierung des Effektes einer Klimaänderung auf aktuell existierende Wälder auf Probepunkten der Österreichischen Waldinventur.

The assessment criteria ac(i) were quantified by the percentage similarity PS (Prentice and Helmisaari 1991) (1).

$$PS = 1 - \frac{\sum_{i=1}^{n} |a_i - b_i|}{\sum_{i=1}^{n} (a_i + b_i)} \qquad (1)$$

a_i = proportion (absolute or relative) of species (i) in set a

b_i = proportion (absolute or relative) of species (i) in set b

This measure not only evaluates differences in species proportions but also integrates the absolute amount of biomass a species is able to accumulate at a site. PS can take values between 0 (totally different species composition) and 1 (identical species composition). The calculation of the short- to midterm endpoint measures ($ac_{1\text{-}5}$) as well as the comparison of simulated potential natural vegetation compositions (ac_6) was based on aboveground species biomass [t/ha] whereas for the matching of observed vegetation and simulated PNV relative abundances of species groups were used (ac_7). The grouping aimed at combining species with similar ecological requirements which eventually might be directly affected by a changing climate (Table 3-1). The rationale was, that it seemed somewhat restrictive to strictly operate at the species level when comparing observed "real" with simulated "virtual" data.

Table 3-1. Species groups for the comparison of current vegetation observed at sample points of the Austrian Forest Inventory with the species composition of simulated potential natural vegetation (PNV).

Tab. 3-1: Artengruppen für den Vergleich von aktueller Baumartenzusammensetzung auf Inventurpunkten mit der simulierten PNV.

Species group	Species included
1	Pinus sylvestris, Pinus mugo
2	Larix decidua
3	Pinus cembra
4	Picea abies
5	Abies alba, Taxus baccata
6	Fagus sylvatica, Acer pseudoplatanus, Fraxinus excelsior, Ulmus glabra
7	Acer campestre, Acer platanoides
8	Quercus spp., Castanea sativa
9	Carpinus betulus, Tilia cordata, Tilia platyphyllos
10	Betula pendula, Sorbus aucuparia, Sorbus aria, Alnus glutinosa, Alnus viridis

3.1.2 Evaluation of endpoint measures

The similarity measures (compare eq. 1) employed to quantify the impact of climate change on forest vegetation do not include an explicit valuation with regard to the expected effects of changes in vegetation development which they indicate. It is not very realistic to assume a linear relationship between the similarity of vegetation under current climate to the vegetation under a climate change scenario and its meaning with regard to forest sensitivity. In other words, each specific value an assessment criterion might take on must be evaluated for its relevance regarding an adverse effect of the changing climate. For instance, considering the assessment criterion ac_2 which characterises the divergence of simulated vegetation under baseline to simulated vegetation under climate change conditions in simulation year 2020 one might conclude that a value of $ac_2 = 0.2$ is not necessarily twice as good as a value of $ac_2 = 0.1$. It is obvious, that the evaluation of dissimilarities (i.e. differences between species sets simulated under contrasting climatic conditions) relies on expert judgement. In Figure 3-3 the relationship between the assessment criteria and their relevance regarding adverse climate change impacts is shown. The rationale for the shape of the curve is, that small potential changes in vegetation composition due to climate change as well as changes beyond a certain threshold are of minor relevance. This means that it was considered negligible whether similarity of the simulated forests under the baseline scenario (current climate) to the simulated forests under a climate change scenario was $ac(i) = 0.10$ or $ac(i) = 0.20$.

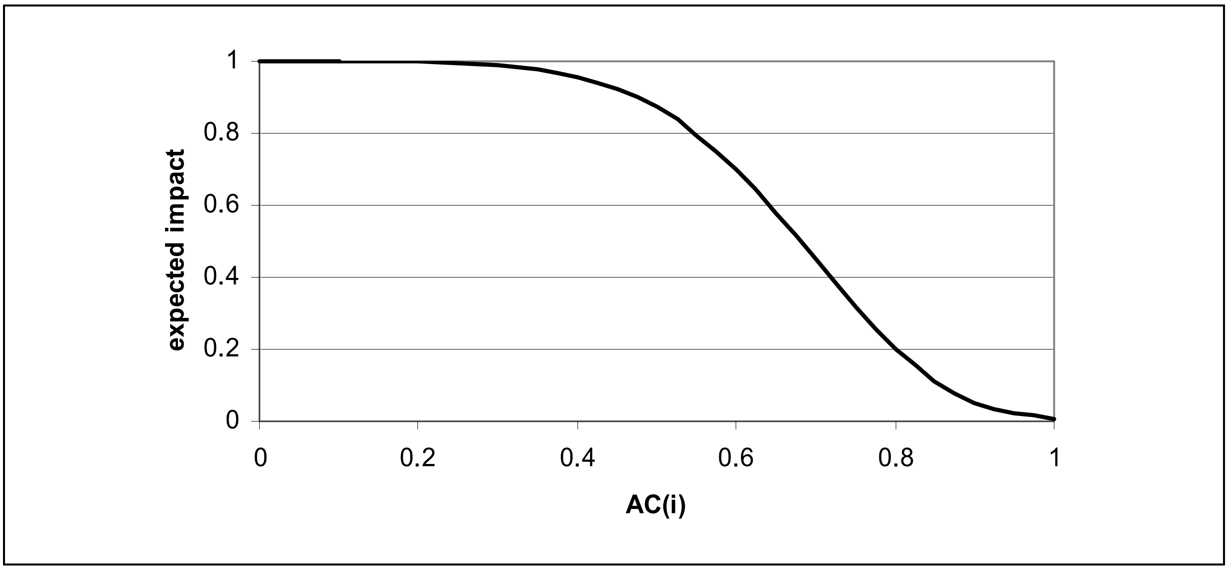


Figure 3-3. Relationship between assessment criteria ac(i) and their relevance regarding the expected adverse impact of a changing climate.

Abb. 3-3: Gutachtliche Beziehung zwischen Kriterium ac(i) und daraus erwartetem negativen Effekt.

The function in Figure 3-3 was estimated by the eigenvalue method as applied in the analytic hierarchy process (Saaty 1977, 1996). Essentially, the approach of Saaty requires a priori knowledge of all elements to be compared. However, the assessment criteria can take any value between 0 and 1. Thus, the original method of Saaty had to be modified. Instead of comparing already realised outcomes for a criterion we partitioned the entire possible range for a criterion (0-1) in eight categories of equal width and used the midpoints of these categories as elements in the pairwise comparison procedure. In Table 3-2 the recommended verbal characterisations of the ratings are given. Readers interested in further details of the method are referred to Lexer (2000).

Table 3-2. Numerical values and corresponding linguistic terms for the pairwise comparisons (modified according to Saaty, 1996).

Tab. 3-2: Numerische Werte und linguistische Terme für den paarweisen Vergleich nach Saaty (1996).

Rating	Linguistic term
9	Extremely more relevant
7	Very strongly more relevant
5	Strongly more relevant
3	Moderately more relevant
1	Equally relevant
1/3	Moderately less relevant
1/5	Strongly less relevant
1/7	Very strongly less relevant
1/9	Extremely less relevant

2, 4, 6, 8 and $^1/_2$, $^1/_4$, $^1/_6$, $^1/_8$ are intermediate values

The ratings are arranged in a symmetric reciprocal matrix and the principal right eigenvector (i.e., the eigenvector with the largest eigenvalue) is calculated. The resulting priorities were scaled to 1. Thus, we arrived at the continuous function shown in Figure 3-3 which subsequently could be employed to calculate the expected relevance for any realisation of an assessment criterion ac(i) regarding the potential adverse effects of a changing climate. The functional relationship depicted in Figure 3-3 was used to evaluate all assessment criteria except ac_7. In view of difficulties with consistent ratings for the criterion ac_7 (i.e., difference between similarity of observed forest vegetation and simulated PNV under baseline and climate change conditions respectively) and for the sake of simplicity we assumed a linear transfer function for this measure.

3.1.3 Combining indicators of climate change impacts

Figure 3-4 shows the hierarchy of criteria used to synthesise an overall index for the sensitivity of current forests to scenarios of climatic change. The short- to midterm sensitivity (SMS) of forests to changing climatic conditions was calculated from the expected impacts which had been derived from the difference in species composition [aboveground biomass in t/ha] between the simulated vegetation development under current and changing climate respectively at 10year-intervalls for the period from 2000 to 2050 (AC_{SMS1-5}). As an indicator for adverse effects induced by changes in the ecological site potential the divergence of PNV under current to PNV under the assumed future climate was calculated (AC_{LI1}). Finally the current species set observed by the Austrian Forest Inventory is matched with the equilibrium species composition under current and altered climatic conditions. The resulting difference was evaluated for the long-term impact of a changing climate on current forests (AC_{LI2}).

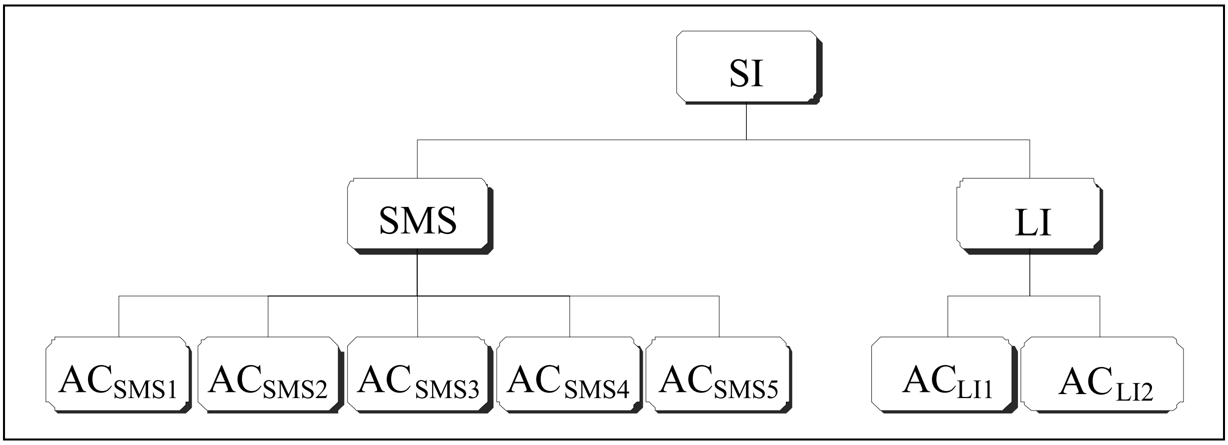


Figure 3-4. Hierarchy of criteria used to evaluate the sensitivity of current forests to scenarios of climatic change.

Abb. 3-4: Hierarchische Anordnung der Analysekriterien zur Beurteilung der Effekte einer Klimaänderung.

To calculate an index for the expected overall impact of scenarios of climatic change (i.e., the severity of potential adverse climate change impacts) on a given forest stand an approach that borrows from multiple-attribute utility theory was adopted. This method requires the mathematical characterisation of preferences over a set of attributes (Goicoechea et al. 1982). According to Figure 3-4 the potential overall sensitivity of a forest to a climate change scenario was composed of measures for the short- to midterm sensitivity (SMS) and an index for the long-term impact of climatic change (LI) respectively. The indices SMS and LI were calculated from eqs. (2a-b) and eqs. (3a-b) respectively.

$$\boldsymbol{SMS} = \boldsymbol{a}_1 \cdot \boldsymbol{AC}_{\boldsymbol{SMS}1} + \boldsymbol{a}_2 \cdot \boldsymbol{AC}_{\boldsymbol{SMS}2} + \boldsymbol{a}_3 \cdot \boldsymbol{AC}_{\boldsymbol{SMS}3} + \boldsymbol{a}_4 \cdot \boldsymbol{AC}_{\boldsymbol{SMS}4} + \boldsymbol{a}_5 \cdot \boldsymbol{AC}_{\boldsymbol{SMS}5} \tag{2a}$$

$$\sum_{i=1}^{5} a_i = 1 \tag{2b}$$

$$\boldsymbol{LI} = \boldsymbol{b}_1 \cdot \boldsymbol{AC}_{\boldsymbol{LI}1} + \boldsymbol{b}_2 \cdot \boldsymbol{AC}_{\boldsymbol{LI}2} \tag{3a}$$

$$\sum_{j=1}^{2} b_j = 1 \tag{3b}$$

The parameters $a_{(i)}$ and $b_{(j)}$ in eqs. (2a) and (3a) characterise the relative weight of an assessment criterion in calculating the index SMS and LI respectively. The parameters $a_{(i)}$ and $b_{(j)}$ were calculated with the eigenvalue – method as described in section 3.1.2. The rationale in deriving the pairwise ratings for $a_{(i)}$ was that the relative importance of an assessment criterion decreased with increasing time. In other words, the highest weight in calculating SMS (compare eq. 2a) was assigned to assessment criterion AC_{SMS1}, the smallest to AC_{SMS5}. In calculating the long-term index LI the assessment criterion AC_{LI2} which includes a direct comparison of today's forest composition with simulated PNV both under current climate and conditions of climatic change was assigned more weight than AC_{LI1}. Table 3-3 presents all parameter values as used in the present study.

Table 3-3. Parameter values for calculating the climate change impact indices SMS and LI.

Tab. 3-3: Parameterwerte zur Berechnung der Indikatoren SMS und LI.

parameter	numerical value
a_1	0.376
a_2	0.186
a_3	0.160
a_4	0.148
a_5	0.130
b_1	0.400
b_2	0.600

To combine SMS and LI to an overall index for the potential impact of climatic change (CCI) a matrix approach was employed. The rationale in designing the matrix (compare Table 3-4) was that extreme sensitivity at short- to midterm scale (as indicated by SMS) should not be counterbalanced by less extreme climate change impacts eventually indicated by the long-term index LI. Though it is possible to include such considerations in the approach applied to calculate SMS and LI (compare eqs. 2a and 3a), it appeared more convincing to apply logical combinations of SMS and LI respectively at an ordinal scale (Table 3-4). The indices

SMS and LI respectively originally calculated at a continuous scale between 0 and 1 (compare eqs. 2a and 3a) were categorised into 5 classes of equal width. Overall climate change impact index CCI was defined for four categories. Category 1 of CCI characterised negligible low impact conditions, category 2 represented moderate impact, category 3 indicated substantial impact, and finally category 4 was assigned to conditions were severe climate change impacts were expected.

Table 3-4. Potential overall impact of climatic change on current forests (CCI) for combinations of the short-/midterm index SMS and the long-term index LI. CCI = 1: low impact, CCI = 2: moderate impact, CCI = 3: substantial impact, CCI = 4: severe impact.

Tab. 3-4: Ansprache des Indicators CCI für den potentiellen Gesamteffekt einer Klimaänderung anhand des Kurz-/Mittelfristindikators SMS und des Langfristindikators LI.

LI	**SMS**				
	1 very low	**2 low**	**3 moderate**	**4 substantial**	**5 severe**
1 (very low)	1	2	3	4	4
2 (low)	1	2	3	4	4
3 (moderate)	2	2	3	4	4
4 (substantial)	2	3	3	4	4
5 (severe)	3	3	4	4	4

The content of Table 3-4 is exemplified by two examples. An off-site Norway spruce forest at low elevations shows catastrophic bark beetle induced mortality in the period 2000 to 2050 due to climatic change. Consequently the short-/midterm index SMS yields the very unfavourable impact category 5 (severe impact). The site currently occupied by the Norway spruce forest naturally supports a beech/oak-community as potential natural vegetation (PNV). This PNV-type responds just weakly to the changing climatic conditions. This means that the ecological site potential under climate change conditions still corresponds to a beech/oak-community. Subsequently the long-term impact index LI yields the favourable impact category 2 (low impact). Nevertheless, the overall impact rating (CCI) for this forest yields category 4 (severe). As a contrasting example a high-elevation Norway spruce forest is considered. This forest shows no immediate adverse impact due to the changing climate and continues to grow, eventually responds to the warmer climate with increased increment. The short-/midterm index SMS yields category 1. However, the simulated potential natural vegetation (PNV) changes from a spruce forest under current climate to a spruce/fir/beech-forest under the climate change scenario which results in impact category 4 (substantial) in case of the long-term index LI. The combined indices are considered to correspond to a moderate overall impact CCI (category 2).

3.2 The forest dynamics model PICUS v1.2

3.2.1 Model structure

In this section the basic structure and core functions of the newly developed forest dynamics model PICUS v1.2 are presented. For details see Lexer and Hönninger (1998a) and Lexer and Hönninger (2000a) (compare Figure 3-5). On patches of 10 x 10 m^2 growth, mortality and reproduction of individual trees are modelled. A simulated forest stand consists of an array of patches arranged on a regular grid spread out in x, y -dimensions. The vertical dimension z is accounted for by crown elements of 5 m width. Thus, the simulated forest consists of 10 x 10 x 5 m^3 cubic elements which carry all available information on ecosystem attributes and on the distribution of tree biomass in space. From this point of view PICUS is a descendant of the ZELIG-model (Urban 1990). A similar approach was presented by Huth and Ditzer (2000) for tropical forests. Unlike in conventional gap models which in fact can be considered as "point"- models, the simulated forest changes over time as an interactive unit rather than as a series of independent plots. Because PICUS includes a fairly detailed model of the above- and within-canopy light regime interactions among neighbouring patches as well as the effect of slope and orientation on incoming radiation is considered. Moreover, it allows to differentiate the light conditions at different sites with respect to shielding effects of surrounding topography. The range of spatial interactions between patches depends on the characteristics of the vegetation on the simulated patches (i.e. tree height, crown length), site characteristics (slope, orientation, latitude) and season (i.e., solar altitude, sun angle and direction).

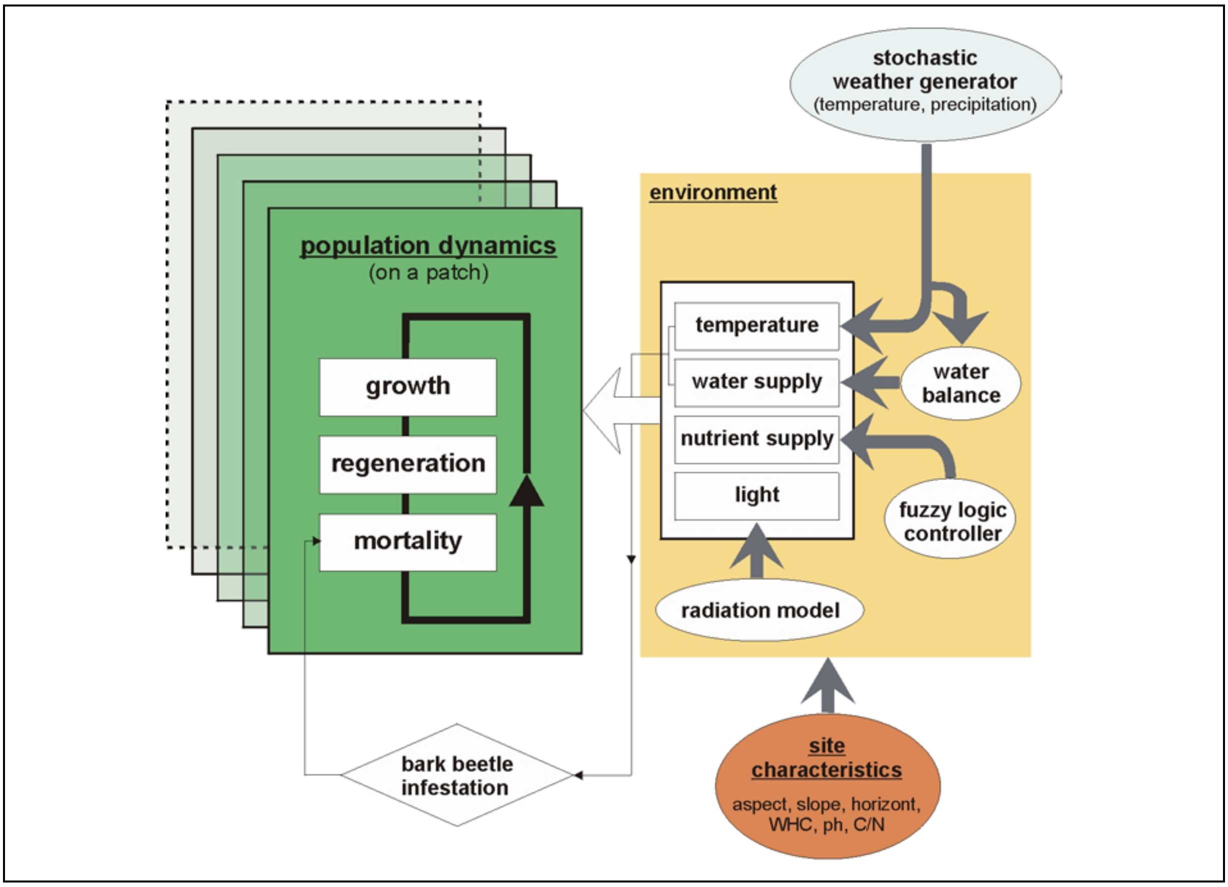


Figure 3-5. Model structure of PICUS v1.2.

Abb. 3-5: Modellstruktur von PICUS v1.2.

3.2.2 Growth

Diameter growth of individual trees is derived from a species specific growth potential which has been derived from data in the literature and from data on open grown trees in Austria (Hasenauer et al. 1994, Lexer, unpublished material). Optimum diameter increment is calculated with the approach given by Moore (1989). Other dimensional tree attributes such as tree height and leaf weight (Bugmann 1994) are calculated from breast height diameter. Leaf weight is distributed equally along the bole. Determination of the height to the live crown is based on species-specific light requirements (light compensation point) and the radiation regime a tree experiences. Growth under optimum site conditions and without any competition from other trees is modified by the effect of the chemo-physical environment a tree experiences.

3.2.3 Recruitment of new trees

New trees are generated by a recruitment submodel and are explicitly modelled beyond a diameter threshold of 1.0 cm +/- 0.2 cm. In contrast to other patch models PICUS considers seed production by overstorey trees and seed dispersal explicitly. The seed production of each adult tree is modelled as a function of tree size, a species' seed production characteristics and light consumption of the parent tree. If winter minimum temperatures do not meet chilling requirements of species with dormancy no seed is produced in that year. Seed dispersal of each seed producing tree is modelled as a cone-shaped density function around the centre of each parent tree's patch where the cone is defined by tree height and maximum dispersal range (e.g., Rohmeder 1987). For selected species zoochorous seed dispersal is considered as well. The total number of available seed at a patch is calculated as the sum from the sections of all density functions covering a particular patch. This number is filtered by species specific germination rates and an array of environmental filters including heat sum, frost occurrence, chemical site properties (pH, C/N-ratio), water supply and available light at the forest floor. Finally a random number decides, which species regenerates position by position open to recruitment. A maximum number of 100 individuals per patch controls stand density during the early stand development phases (compare Shugart 1984).

3.2.4 Tree mortality

Similar to other patch models, tree mortality is modelled as a stochastic process where trees can die either from an inherent risk of death (chance events such as windfall or lightning strike) or from a growth-related mortality (Botkin 1993). The inherent risk of death is increased under unfavourable conditions when a tree fails to realise a specified minimum diameter increment for a number of successive years. This approach is conceptually based on a hierarchical pattern of carbon allocation where diameter increment is of low priority and thus an indicator of reduced tree vigour (Kozlowski et al. 1991). For Picea abies bark beetle mortality is considered explicitly by coupling the patch model with a 2-stage-stand risk model (Lexer and Hönninger 1998a). In PICUS v1.2 the potential number of bark beetle generations for two major insect species (Ips typographus, Pityogenes chalcographus) is explicitly modelled by means of a thermo-energetic approach similar to those suggested by Coeln (1997). Bioclimatic parameters in this submodel are snow cover, heat sums which control the development of different life stages of the insects and day length to account for photoinhibition during insect development (e.g., Schopf 1989). Two completed insect life cycles per year at a minimum are required as a prerequisite to eventually trigger a mortality event in Picea abies populations. Other predictors of damage probability are the proportion of Picea abies basal area, stand age, the proportion of Picea individuals with a negative increment trend with respect to two successive 4-year periods and the number of days during growing season where the soil water suction is below – 2.0 bars. Damage intensity is a function of Picea abies basal area and an index for water stress experienced by the trees (compare Lexer and Hönninger 1998a). The core functions of the bark beetle module had been derived from work in Lexer (1995a).

3.2.5 The abiotic environment

3.2.5.1 Temperature

A submodel within PICUS computes all environmental factors influencing tree population dynamics. In PICUS v1.2 the temperature regime, the soil moisture supply, the nutrient status of a site as well as the light regime a tree experiences are considered. The temperature regime is represented by a heat sum above a threshold of 5.5 °C and winter minimum temperature (WT). The former is considered to characterise the seasonal thermal conditions for photosynthesis. The latter is evaluated twofold: first, with regard to the frost tolerance of tree species, and second, with regard to chilling requirements to induce dormancy and subsequently break of flower buds (Sykes et al. 1996, Larcher 1995). The coldest month of a year is taken as an estimate for WT (Bugmann 1994) and is also used to evaluate, whether the chilling requirements for species requiring dormancy are satisfied. In PICUS v1.2 tree growth is not restricted at super-optimal temperatures. Based on the consideration that tree growth at a species' southern range limit is not necessarily constrained by temperature per se (compare Bugmann and Solomon 2000, Bonan and Sirois 1992) we derived new temperature response functions from the combined network of forest inventory data, soil and meteorological data (Lexer and Hönninger 1998b).

3.2.5.2 Water supply

An index for plant water supply is derived from a site specific water balance. The state variable soil water content (SWC_m) is updated via input and output flows. Input of water into the soil occurs via precipitation (P) and snowmelt (SM), output of water from the soil either as evapotranspiration (AET) or as runoff (RO) (eq. 5).

$$SWC_{m+1} = SWC_m + P_m + SM_m - AET_m - RO_m \tag{5}$$

The water holding capacity (WHC) of a site defines the "bucket" where water is stored. SM is calculated as a function of temperature according to Dunne and Leopold (1978). AET_m represents the monthly proportion of the atmospheric evaporative demand (PET_m) that can be satisfied by available soil water. An estimate for PET_m is computed applying formulae of Thornthwaite and Mather (1957). Given unlimited water supply AET equals PET. When the soil moisture content decreases, PET is modulated depending on soil texture and the amount of water in the soil (6).

$$AET_m = PET_m \cdot f_s\left(\frac{SWC_m}{WHC}\right) \tag{6}$$

Formulations f_s for three different soil texture types were taken from Dunne and Leopold (1978). Depending on a general characterisation of the soil texture type f_s considers the decreasing proportion of depletion demand which can be satisfied if soil water content decreases and thus soil water tension increases. PICUS v1.2 is driven with time series of monthly temperature and precipitation data either directly provided to the model or generated internally by sampling from empirically fitted distributions of monthly temperature and precipitation. A normal distribution represented by long-term mean and standard deviation is used for temperature, a 2-parameter gamma distribution for precipitation. Lasch et al. (1998) demonstrated the potential effects of different temporal resolutions of climate data in driving forest succession models. The water balance calculations appeared to be particularly sensitive. To provide daily weather data for heterogeneous alpine terrain still is a challenging task (e.g., Scheifinger and Kromp-Kolb 2000). To minimise possible adverse effects on water balance calculations we provided a parameterised representation of the simultaneous processes of water infiltrating into the soil and water being depleted from the soil. Input and output from the bucket were calculated in 3 time steps per month where the sequence of water input and output varies stochastically. With this approach the divergence of soil moisture values generated by the monthly model in PICUS to values simulated with a detailed physiologically based water balance model operating at daily temporal resolution (Lexer 1995b) was reduced.

The ratio of evaporative demand and supply integrated over the growing season was considered a reliable proxy of drought stress experienced by vegetation (eq. 7). Under conditions of unlimited water supply the actually possible evapotranspiration (AET) will equal the evaporative demand of the atmosphere (PET) which results in a values of SMI = 0. If the soil is totally dry during the growing season AET will approach zero which will result in a value of SMI = 1.

$$SMI = 1 - \frac{\sum_{bgs}^{egs} AET}{\sum_{bgs}^{egs} PET} \tag{7}$$

bgs = begin of growing season (temperature exceeds 5.5 °C)
egs = end of growing season (temperatures below 5.5 °C)

Similar to the derivation of the temperature response the data of the Austrian Forest Inventory were utilised to derive soil moisture response functions.

3.2.5.3 Light

An index of available light for each individual tree is calculated from the available light a tree crown in the simulated stand actually experiences. The radiation submodel within PICUS differentiates between direct and diffuse radiation and considers the shielding effect of surrounding superelevated topography. For details on the radiation submodel we refer to Lexer and Hönninger 2000).

3.2.5.4 Nutrient supply

In contrast to other gap models PICUS v1.2 doesn't rely on the nitrogen supply function as originally presented by Pastor and Post (1985). Instead the water holding capacity at a site (WHC), the pH-value (pH) as well as the C/N-ratio (CN) of the top soil (uppermost 30 cm of mineral soil) are employed to characterise the nutrient status of a site. By means of a fuzzy logic control unit these indicators of site nutrient status are linked to tree growth performance by means of a rule base. Rules were constructed for each of four response categories (tolerant, intolerant, PH-sensitive, CN-sensitive). By linear interpolation between these four main response categories additional response categories were defined. Based on ecological literature (e.g. Ellenberg 1996, Leibundgut 1994) each species was assigned to one of these response categories. A detailed description of the methodological approach is given in Lexer et al. (2000).

3.2.5.5 Combining the effect of environmental factors

Finally all considered environmental scalars have to be integrated for the combined effect on tree development. Various approaches have been proposed. Following Liebig's law of the minimum Botkin et al. (1972) and Kienast (1987) employed the minimum-operator to derive the aggregate environmental response. In Botkin (1993) the multiplicative combination of all environmental factors was used whereas Bugmann (1994) proposed the geometric mean which implicitly considers compensation between environmental factors. In PICUS v1.2 compensation as well as intensification was considered explicitly. The below-ground factors soil moisture (R_{sm}) and nutrient supply (R_n) were linked via eqs. (8a)-(8c).

$$R_{soil} = R_{biom} \cdot f_{soil}(R_{sm}, R_n; 0.3) \tag{8a}$$

$$effect = \frac{0.3 \cdot (\max(R_{sm}, R_n) - 0.5)}{0.5} \tag{8b}$$

$$fsoil = \begin{cases} \min[R_{\max}, R_{\min} + (R_{\max} - R_{\min}) \cdot effect]; effect > 0.0 \\ \min[R_{\min}, R_{\min} + (R_{\min} - R_{\min} \cdot R_{\max}) \cdot effect; else] \end{cases} \tag{8c}$$

$R_{min} = \min(R_{sm}, R_n)$
$R_{max} = \max(R_{sm}, R_n)$

Thus, if both soil moisture and nutrient supply are suboptimal, the effect of the most limiting factor is intensified. If one environmental factor satisfies species requirements better than average ($R_{max} \geq 0.5$), the effect of the limiting factor is supposed to be partly compensated. The combined effect of R_{sm} and R_n was further intensified by R_{biom} which decreases with increasing accumulated biomass at the simulated patches as a function of the maximum possible biomass. Based on the approach of Fischlin et al. (1995) site-specific estimates of maximum biomass were calculated from temperature, an index of soil water availability (compare eq. 7) and the index for site nutrient status as described in the preceding section. The same approach was used to combine the aboveground effects of temperature (R_{gdd}) and light (R_{al}). The final overall response to all involved environmental factors was calculated from the combined below and aboveground effects again utilising the compensation algorithm from eqs. 8a-c.

The performance of PICUS in generating plausible site-specific equilibrium species compositions along a transect through the eastern Alps in Austria already has been demonstrated in Lexer and Hönninger (2000a) and Lexer and Hönninger (2000b). In a recent model intercomparison exercise PICUS performed sufficiently well at a number of sites scattered all temperate forest zones over the of Europe (Badeck et al., in revision).

3.3 Initialising PICUS v1.2 with forest inventory data

3.3.1 Site and soil data

To utilise available data and to further enhance the information content of existing data bases the present study was based on the sampling grid of the Austrian Forest Inventory (FBVA 1995). The Austrian Forest Inventory (AFI) samples site and vegetation data on a systematic 3.89 km grid of permanent plots. At each grid location a cluster of four plots is located at the vertices of a 200 m square. For this risk assessment study a subsample was taken which is considered to represent the variety of site-vegetation combinations of Austria's forests. For each plot included in the risk assessment study an array of site and soil parameters was required to initialise the model runs (Table 3-5). Geographical location, aspect as well as slope are standard site descriptors recorded by the Austrian Forest Inventory (AFI). The surrounding superelevated topography in the four main directions (horizons) was retrieved from a digital elevation model of 250 m spatial resolution implemented in GIS ARC/Info.

Lack of quantitative soil data is a weak point of many large-scale forest inventories. To circumvent this problem Lexer and Hönninger (1998c) and Lexer et al. (1999) developed a routine for the estimation of soil parameters for sample plots of the AFI from available more general site characteristics based on Bayesian probability theory. This approach was employed to calculate estimates for the soil parameters WHC (site water holding capacity), pH (pH-value of the uppermost 30 cm mineral soil) and CN (C/N-ratio of the uppermost 30 cm mineral soil) for all inventory plots included in the impact study. The data of the Austrian Forest Soil Survey (AFSS) (Englisch et al. 1991) were used to calibrate probabilistic relationships between the target variables and site characteristics available for both, the AFI and the AFSS. For details we refer to Lexer and Hönninger (1998c) and Lexer et al. (1999). Table 3-5 lists all site parameters required to initialise the forest model.

Table 3-5. Site and soil parameters required to initialise PICUS v1.2.

Tab. 3-5: Zur Initialisierung von PICUS v1.2 benötigte allgemeine Standortsmerkmale und Bodenparameter.

Parameter	Unit	Characterisation
co-ordinates	[°, ´, ´´]	location of site
aspect	[°]	eight categories
slope	[%]	inclination of slope,
horizon (1, 2, 3, 4)	[°]	angle to horizon in directions north, east, south, west
water holding capacity	[cm]	uppermost 30 cm mineral soil [minimum: 7 cm]
pH-value	-	average of the uppermost 30 cm mineral soil
C/N-ratio	-	from carbon and nitrogen of the uppermost 30 cm mineral soil

3.3.2 Vegetation data

At each sample plot of the AFI vegetation data is recorded. Using variable radius plot sampling (Bitterlich 1948) with a basal area factor of 4 m^2/ha trees larger than 10.4 cm in diameter are recorded at least by dbh (diameter at breast height) and species. All trees with diameter between 5 and 10.4 cm are recorded on a fixed area plot located at the plot centre with a radius of 2.6 m. No trees smaller than 5 cm diameter are sampled. From this information a species specific diameter distribution was generated for each investigated sample plot.

The spatial resolution of PICUS would allow for the consideration of horizontal species mixture patterns (compare section 3.2). However, AFI does not provide sufficient information on stand texture. Thus, trees larger than 5 cm in dbh were assigned randomly to the patches of the simulated forest starting from the largest diameter class. Tree height and leaf weight were calculated by the model-internal relationships. The initial height to the live crown was determined by calculating the light regime in the initialised stand with the radiation submodel of PICUS. Initial leaf weight below the light compensation point of a species was pruned.

Regeneration at a site required particular consideration as it represents the potential next generation of trees. Unfortunately the AFI provides just semi-quantitative information on the regeneration status at a sample plot (compare FBVA 1995). For AFI a specific minimum number of saplings is required depending on the average height of the saplings (minimum height = 10 cm) to proceed with data collection. Thus, plots with existing sparse regeneration might occur in the data records with the label "no regeneration". From the attributes which are subsequently recorded three were utilised for the present study to quantify the regeneration status at a sample plot: (i) the spatial distribution of available saplings (categories: whole area, in groups, single), (ii) for a maximum of five species the percent cover (i.e., crown projection area) of the dominating height class of a species (from a total of 6 height categories) as well as (iii) the mixture type of that particular species (categories: pure, groups, random). From the cover percentages the number of saplings per hectare was calculated with (9)

$$a = x \cdot d_c \tag{9}$$

where a [m] is the average distance between neighbouring saplings, d_c is the average crown diameter [m] of a species of a given height class and x is a constant specific for a cover percentage class as given in FBVA (1995). The species specific crown diameters for given heights were calculated from formulae in Hasenauer (1997). Once the average distance $a_{(i)}$ between neighbouring individuals of a species is known, the expected number of saplings ($n_{(i)}$/ha) was calculated from (10) assuming a triangular tree distribution.

$$n_{(i)} / ha = \frac{10000}{\frac{a_{(i)}^{2} \cdot \sqrt{3}}{4} \cdot 6} \tag{10}$$

With this approach a pool of available saplings at a site was computed and used as input to PICUS. Recruitment of new trees in PICUS draws on this sapling pool as long as saplings are available. Sapling numbers in the pool were either reduced by the recruitment process or by unfavourable environmental conditions characterised by the environmental filters of PICUS (see section 3.2).

3.4 Climate data

3.4.1 The baseline scenario: Current climate

For the risk assessment we required current climate and climate change scenarios at all investigated inventory plots. Although monthly temperature and precipitation data already had been extrapolated to all plots of the AFI in an earlier study (compare Lexer and Hönninger 1998b), it was decided to update the applied methodology in order to improve the reliability of climate information at the sample plots of the AFI.

Current climate at the plots was derived from a network of more than 600 weather stations of the Austrian weather services (Zentralanstalt für Meteorologie und Geodynamik, Hydrographischer Dienst). For this purpose Austria was divided into 8 regions (compare Tabony 1985). A region is comprised by a valley system with borders running along mountain ridges. Thus, it should be guaranteed that most of the region share the same air mass with more or less the same vertical temperature distribution. Temperature was supposed to show no significant horizontal gradients within one region so that a single vertical temperature – altitude relationship could be deduced using data from all available weather stations within a region. Temperature values for each inventory point are calculated with this polynomial temperature – altitude relationship for each individual month and region with the elevation of the inventory point as input. In a subsequent step the temperature values are then modified with regard to topography (aspect, slope, horizon) utilising the ratio of incoming short-wave radiation at the particular point and incoming radiation under the assumption of a flat horizon and zero slope (compare Hungerford et al. 1989).

A more detailed approach was applied to the spatial interpolation of precipitation. For each AFI- plot per individual month a precipitation – altitude relationship was deduced fitting a linear model to the precipitation of the nearest 20 weather stations (Lauscher 1976). With this model residuals for each of the 20 weather stations were calculated and a residual was interpolated for the point of interest by an inverse distance weighting procedure. With the point-specific residual, the precipitation – altitude relationship and the altitude of the point of interest a precipitation value can then be recalculated for each AFI-plot (for details see Scheifinger and Kromp-Kolb 2000).

3.4.2 Climate change scenarios

3.4.2.1 From global to regional scales

All current attempts to look into the future of the earth's climate rely on the assumption that global circulation models (GCM) capture the major physico-chemical processes driving the climate system at the global scale. GCMs operate on grid scales of a few degrees spatial resolution corresponding to grid cells of about some hundred square kilometres. This poor spatial resolution implies that it might be misleading to apply GCM scenario output to a particular location at a much finer scale such as forest inventory plots. GCMs are able to reproduce climate phenomena with a wavelength of several grid distances ("skilful scale") but sub-grid scale processes (e.g., climate pattern caused by steep orography) cannot be resolved satisfactory with current model versions. Particularly in heterogeneous landscapes such as the Alps with steep topographical gradients the direct use of GCM grid point data might lead to totally unrealistic results. In general there are three distinct approaches to construct regional climate change scenarios based on raw output of GCMs (Hewitson et. al. 1996).

(1) addition of spatially interpolated GCM-generated climate parameter anomalies to local climate data,

(2) statistical downscaling techniques (e.g., Gyalistras et al. 1994, Werner and Gerstengarbe 1994, v.Storch et al. 1994),

(3) nesting of regional climate models (RCMs) within global circulation models (e.g., Giorgi et al. 1994).

Common understanding evolved during the last years that simple interpolation procedures are inadequate to transfer information from the coarse grid of GCMs to regional and local scales. Nested RCMs are believed to deliver the most reliable results for regional scale analysis. However this strategy is in a rather early stage of development, requires detailed surface climate data, and is dependent on high-end computer availability, whereas empirical relationships offer a more immediate solution and impose significantly lower computer requirements. Statistical downscaling techniques establish relationships between a set of predictors at a coarse scale (macro variables) and predictands (e.g., temperature) at much finer scales (micro variables) to predict the effect of synoptic weather patterns simulated by GCMs on the regional climate.

3.4.2.2 Regionalizing GCM-output

To provide regionalized climate change scenario data we employed statistical downscaling techniques which were based on the following data sets:

(1) NCEP/NCAR data set for the period from 1961 to 1995 (Kalnay et al. 1996). They involved monthly temperature, relative humidity and geopotential height at three pressure levels (850hPa, 700hPa and 500hPa). NCEP/NCAR provides this data on a grid of 2.5 x 2.5 degrees which appr. corresponds to the grid scale of the global circulation model ECHAM4/OPYC3 (Roecker et al. 1996). We considered the section from 50° West to 30° East, and 35° to 65° North.

(2) At the local scale time series of monthly mean values for the surface temperature and precipitation for the period 1961-1995 interpolated to sample points of the AFI (compare section 3.4.1).

(3) The DKRZ ("Deutsches Klimarechenzentrum") provided two time series generated by the coupled atmosphere/ocean global circulation model ECHAM4/OPYC3 (Roecker et al. 1996) for the same meteorological fields as provided by NCEP/NCAR for the period 2000 - 2065. One time series is the "control run" which is a 300-year simulation with trace gas concentrations kept at the level of 1990, the second is the "disturbed run" under the greenhouse emission scenario IS92a (Houghton et al. 1990). The disturbed run uses historical greenhouse gas forcing from 1860 to 1990 followed by an annual increase of radiate forcing of 1% from 1990 to 2099.

Because we used 35-year time series of different climatological variables at a total of 429 grid points we have to cope with large data sets. To reduce the amount of data without loosing too much information we applied principal component analysis (PCA) (Yarnal 1993, Widmann 1996) to the NCEP/NCAR data. The empirical orthogonal functions (EOF) resulting from this analysis were evaluated for the amount of variation in the pertinent meteorological variable which they explained. In case of geopotential height the first five eigenvectors (EOF) explained 90% of variation, in case of temperature nearly 80 %. For relative humidity fifteen EOFs were necessary to achieve approximately 75% of explained variation. There are different criteria to select the number of eigenvectors (e.g., Widmann 1996, Preisendorfer 1988). We used the LEV (log-eigenvalues) diagram to decide on the appropriate number of eigenvectors. The principal components for each meteorological variable resulted from multiplying the eigenvectors (EOF) with the data vector of the meteorological variable.

The principal components of the full time period 1961 to 1995 were then tested as predictors in multiple linear regression models of monthly temperature and precipitation respectively at each involved inventory point at the local scale. It is important to note, that the seasonal trend in the monthly temperature and precipitation data had been removed by dividing each monthly value by its long-term mean. The coefficient of determination (R^2) was used as the main evaluation measure. The best model for monthly mean temperature at the local scale included geopotential height and the temperature field respectively at a pressure level of 850hPa as predictors and explained between 59 and 85% of the variability in mean monthly temperature at the involved inventory plots. Precipitation at the local scale was best described by geopotential height and relative humidity at a pressure level of 700hPa. The precipitation models accounted for 13 to 52% of the variation in mean monthly precipitation at the inventory plots. It is important to note that our approach did neither distinguish between different regions nor the four seasons.

In a preliminary evaluation of the developed approach we split the available time series 1961-1995 in the periods 1961-1978 and 1979-1995. The period 1961-1978 was used to calibrate the regression models a second time. Subsequently the models were employed to estimate temperature and precipitation of the second period 1979-1995. For monthly temperature the correlation coefficient of estimated and measured values was $R = 0.47 \pm 0.08$. Unfortunately, the models for precipitation did not perform as well. In order to investigate a possible influence of seasonality on the performance of the precipitation model we calculated R separately for every month. This analyses revealed that the linear models reproduced precipitation better in winter than in summer with the best results in February. Nevertheless, with regard to precipitation it was concluded that operating at this temporal resolution the magnitude of the correlation coefficient was unsatisfactory.

After developing the models for temperature and precipitation with the NCEP/NCAR data they were used to transfer the simulation output of the global circulation model ECHAM4 from the coarse gridscale to the local scale of the inventory plots. The results were time series of monthly mean temperature and precipitation at each involved forest inventory point for the period 2000 to 2065. At each inventory plot the time series 2000-2050 was provided to drive PICUS v1.2 during the transient phase of the climate change scenario. From simulation year 2051 on the stochastic weather simulator within PICUS generated monthly temperature and precipitation data according to the climate of the period 2035-2065. Temperature was stochastically sampled from a normal distribution, precipitation from a 2-parameter gamma distribution.

4 DATA RESULTS

4.1 Climate data

4.1.1 Current climate

Figures 4-1a-b and 4-2a-b characterise the baseline climate for selected seasons as derived by statistical interpolation procedures (Scheifinger and Kromp-Kolb 2000).

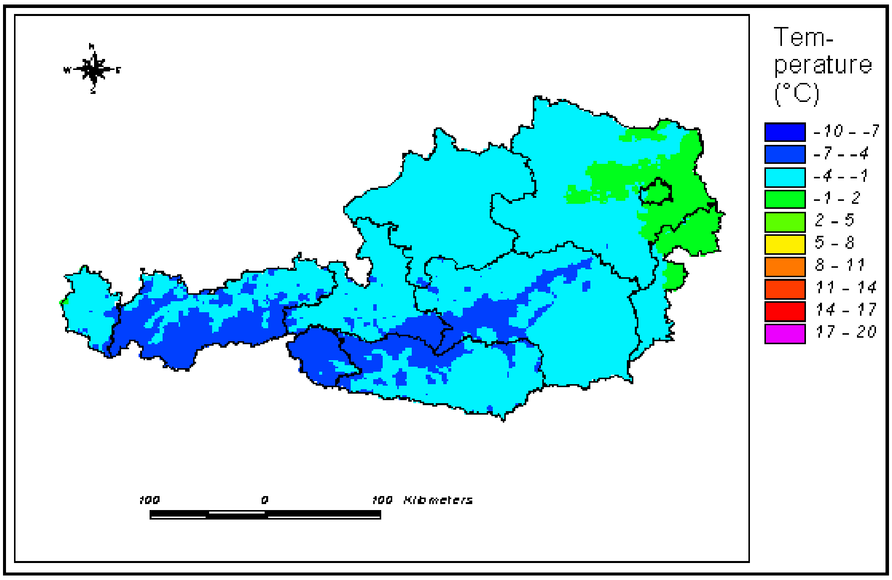


Figure 4-1a. Statistically interpolated winter temperature (December-February, average 1961-1995).

Abb. 4-1a: Interpolierte Wintertemperaturen (Dezember-Februar) als Durchschnitt der Periode 1961-1995.

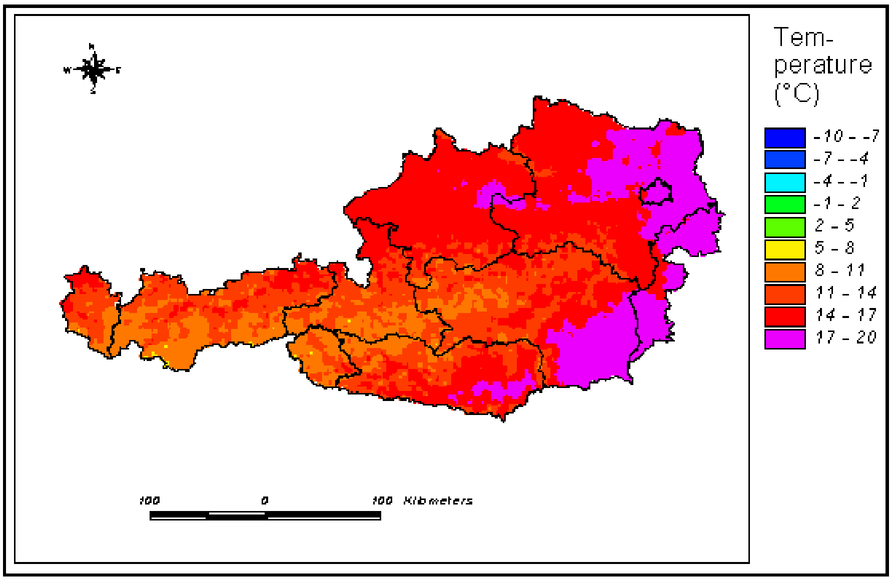


Figure 4-1b. Statistically interpolated summer temperature (June-August, average 1961-1995).

Abb. 4-1b: Interpolierte Sommertemperatur (Juni-August) als Durchschnitt der Periode 1961-1995.

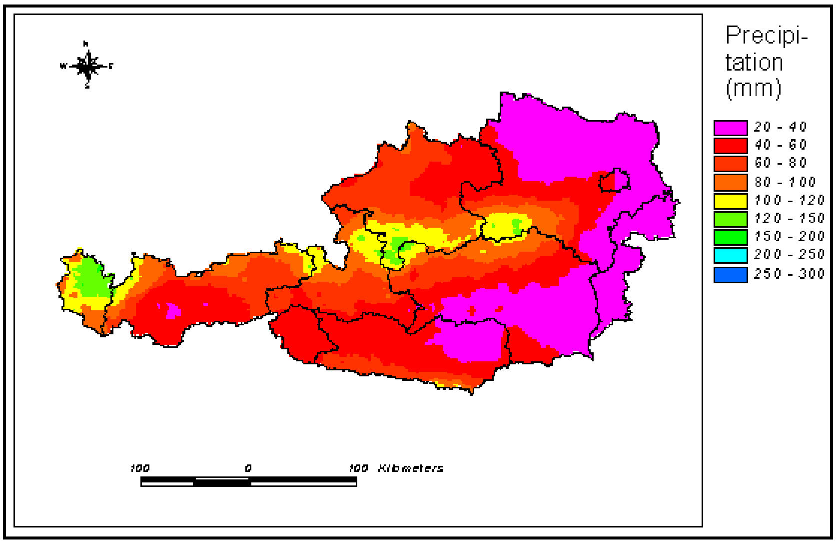


Figure 4-2a. Statistically interpolated winter precipitation (December-February, average 1961-1995).

Abb. 4-2a: Interpolierter Niederschlag (Dezember-Februar) als Durchschnitt der Periode 1961-1995.

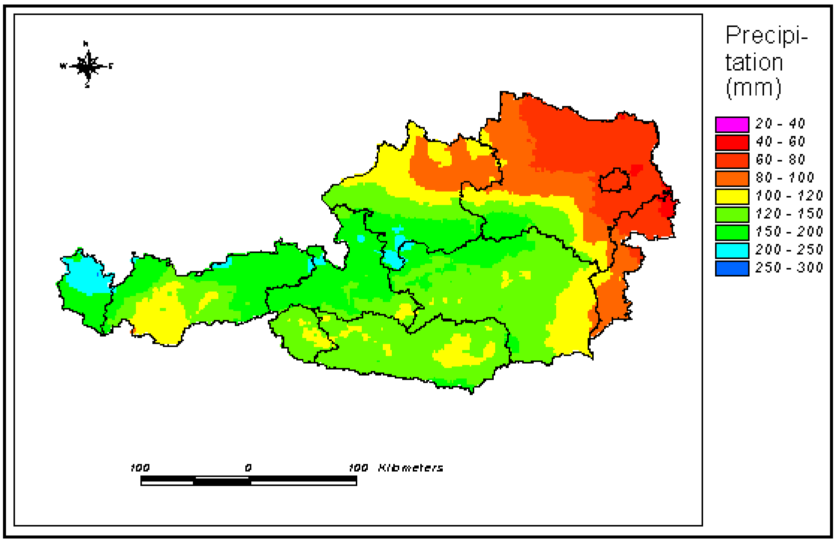


Figure 4-2b. Statistically interpolated summer precipitation (June-August, average 1961-1995).

Abb. 4-2b: Interpolierter Niederschlag (Juni-August) als Durchschnitt der Periode 1961-1995.

A cross validation procedure yielded monthly root mean square errors (RMSE) between 0.5 and 2.0 °C with lower values for RMSE at lower elevations and during summer season. The former is mainly due to the higher density of weather stations, which concentrate at the valley bottoms, the latter originates from frequently occurring temperature inversions during winter season. Monthly RMSE for precipitation were between 10 and 40 mm per month during winter season and between 20 and 40 mm during summer season.

4.1.2 Climate change scenarios

Due to the uncertainties involved with projections of future climates a set of three climate change scenarios was constructed for the present impact study. Core of this task was the regionalized climate change scenario scA which had been derived from simulation output of the global circulation model ECHAM4 (Roecker et al. 1996) under the IS92a greenhouse gas emission scenario (Houghton et al. 1990). We refer to this regionalized scenario as scenario scA. To expand the analysis of potential climate change impacts on forest ecosystems two additional climate change scenarios were constructed. These additional scenarios will be refered to as scenarios scB and scC respectively (Table 4-1).

Table 4-1. Characteristics of climate change scenarios used in the impact analyses.

Tab. 4-1: Charakterisierung der verwendeten Klimaänderungsszenarien.

Parameter	ScA	scB	scC
Temperature 2000-2050	transient, statistical downscaling from GCM	based on scA, linear increase	as in scB
temperature 2050+	+0.8 °C (spatial average)	+2.0 °C	+2.0 °C
Precipitation 2000-2050	transient, statistical downscaling from GCM	as in scA	based on scA, linear decrease
precipitation 2050+	+/- 7 %	as in scA	scA reduced by 15% during summer season

4.1.2.1 Scenario ScA

Averaged over Austria this scenario leads to an approximate increase of +0.8 °C in mean annual temperature by the year 2050 (represented by the average of the period 2035-2065) compared to the average of the period 1961-1995 (Figure 4-3a-d).

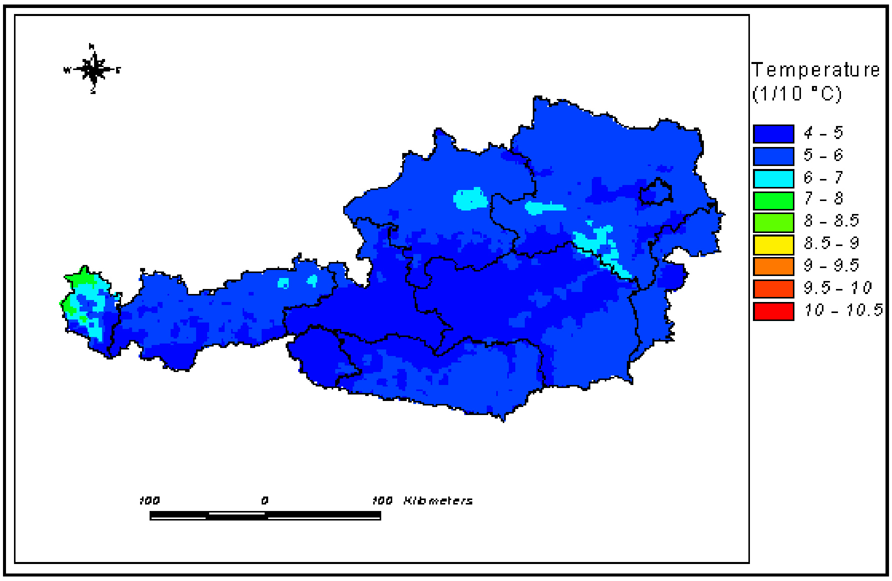


Figure 4-3a. Spatial distribution of monthly mean temperature increase (average of the period 2035-2065) in winter (December - February) under climate change scenario scA (moderate warming). – Reference: average 1961-95.

Abb. 4-3a: Anstieg monatlicher Mitteltemperaturen (Dezember-Februar) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

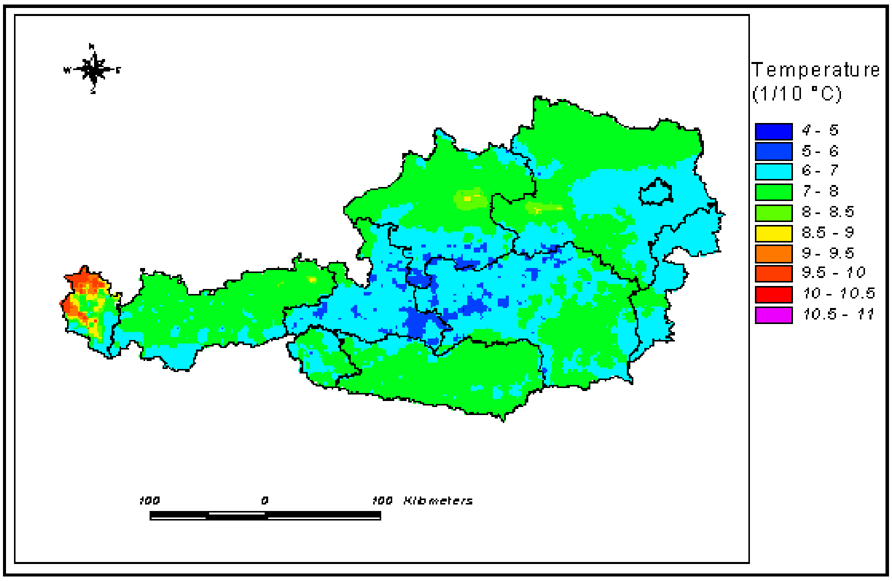


Figure 4-3b. Spatial distribution of monthly mean temperature increase (average of the period 2035-2065) in spring (March – May) under climate change scenario scA. – Reference: average 1961-95.

Abb. 4-3b: Anstieg monatlicher Mitteltemperaturen (März-Mai) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

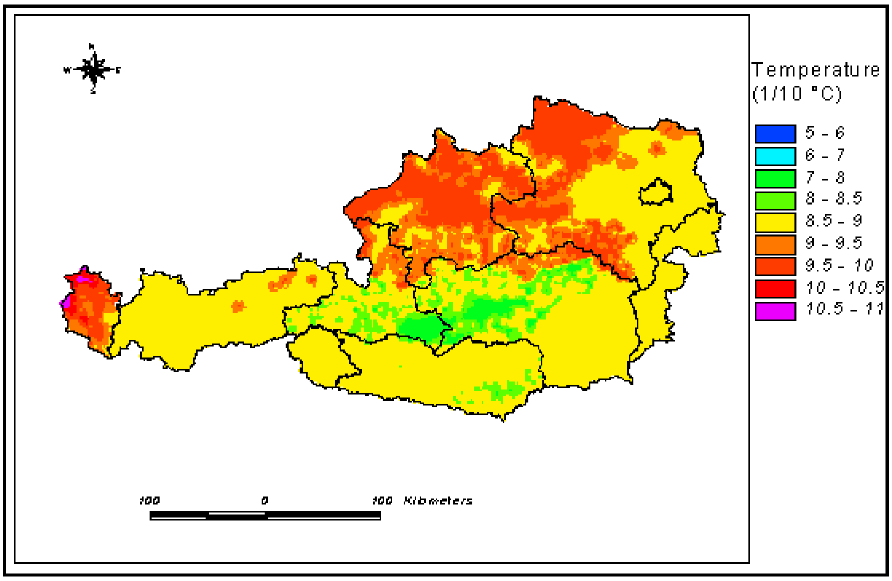


Figure 4-3c. Spatial distribution of monthly mean temperature increase (average of the period 2035-2065) in summer (June – August) under the climate change scenario scA. – Reference: average 1961-95.

Abb. 4-3c: Anstieg monatlicher Mitteltemperaturen (Juni-August) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

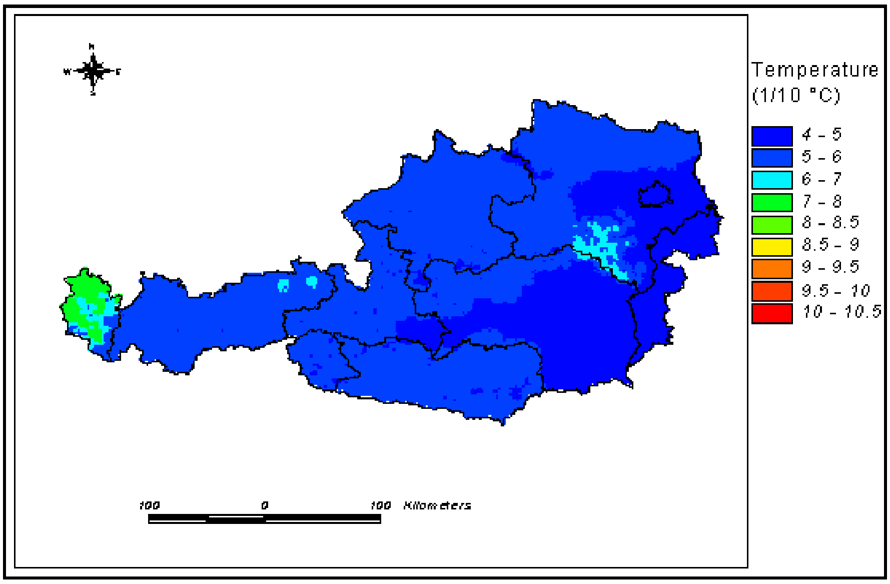


Figure 4-3d. Spatial distribution of monthly mean temperature increase (average of the period 2035-2065) in autumn (September – November) under the climate change scenario scA. – Reference: average 1961-95.

Abb. 4-3d: Anstieg monatlicher Mitteltemperaturen (September-November) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

From Figures 4-3a-d it can be seen that (a) the modelled temperature increase was largest during the warm season, and (b) the increase in temperature was largest in the northern and most western parts of Austria. During the cold season the expected temperature increases were fairly homogeneous all over Austria. To exemplify the transient phase 2000 – 2050 growing degree days calculated from downscaled temperature are shown for an investigated sample plot (Figure 4-4). The climate data for the simulation years 2051 to 3400 needed for the simulation of the equilibrium species composition (i.e., PNV) were represented by the regionalized data of the period 2035 – 2065.

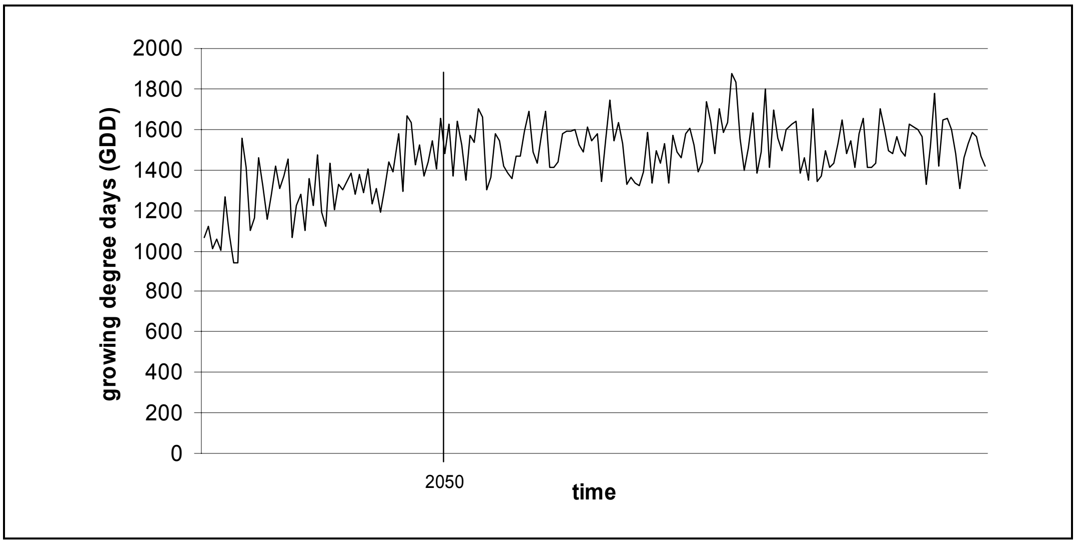


Figure 4-4. Example of climate change scenario data used within PICUS v1.2: Transient phase (years 2000 - 2050) of climate change scenario scA (parameter: growing degree days) for an investigated sample point of the Austrian Forest Inventory. From 2050 onward stochastically generated climate was based on the climate of the period 2035-2065.

Abb. 4-4: Beispiel für ein punktbezogenes Klimaänderungsszenario unter Szenario scA. Transiente Phase 2000-2050 wie regionalisiert, ab 2050 stochastisch generiert auf Basis der regionalisierten Periode 2035-2065.

The mean monthly precipitation anomalies for the year 2050 under scenario scA showed much higher spatial heterogeneity and comprised both, decreasing and increasing precipitation (Figure 4-5a-d).

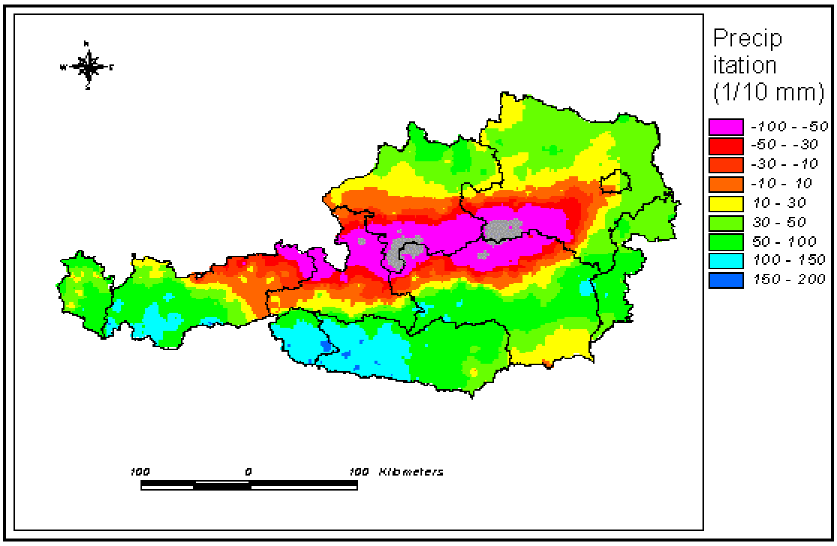


Figure 4-5a. Spatial distribution of monthly mean precipitation changes (average of the period 2035-2065) in winter (December – February) under climate change scenario scA. – Reference: average 1961-95.

Abb. 4-5a: Veränderung monatlicher Niederschlagswerte (Dezember-Februar) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

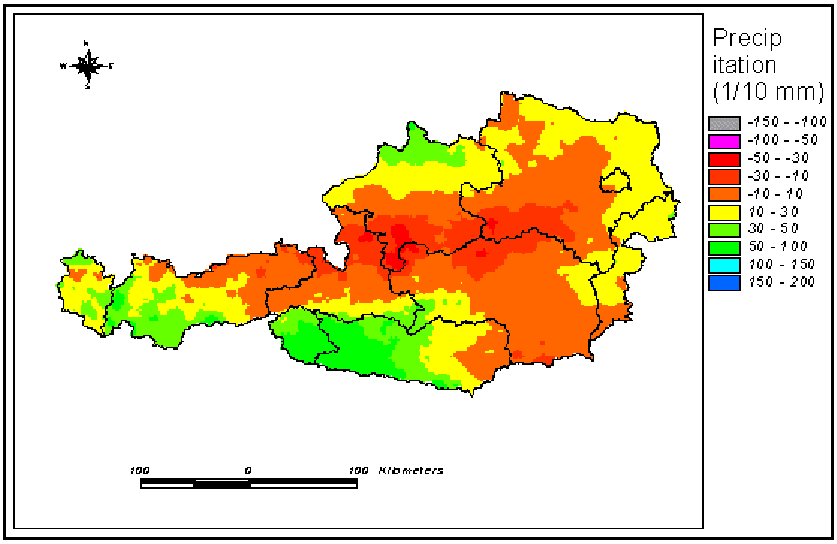


Figure 4-5b. Spatial distribution of monthly mean precipitation changes (average of the period 2035-2065) in spring (March – May) under climate change scenario scA. - Reference: average 1961-95.

Abb. 4-5b: Veränderung monatlicher Niederschlagswerte (März-Mai) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

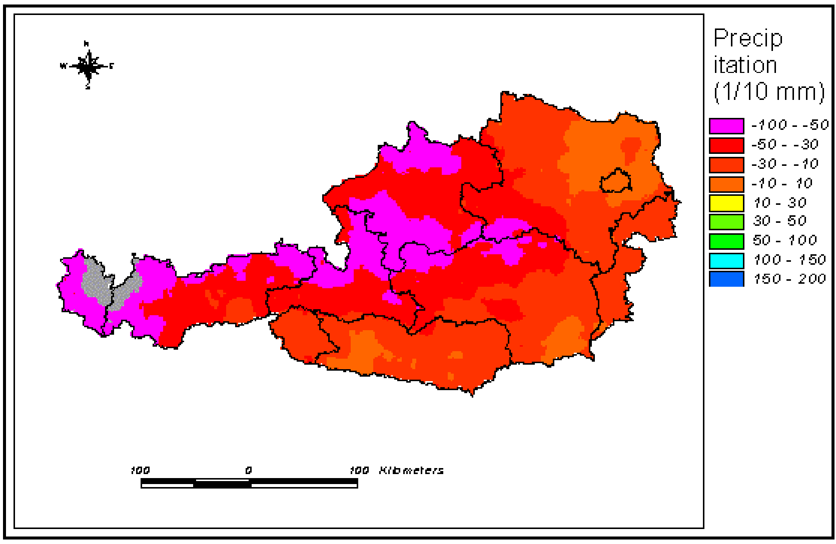


Figure 4-5c. Spatial distribution of monthly mean precipitation changes (average of the period 2035-2065) in summer (June – August) under the climate change scenario scA. – Reference: average 1961-95.

Abb. 4-5c: Veränderung monatlicher Niederschlagswerte (Juni-August) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

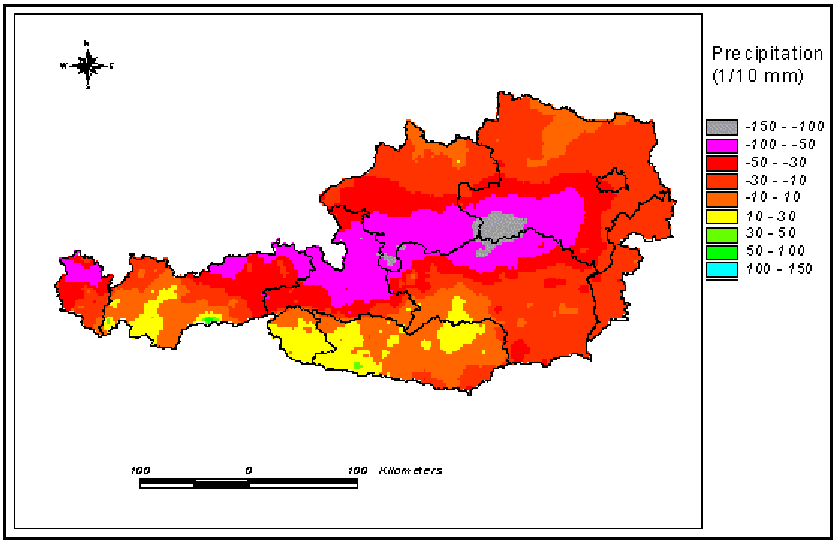


Figure 4-5d. Spatial distribution of monthly mean precipitation changes (average of the period 2035-2065) in autumn (September – November) under the climate change scenario scA. – Reference: average 1961-95.

Abb. 4-5d: Veränderung monatlicher Niederschlagswerte (September-November) als Durchschnitt 2035-2065 bezogen auf 1961-1995 für Szenario scA.

According to the presented results the spatial heterogeneity of precipitation anomalies was largest for the winter season. Precipitation decreased most strongly at the northern front range of the Alps, a region with precipitation sums of up to 2000 mm/year under today's climate. In essentially all other parts of Austria winter precipitation was predicted to increase slightly. During the warm season the expected increases were rather small and mainly confined to smaller regions in the south of Austria. The strongest overall reduction in precipitation was expected to occur along the northern front range of the Alps.

4.1.2.2 Scenario scB

For scB the temperature increase compared to the baseline scenario (current climate) at all sample points was assumed to be +2 °C for the year 2050 (represented by the 30-year average 2035-2065). The transient phase for each sample point was constructed based on the corresponding temperature time series 2000-2065 from scenario scA (compare Figure 4-6). With this approach we preserved the temporal pattern of the transient phase from scenario scA.

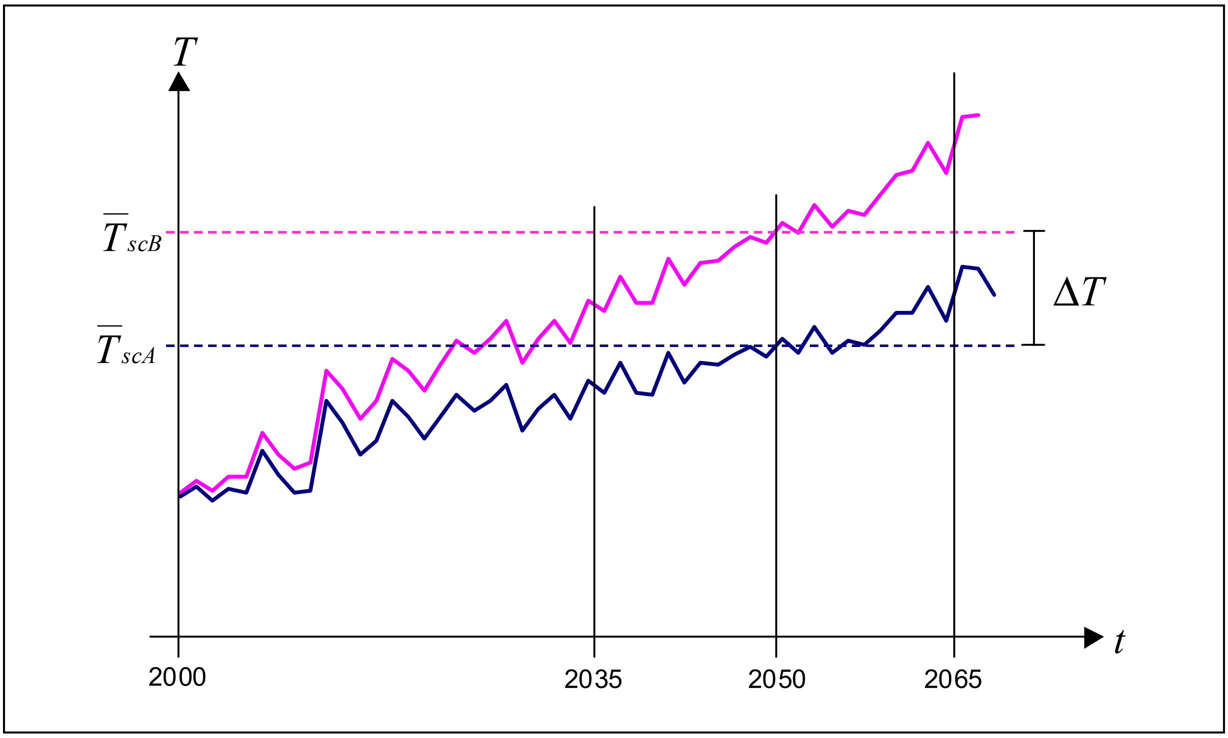


Figure 4-6. Scheme for the construction of the transient phase for temperature in scenario scB. – Blue line = temperature time series from statistical downscaling (scenario scA), red line = temperature time series derived for scenario scB.

Abb. 4-6: Schema für die Konstruktion der transienten Phase in Klimaänderungsszenario scB.- Blaue Linie = Temperaturzeitreihe aus Szenario scA, Rote Linie = abgeleitete Temperaturzeitreihe für Szenario scB.

ΔT in Figure 4-6 is the difference between the required temperature increase of +2 °C and the corresponding temperature increase of scenario scA (moderate warming). The climate generated stochastically within PICUS v1.2 for the simulation period 2051 to 3400 (this simulation period was necessary to generate the steady state species composition at a site) was based on the climate characteristics of the period 2035 – 2065. Precipitation data in scenario scB were equivalent to those used in scenario scA.

4.1.2.3 Scenario scC

To provide a climate change scenario with the combined signal of strong temperature increase and strong precipitation decrease respectively scenario scC included the temperature response as constructed for scenario scB, and additionally assumed a linear decrease in summer season precipitation (May to September) of 15% with regard to the average 2035-2065 of precipitation employed in scenario scA. The parameters (a, b) of the gamma distribution which is employed to generate monthly precipitation for the simulation period 2051 to 3400 were estimated from the 30-year period 2035-2065. According to that approach the spatial heterogeneity of precipitation anomalies from scenario scA was preserved.

4.2 Selecting sub samples of the Austrian Forest Inventory

The Austrian Forest Inventory (FBVA 1995) monitors the state of Austrian forests at more than 10000 permanent sample plots (compare section 3.3). For the present study a subsample was selected. The sample population was reduced due to the initialisation requirements of PICUS (i.e., required information on regeneration, sufficient mensurational data on adult individual trees, estimation of soil parameters possible) and due to limits of the current model version (i.e., no water logged sites can be simulated realistically). In addition to floodplain forests (due to difficulties in computing soil moisture indices) protection forests of very low productivity (protection forests without commercial yield) were also excluded from the simulation study. The reasons were twofold: first, at sample plots located in such forests AFI records a reduced set of tree attributes, and second, major portions of this class of forests are situated at high altitudes where processes not identifiable from plot data (e.g., avalanches) might substantially affect vegetation development. It is worth noting, that also the required computer time for the extensive simulation runs restricted the possible number of plots for this study. Therefore we decided to a priori exclude two of the four plots of each AFI-cluster from the selection process. After considering these restrictions a subsample of 2830 plots remained. This sample represented 63% of the forest area of Austria which corresponds to appr. 2.5 mill. hectares of forest (productive high forest, coppice forest).

The full set of 2830 plots was simulated for the baseline scenario (current climate) and the climate change scenario scA (moderate warming). For the simulation runs under the climate change scenarios scB (mean annual temperature increases by +2.0 C until 2050, precipitation as in scenario scA) and scC (mean annual temperature increases by +2.0 °C until 2050, precipitation decreases by 15% in summer compared to scenario scA until 2050) the number of simulated inventory points was further reduced to 708 by selecting every fourth sample plot from the base sample.

5 RISK ASSESSMENT RESULTS

5.1 Simulated potential natural vegetation (PNV) under current climate

PICUS v1.2 was run under current climate as well as under three climate change scenarios as defined in section 4.1.2 for 1400 years each. In earlier model tests this period was found sufficient to reach equilibrium species composition. Size of the simulated forest was 1.0 ha. For the first 50 years (simulation years 2000 – 2050) model output was stored every year, from year 2051 onwards every 10th year was written to an output file to increase computation speed. Equilibrium species composition was estimated as the average of the final 300 years of the simulation period. Due to eventually occurring computer problems it was rarely possible to provide complete output sets for all of the involved inventory points of a particular climate scenario (compare section 4.2). Thus, the number of involved plots with complete data vector differed slightly among the scenarios. Whenever maps of simulated attributes such as the potential natural vegetation (PNV) or risk indices are shown in the following sections we present point maps. We decided, neither to spatially extrapolate information given for a particular inventory point nor to aggregate several inventory points within a moving spatial window. We are aware of possible "outliers" at individual sample points. However, by doing so we feel to better communicate the spatial variability in the data compared to "lumped" raster maps. In this context it is important to recognise, that (i) PICUS v1.2 mainly had been initialised with site and soil information which per se are subject to estimation errors, and (ii) the model had not been constrained to specific ranges of the simulated output variables.

To evaluate the performance of PICUS v1.2 in generating plausible equilibrium species compositions at sample points of the AFI model output was compared with expert reconstruction of PNV available for each inventory point. For a total of 2759 sample plots PNV had been simulated under the baseline scenario (current climate). As a prerequisite for a consistent and quantitative comparison of model output with expert-PNV the simulated equilibrium species compositions had to be classified into categories of PNV compatible with the scheme used within the Austrian Forest Inventory. The employed classification procedure was based on quantitative characterisations of PNV-types with regard to possible ranges of tree species proportions for each of the PNV-types considered within this study (Table 5-1). In the present study the term PNV was exclusively related to tree species and did not include ground vegetation. All simulated equilibrium species compositions were evaluated whether they fitted into one of the predefined PNV-types. Each equilibrium species composition that could not be assigned to one of the considered PNV-types was set aside as unclassified. Table 5-2 shows the number of unclassified inventory points for all simulated climate scenarios.

Table 5-1. Types of potential natural vegetation (PNV) according to FBVA (1995) represented by the complete sample of 2830 inventory plots selected for this study.

Tab. 5-1: Potentielle natürliche Waldtypen wie sie von der Österreichischen Waldinventur verwendet werden (FBVA 1995).

PNV-type	Characterisation / dominating species
01	Larix decidua/Pinus cembra – forest
02	Larix decidua – forest
03	Subalpine Picea abies – forest
04	Montane Picea abies – forest
05	Picea abies/Abies alba – forest
06	Picea abies/Abies alba/Fagus sylvatica – forest
6.I	Upper montane Acer pseudoplatanus/Fagus sylvatica – forest
07	Fagus sylvatica – forest
08	Quercus spp./Carpinus betulus – forest
09	Quercus spp. – forest on acidic sites
9,1	Subcontinental mixed Quercus spp. forest
10	Quercus pubescens – forest
12	Tilia spp. Forest
13	Acer pseudoplatanus/Fraxinus excelsior – forest
21	Pinus sylvestris – forest on calcareous sites
22	Pinus sylvestris – forest on acidic sites
23	Pinus nigra – forest

Table 5-2. Number and percentage of unclassified inventory points regarding the expert scheme of potential natural vegetation (PNV) for all simulated climate scenarios.

Tab. 5-2: Anzahl und Prozentsatz nicht klassifizierter simulierter Equilibriumartenzusammensetzungen unter allen Szenariobedingungen.

Scenario	points simulated	Unclassified	
		n	%
baseline scenario	2759	411	14.9
scenario scA	2778	455	16.4
scenario scB	699	122	17.5
scenario scC	701	147	21.0

Hierarchical cluster analyses (average linkage between groups) was employed to group similar mixture types within the subset of unclassified cases. Finally, six additional equilibrium forest types were identified whose deviations were too large to allow a grouping with one of the original PNV-types given by AFI (Table 5-3).

Table 5-3. Additional equilibrium forest types (i.e., PNV) identified by means of cluster analyses of all unclassified cases under the baseline and three climate change scenarios.

Tab. 5-3: Durch Clusteranalysen aus den unklassifizierten Fällen gebildete zusätzliche simulierte potentielle natürliche Waldtypen (PNV).

PNV-type	Characterisation
24	Alnus viridis dominated type, mainly shrub vegetation
25	mixed Betula spp. – forest
26	mixed forests dominated by Picea abies with substantial proportions of Carpinus betulus/Quercus robur
27	mixed beech/fir/spruce – forest with Quercus robur/carpinus betulus
28	forests dominated by broadleaves (Quercus spp., Fagus sylvatica) with substantial proportions of conifers
29	mixed Quercus spp./fagus sylv. – forest, transition type between 07 and 08.

Simulated PNV under the baseline scenario (current climate) is matched with expert-PNV. The intraclass correlation coefficient (i.e., the percentage of correctly classified inventory plots) is 40.2. From Table 5-4 and Figure 5-1 some distinct patterns can be seen. In general the simulated share [aboveground biomass] of Picea abies seems to be too large, mainly to the cost of Fagus sylvatica and partly Abies alba over a range of site conditions where vegetation experts expected mixed spruce/fir (PNV-type 05) and spruce/fir/beech forests (PNV-type 06). The same argument partly holds for the sites with expected beech-dominated PNV (PNV-type 07).

A recurrent pattern is also the divergence of simulated PNV to expert PNV at sites where according to AFI oak-dominated forest types (PNV-types 08, 09, 91) are expected. At such sites PICUS showed the tendency to simulate mainly beech-dominated forests (PNV-type 07) with admixed Quercus spp. and Carpinus betulus. Not surprisingly, rare communities such as PNV-type 12 (Tilia spp.- forest) are "overseen" by the model. Apparently the niche for such species compositions can not be described with the set of parameters currently used within PICUS. The lack of simulated pine forests is surely mainly due to the applied minimum threshold for the site water holding capacity (compare section 3.3.1). However, pine-dominated forest communities comprise only a few percent of the total forested area. Substantial proportions of sites classified by AFI as spruce/fir/beech – type (PNV-type 06) were assigned to the "cluster" PNV-types 26 to 29, thus indicating that PICUS v1.2 seemed to produce a fairly continuous transition from coniferous forests typical for the upper montane vegetation belt to the broadleaf-dominated communities of the lowlands.

Table 5-4. *Comparison of simulated potential natural vegetation (PNV) with expert-PNV at sample plots of the Austrian Forest Inventory (AFI). – Simulated species compositions not recognised by the expert scheme are shaded light grey.*

Tab. 5-4: *Vergleich simulierter PNV mit Expertenansprachen auf Erhebungspunkten der Österreichischen Waldinventur.- Hellgrau = nicht klassifizierte Fälle.*

	PNV Austrian Forest Inventory													
PNV simulated	**1,2**	**3**	**4**	**5**	**6**	**6.1**	**7**	**8**	**9,9.1,10**	**12**	**13**	**21,22,23**	**N**	**%**
1,2	**21**	23	1	0	0	0	0	0	0	0	0	0	45	1.6
3	22	**145**	0	10	5	0	0	0	0	0	0	0	182	6.6
4	9	0	**242**	262	256	7	30	2	10	1	20	6	845	30.6
5	2	9	31	**129**	91	3	36	8	5	0	6	0	320	11.6
6	0	0	19	28	**409**	2	91	32	12	1	11	5	610	22.1
6.1	0	0	6	3	39	**1**	2	0	0	0	0	5	56	2.0
7	0	0	6	2	112	0	**131**	59	31	7	9	4	361	13.1
8	0	0	0	2	17	0	27	**29**	14	2	1	0	92	3.3
9,9.1,10	0	0	0	0	1	0	0	3	**3**	0	0	0	7	0.3
12	0	0	0	0	0	0	0	0	0	**0**	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	**0**	0	0	0
21,22,23	0	0	0	0	0	0	0	0	0	0	0	**0**	0	0
24	3	11	2	0	0	0	0	0	0	0	0	0	16	0.6
25	0	0	0	1	0	0	0	0	0	0	0	0	1	0.004
26	0	0	0	1	19	0	2	2	2	0	1	0	27	1.0
27	0	0	1	2	46	0	21	5	4	0	4	2	85	3.1
28	0	0	0	3	10	0	4	0	0	0	1	4	22	0.8
29	0	0	2	1	42	0	24	11	3	1	3	3	90	3.3
N	57	188	310	444	1047	13	368	151	84	12	56	29	2759	100
%	2.1	6.8	11.2	16.1	37.9	0.4	13.3	5.4	3.0	0.4	2.0	1.0	100	

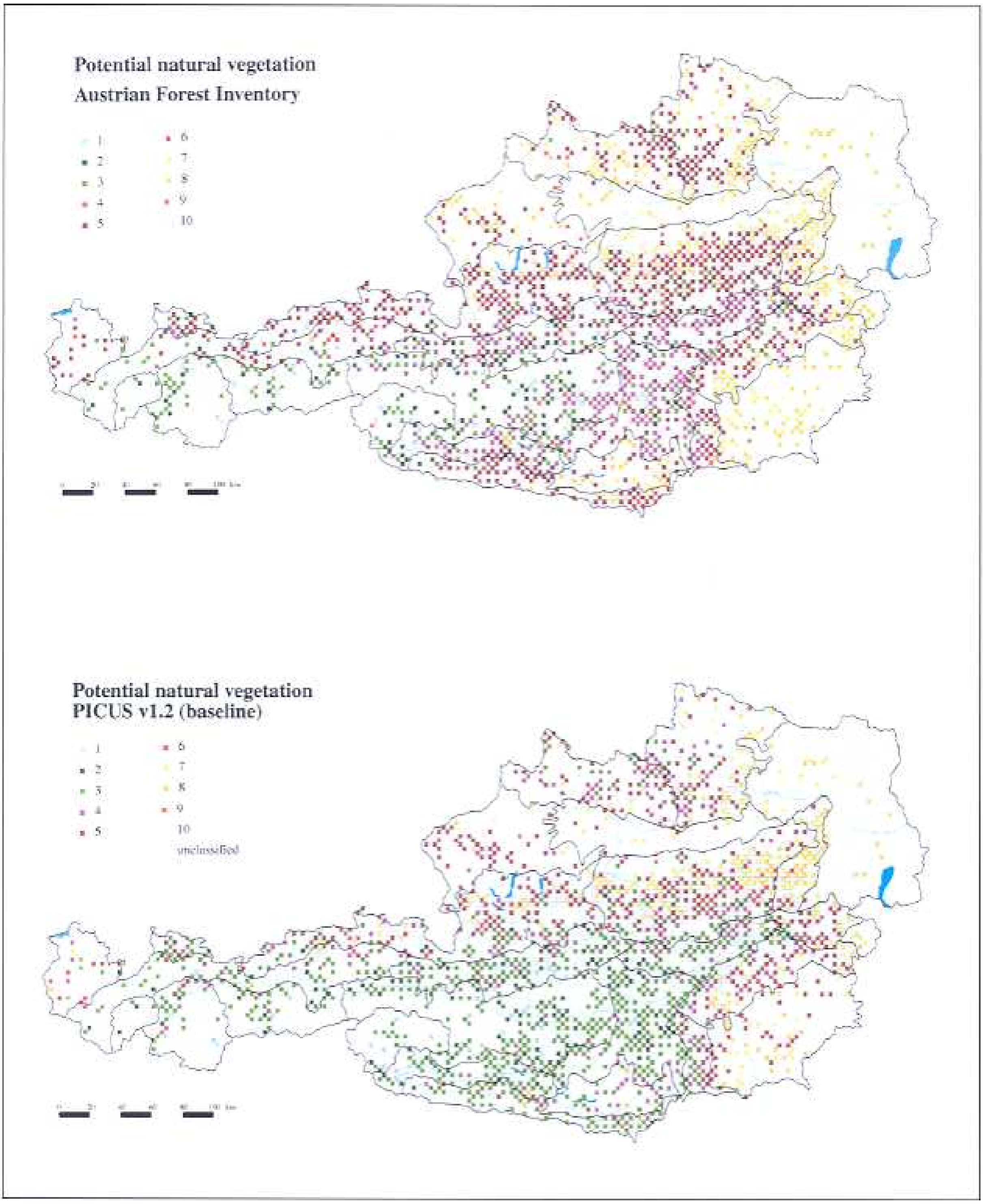


Figure 5-1. *Comparison of simulated potential natural vegetation (PNV) at selected sample points of the Austrian Forest Inventory under current climate (baseline scenario) with PNV as expected by the Austrian Forest Inventory. – 1 = PNV-types 01, 02; 2 = 03; 3 = 04; 4 = 05; 5 = 06; 6 = 6.1; 7 = 07; 8 = 08; 09, 9.1, 10; 9 = 12; 10 = 21, 22, 23. Originally unclassified plots appear white. (see Table 5-1 for description).*

Abb. 5-1: *Vergleich von simulierter PNV unter aktuellem Klima und Expertenansprachen der PNV auf Erhebungspunkten der Österreichischen Waldinventur. (siehe Tab. 5-1 für Erklärung der Waldtypen)*

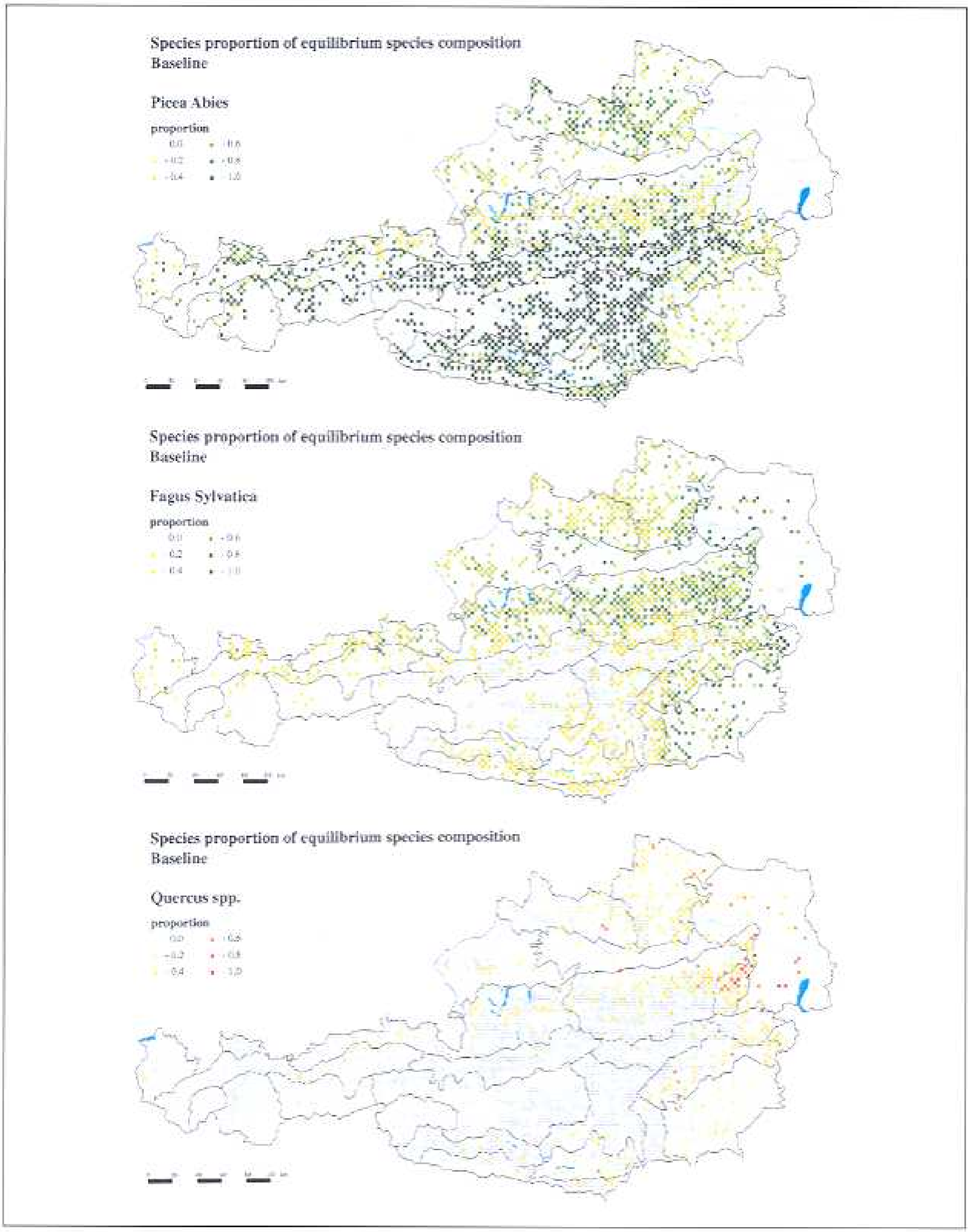


Figure 5-2. Share [aboveground biomass] of Picea abies, Fagus sylvatica and Quercus spp. in the simulated equilibrium species composition (PNV) at selected sample points of the Austrian Forest Inventory under current climate (baseline scenario). - (n = 2759).

Abb. 5-2: Anteile [oberirdische Biomasse] ausgewählter Baumarten in der auf Erhebungspunkten der Österreichischen Waldinventur simulierten PNV unter aktuellem Klima (baseline scenario).

The attempt to classify simulated equilibrium species composition according to the expert scheme of potential natural vegetation types as used by the Austrian Forest Inventory was meant to allow for a consistent comparison between simulated and expected potential natural vegetation (PNV) at inventory points. However, the strength of the dynamic model PICUS compared to static equilibrium models (e.g., Kienast et al. 1996) is, that PICUS operates at the species level. To emphasise the employed individualistic modelling approach the proportions of major tree species in the simulated equilibrium species composition are shown in Figure 5-2. It is obvious that PICUS v1.2 was able to reproduce a very plausible large-scale pattern of species abundance with regard to the potential natural vegetation (PNV). From this model evaluation exercises we concluded that the model realistically captured the synecological behaviour of major European tree species and thus could be employed to study climate change effects on forest vegetation.

5.2 Simulated potential natural vegetation (PNV) under climate change scenarios

Within the concept of potential natural vegetation as used for the evaluation of PICUS v1.2 the impact of climatic change could be represented by changes in the frequency distribution or in a change in the spatial distribution pattern of PNV-types (compare Kienast et al. 1996). Though such an approach apparently is straightforward it is important to recognise, that it might be inappropriate to uncover climate change impacts which do not result in a change of the assigned PNV-type. However, to exemplify how a possible climate change might affect the distribution of equilibrium forest types (PNV) in Austria Figure 5-3 presents simulated PNV under current climate (baseline scenario) and under the climate change scenario scA (moderate warming). From Table 5-5 the quantitative changes of PNV-types under scenario scA can be seen. A general finding was, that the proportion of PNV-types characteristically for higher altitudes (PNV-types 01, 02, 03, 04) decreased, whereas the proportion of mixed conifer-broadleaved forests (PNV-type 06) as well as broadleaf-dominated types (07, 08) increased. It is also interesting to note, that under the climate change scenario scA the overall proportion of essentially "unknown" PNV-types (24, 25, 26, 27, 28, 29) increased slightly by appr. 2%. The pattern in Table 5-5 inherently includes the very heterogeneous distribution of precipitation anomalies of scenario scA (compare section 4.1). Thus, simulated forest composition identified as PNV-type 29 (beech/oak-forest) under current climate (baseline scenario) might appear as PNV-type 07 (beech forest) under the climate change scenario scA. Inspection of such sample points revealed that very often a small change in the share of a single species resulted in a change of the assigned PNV-type.

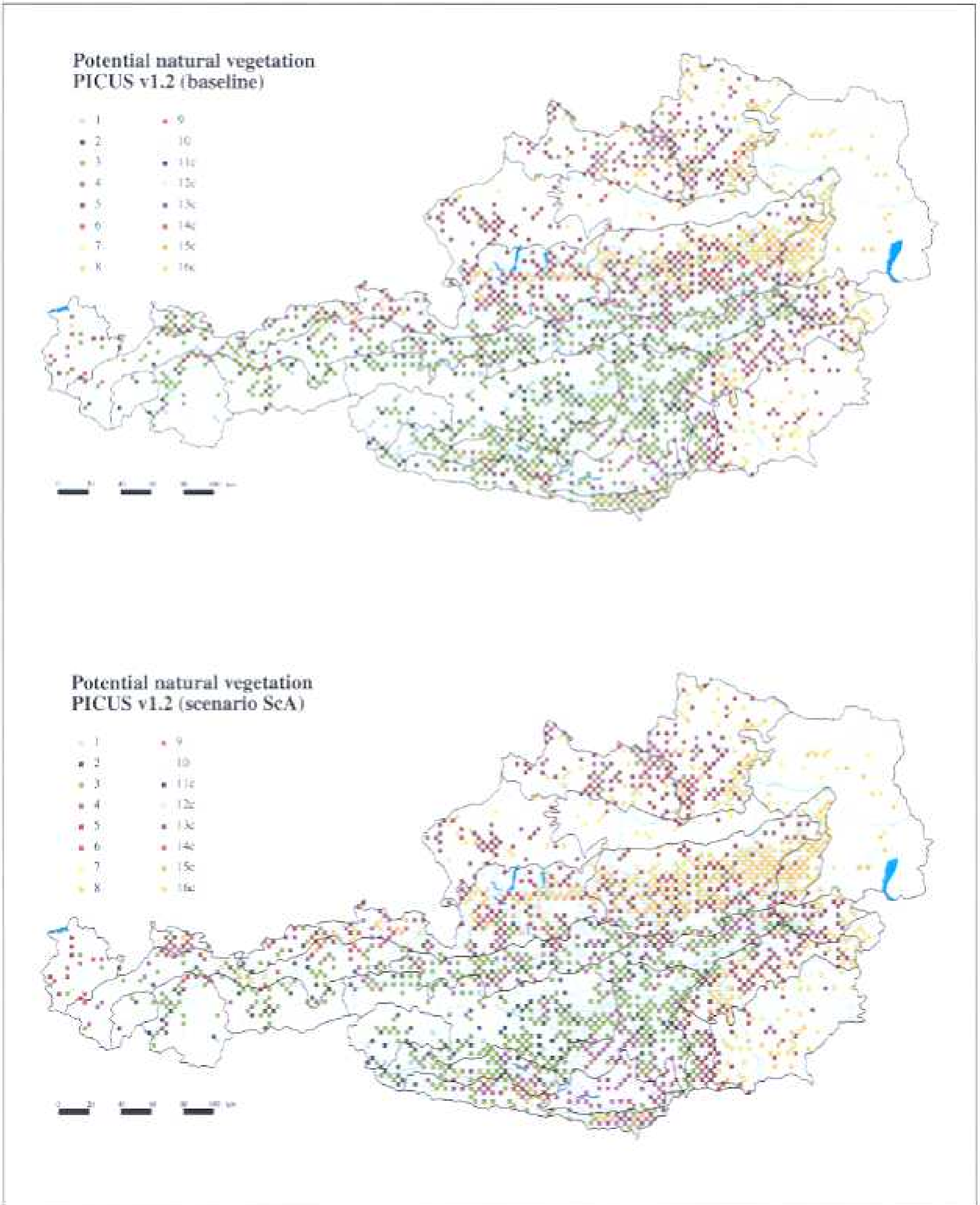


Figure 5-3: Simulated potential natural vegetation (PNV) under current climate (baseline scenario) and under climate change scenario scA (moderate warming) at selected sample points of the Austrian Forest Inventory. – 1 = PNV-types 01, 02; 2 = 03; 3 = 04; 4 = 05; 5 = 06; 6 = 6.1, 7 = 07, 8 = 08, 09, 9.1, 10; 9 = 12; 10 = 21, 22, 23; 11c = 24; 12c = 25; 13c = 26, 14c = 27; 15c = 28, 16c = 29; (compare Tables 5-1 and 5-3 for description).

Abb. 5-3: Auf Erhebungspunkten der Österreichischen Waldinventur simulierte PNV unter aktuellem Klima (baseline scenario) und unter dem Klimaänderungsszenario scA. (siehe Tab. 5-1 und 5-3 für Erklärung der Waldtypen).

Table 5-5. Number of sites within the potential natural forest types (PNV) as simulated by PICUS v1.2 under the baseline scenario (current climate) and the climate change scenario scA (moderate warming).

Tab. 5-5: Probepunkte je PNV-Typ auf Basis simulierter PNV unter aktuellem Klima und unter dem Klimaänderungsszenario scA.

PNV-type	characterisation	baseline scenario		scA	
		n	%	n	%
01,02	Larix decidua/Pinus cembra forest, Larix decidua forest	45	1.60	13	0.50
03	subalpine Picea abies forest	182	6.60	156	5.60
04	montane Picea abies forest	845	30.60	624	22.40
05	Picea abies/Abies alba forest	320	11.60	332	12.00
06	Picea abies/Abies alba/Fagus sylvatica forest	610	22.10	651	23.70
6,1	upper montane Acer pseudopl./Fagus sylv. forest	56	2.00	48	1.70
07	Fagus sylvatica forest	361	13.10	528	19.00
08	Quercus spp./Carpinus betulus forest	92	3.30	121	4.30
09, 9.1, 10	Quercus spp. forest on acidic soils, subcontinental mixed Quercus forest, Qu. pubescens forest	7	0.30	11	0.40
24	Alnus viridis forest	16	0.60	12	0.50
25	mixed Betula spp. forest	1	0.04	2	0.10
26	mixed forests of Picea abies and Carpinus betulus, Qu. robur	27	1.00	27	0.90
27	mixed fagus sylv./Abies alba/Picea abies forest with Qu. robur, Carpinus betulus	85	3.10	121	4.40
28	Quercus spp./fagus sylv. forest with Picea abies, Abies alba	22	0.80	25	0.90
29	mixed Quercus spp./Fagus sylv. forest (transition between 07 and 08)	90	3.30	99	3.60
Total		**2759**	**100.00**	**2778**	**100.00**

Figure 5-4 demonstrates the effect of three climate change scenarios on the proportion of Picea abies in the simulated equilibrium species composition (aboveground biomass). Picea abies, a major species under current climate (see Figure 5-2), showed a smaller "natural" distribution area under conditions of climatic change to the benefit of broadleaves, particularly Fagus sylvatica. This species enlarged its potential natural distribution area into upper montane regions and increased its abundance at sites where it was already present under current climate (baseline scenario). In general, the simulated response of oak species was weaker. Nevertheless, particularly under scenarios scB and scC with a marked increase in temperature, oak species occurred at considerable proportions at montane sites. The positive response (i.e., increase in the share of aboveground biomass) of oak species to warming at sites where under current climate oak had already been the dominant species was – of course – limited. At just a few dry sites the increased share of Pinus sylvestris lead in turn to a decrease in the share of oak species.

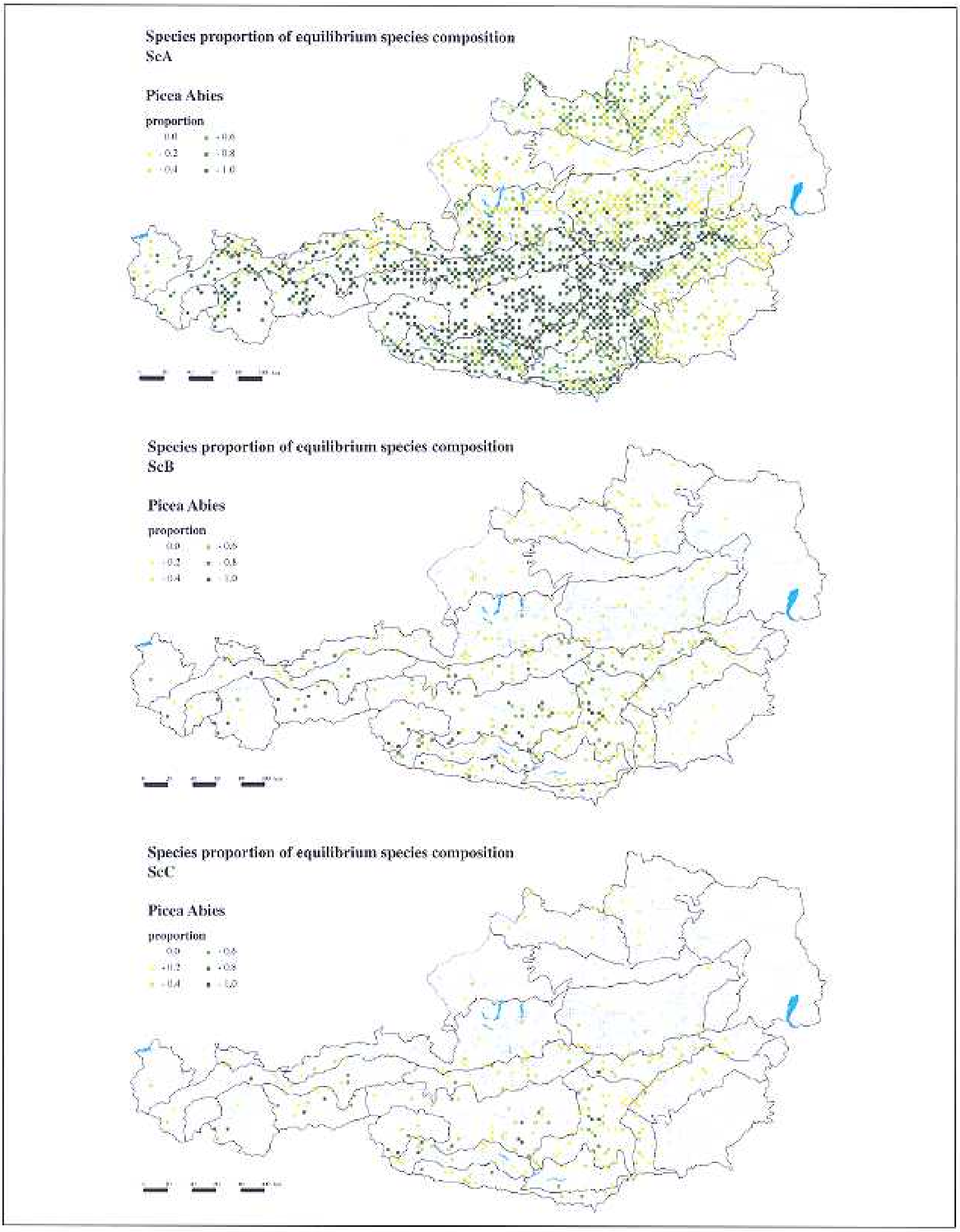


Figure 5-4. *Share [aboveground biomass] of Picea abies in the simulated equilibrium species composition (PNV) at selected sample points of the Austrian Forest Inventory under climate change scenarios scA (n = 2778), scB (n = 699) and scC (n = 701).*

Abb. 5-4: *Anteil [oberirdische Biomasse] von Picea abies in der auf Erhebungspunkten der Österreichischen Waldinventur simulierten PNV unter Klimaänderungsszenarien scA, scB und scC.*

Non-parametric Kruskall-Wallis and Wilcoxon-Mann-Whitney tests (Noether 1990) were employed to compare species abundance simulated under different climate scenarios. In general the interpretation of the results is straightforward (Table 5-6): the proportion of Picea abies decreased, the abundance of Fagus sylvatica and Quercus spp. increased. What is more interesting is, that the behaviour of the three considered species was not the same in all altitudinal zones. Particularly at low-elevation sites (today's submontane and colline vegetation zone) the broad-leaved species showed a somewhat different pattern. Using the baseline scenario (current climate) as a benchmark the proportion of Quercus spp. in the colline zone showed a significant increase only under conditions of scenario scC (strong warming, additional decrease in summer precipitation). No significant increase of Quercus species could be found when scA or scB were used as benchmark scenario. According to the simulation results this means, that it took a marked increase of temperature and a decrease in precipitation to significantly alter the proportion of oak species in the equilibrium species composition in the colline vegetation zone. In the submontane zone Quercus responded at smaller temperature and precipitation anomalies. At higher elevations the simulated species pattern is simpler to interpret. Quercus species and particularly Fagus sylvatica increased, Picea abies decreased. In general this response was significant for all three species (α = 0.05) with the exception of Picea abies under the climate change scenario scA (moderate warming) when compared to the baseline simulation (current climate).

Table 5-6. Wilcoxon-Mann-Whitney tests (two sided, Bonferroni correction) on changes in shares [aboveground biomass] of Picea abies (PA), Fagus sylvatica (FS) and Quercus spp. (QU) under the climate change scenarios scA, scB and scC compared to the baseline scenario (current climate). – Sa = subalpine, um = upper montane, m = montane, lm = lower montane, sm = submontane, co = colline. Ns = not significant at α *= 0.05, * = significant at* α *= 0.05, ** = significant at* α *= 0.001, - = decrease in share of biomass, + = increase in share of biomass, x = no occurrence.*

Tab. 5-6: Wilcoxon-Mann-Whitney Tests (2-seitig, Bonferronikorrektur) auf Unterschiede in Biomassenanteilen für Fichte (PA), Buche (FS) und Eichen (QU) unter den Klimaänderungsszenarien scA, scB und scC im Vergleich zu aktuellem Klima (baseline scenario).- sa = subalpin, um = hochmontan, m = mittelmontan, lm = tiefmontan, sm = submontan, co = kollin. - = Abnahme des Biomassenanteiles, + = Zunahme des Biomassenanteiles, x = tritt nicht auf.

benchmark scenario	**altitudinal zone**	**scA**			**scB**			**scC**		
		PA	**FS**	**QU**	**PA**	**FS**	**QU**	**PA**	**FS**	**QU**
baseline	sa	$-^{ns}$	$+^{*}$	x	$-^{*}$	$+^{*}$	$+^{*}$	$-^{*}$	$+^{*}$	$+^{*}$
	um	$-^{**}$	$+^{*}$	$+^{ns}$	$-^{*}$	$+^{*}$	$+^{*}$	$-^{*}$	$+^{*}$	$+^{*}$
	m	$-^{ns}$	$+^{*}$	$+^{*}$	$-^{*}$	$+^{*}$	$+^{*}$	$-^{*}$	$+^{*}$	$+^{*}$
	lm	$-^{ns}$	$+^{*}$	$+^{ns}$	$-^{*}$	$+^{*}$	$+^{*}$	$-^{*}$	$+^{*}$	$+^{*}$
	sm	$-^{ns}$	$+^{*}$	$+^{ns}$	$-^{*}$	$+^{*}$	$+^{ns}$	$-^{*}$	$+^{*}$	$+^{ns}$
	co	$-^{ns}$	$+^{ns}$	$+^{ns}$	$-^{*}$	$+^{ns}$	$+^{ns}$	$-^{*}$	$+^{ns}$	$+^{*}$

5.3 Bioclimatic indices

Selected bioclimatic indices calculated within the simulation environment of PICUS v1.2 are presented to provide a visual impression of the spatial distribution and the expected changes of environmental key parameters used within PICUS under conditions of three climate change scenarios. In Figure 5-5a-b the thermal heat sum above the threshold of 5.5 °C (Growing Degree Days) is shown.

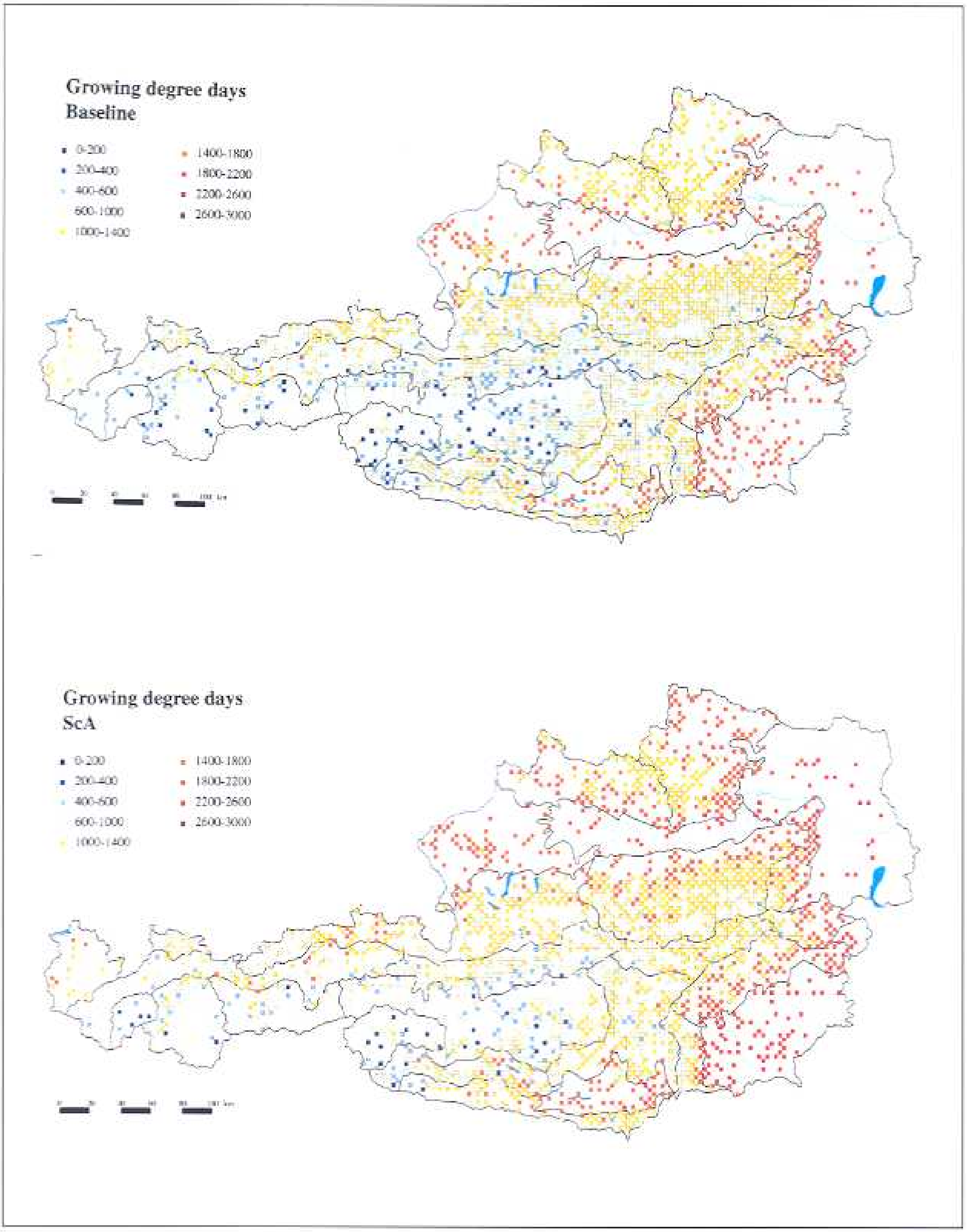


Figure 5-5a. Average heat sum above 5.5 °C (Growing Degree Days) at investigated sample points of the Austrian Forest Inventory under current climate (baseline scenario) [above] and climate change scenario scA (moderate warming) [below].

Abb. 5-5a: Durchschnittliche Temperatursumme >5.5 °C (Growing Degree Days) auf Erhebungspunkten der Österreichischen Waldinventur unter aktuellem Klima [oben] und Klimaänderungsszenario scA [unten].

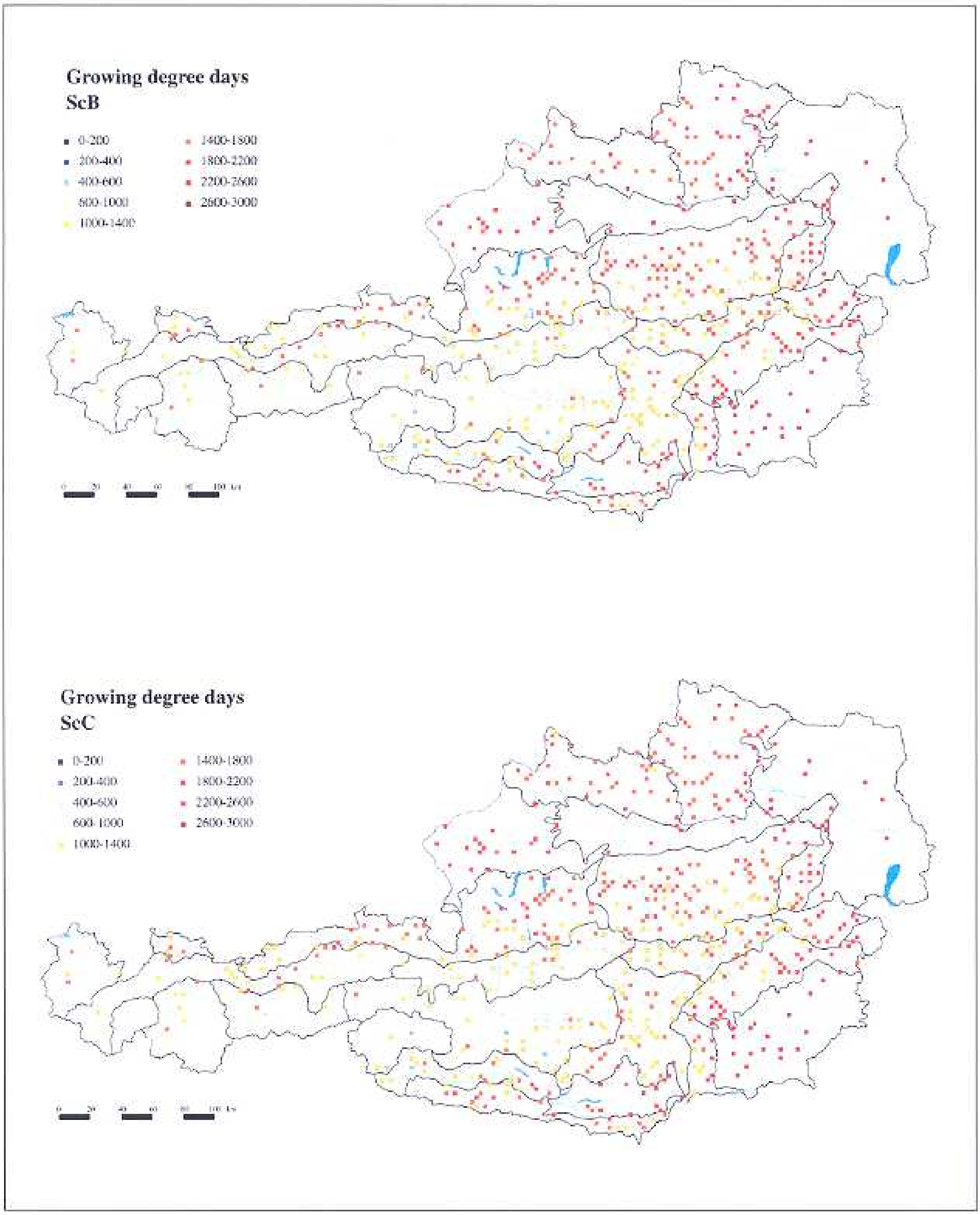


Figure 5-5b. Average heat sum above 5.5 °C (Growing Degree Days) at investigated sample points of the Austrian Forest Inventory under climate change scenario scB (strong warming) [above] and climate change scenario scC (strong warming, additional decrease in summer precipitation) [below].

Abb. 5-5b. Durchschnittliche Temperatursumme >5.5 °C (Growing Degree Days) auf Erhebungspunkten der Österreichischen Waldinventur unter Klimaänderungsszenario scB [oben] und Klimaänderungsszenario scC [unten].

The computation of the soil moisture index (SMI) (compare section 3.2) integrates soil (water holding capacity), temperature and precipitation data. Thus, the small scale heterogeneity of this parameter was substantially larger compared to the growing degree days (GDD) which depended on temperature only. From the cluster of sample points with soil moisture indices indicating suboptimal water supply at the eastern edges of the Alps the effect of low water holding capacities at calcareous shallow soils can be seen. On the contrary, the low soil moisture values at sample points in the eastern parts of Austria ("Marchfeld") are primarily due to rather low precipitation sums of about 700 mm per year under current climate. Water holding capacities in this region are fairly high (compare Englisch et al. 1991) and not a limiting factor regarding water supply (Figure 5-6).

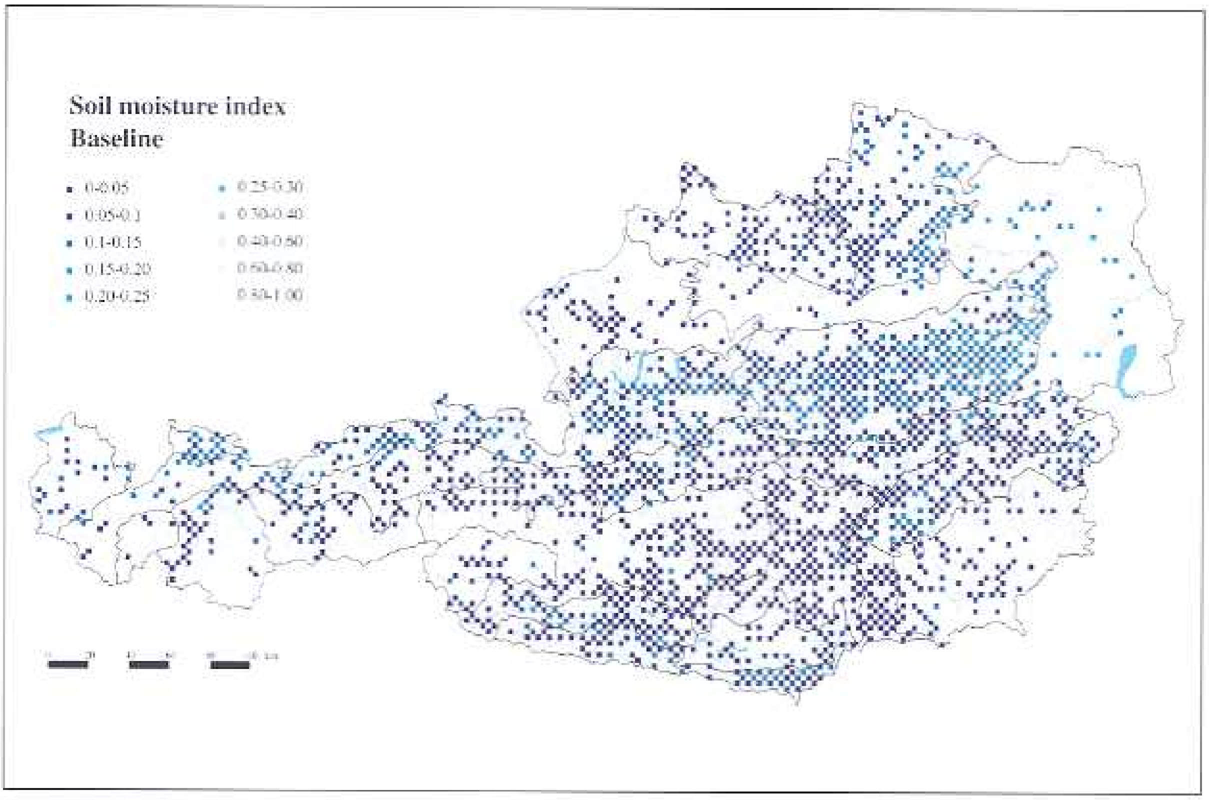


Figure 5-6: Average soil moisture index (SMI) at investigated sample points of the Austrian Forest Inventory as calculated within PICUS v1.2 under current climate (baseline scenario).- SMI = 0 indicates unlimited water supply, SMI > ca. 0.4 indicates severe drought stress.

Abb. 5-6: Von PICUS v1.2 simulierter durchschnittlicher Wasserversorgungsindikator SMI auf Erhebungspunkten der Österreichischen Waldinventur unter aktuellem Klima (baseline scenario).- SMI = 0 charakterisiert nicht limitierte Wasserversorgung, SMI > ca. 0.4 starker Trockenstress.

Finally Figure 5-7a-b shows the sequence of potential bark beetle life cycles for Ips typographus, a major disturbance agent in secondary Norway spruce forests under contrasting environmental conditions. The underlying model computations included several heat sum indicators specific for different life stages of the insect (e.g., Coeln et al. 1996, Coeln 1997, Schopf 1989), a set of threshold temperatures and snow cover duration in spring. It can be seen that the potential problem areas for Picea abies where the beetle is potentially able to frequently complete a second life cycle per season increased substantially under conditions of climatic change.

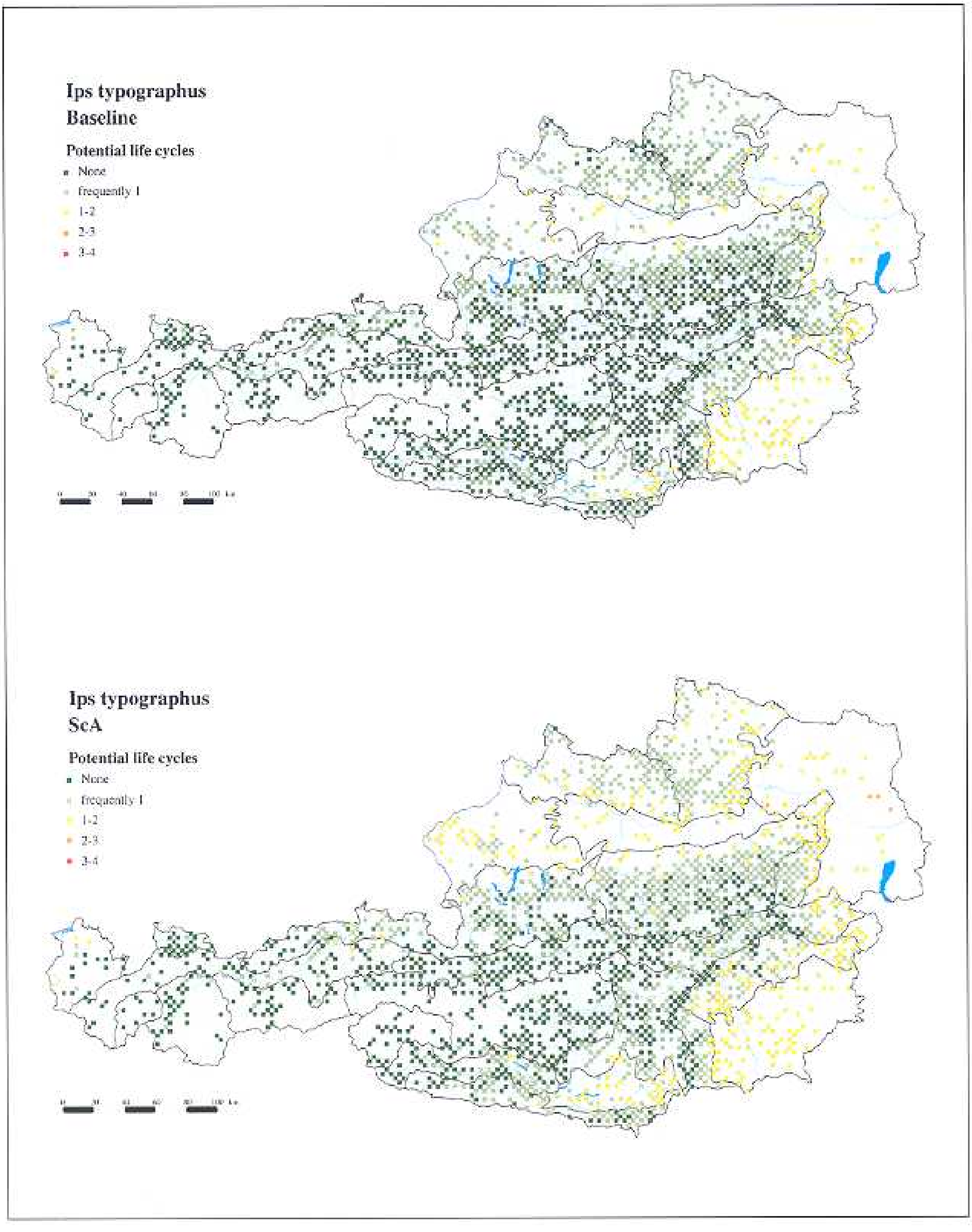


Figure 5-7a. Simulated average potential completed life cycles of Ips typographus at investigated sample points of the Austrian Forest Inventory under the baseline scenario (current climate) [above; n = 2759] and the climate change scenario scA (moderate warming) [below; n = 2778].

Abb. 5-7a: Simulierte durchschnittliche potentielle Generationszahl von Ips typographus auf Erhebungspunkten der Österreichischen Waldinventur unter aktuellem Klima [oben] und dem Klimaänderungsszenario scA [unten].

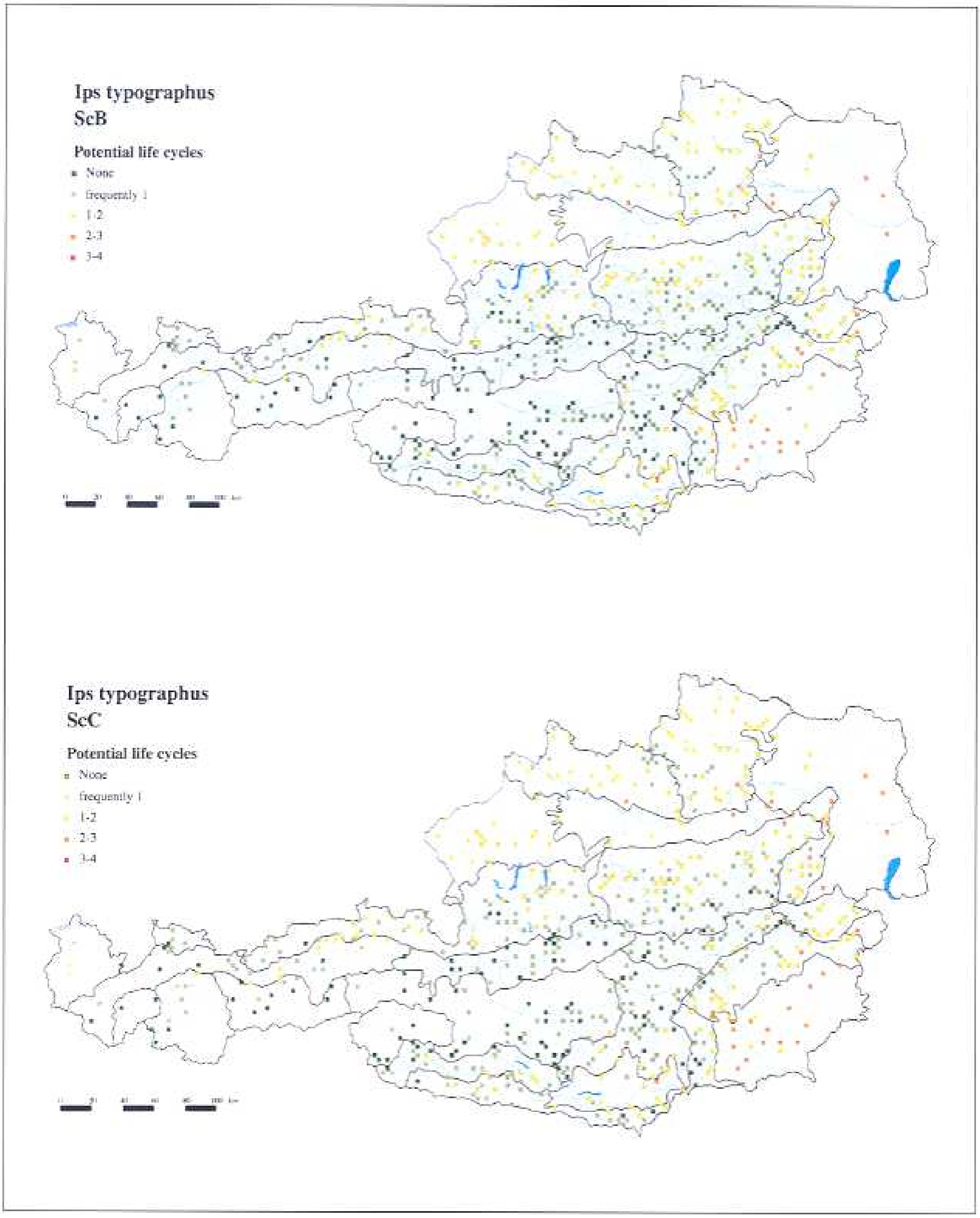


Figure 5-7b. Simulated average potential completed life cycles of Ips typographus at investigated sample points of the Austrian Forest Inventory under the climate change scenarios scB (strong warming) [above; n = 699] and scC (strong warming, additional decrease in summer precipitation) [below; n = 701].

Abb. 5-7b: Simulierte durchschnittliche potentielle Generationszahl von Ips typographus auf Erhebungspunkten der Österreichischen Waldinventur unter Klimaänderungsszenario scB [oben] und dem Klimaänderungsszenario scC [unten].

5.4 The sensitivity of current forests to scenarios of climatic change

The results presented in section 5.2 were confined to changes in categories of potential natural vegetation (PNV). Though this approach is well suited to demonstrate the effects of climatic change in the abstract space of PNV-formations, it misses the explicit consideration of current forest vegetation. In the following sections we will address the potential short- to midterm sensitivity of existing forests during the transient phase of a climate change as well as the potential long-term impact of climatic change on current forests.

5.4.1 Short- to midterm response to transient climatic change scenarios

5.4.1.1 Short- to midterm sensitivity to climatic change: Tree mortality

As outlined in section 2 this study aims at identifying forest areas and ecological conditions that might be affected by climatic change. Thus, the analysed disturbance factor was not climate per se, but changes in climatic conditions. Therefore all assessment criteria defined within this study strictly represented the impact of applied climate change scenarios on forest vegetation utilising the baseline simulation under current climate as a benchmark scenario (compare Figure 3-2 in section 3.1). All assessment criteria used to estimate the potential short- to midterm sensitivity of existing forests (SMS) as well as the potential long-term impacts of climatic change on existing forests (LI) and the overall index of forest sensitivity to climatic change (CCI) represent a measure of the potential adverse effects induced by climate change. For instance, an index value for CCI indicating low impact under a climate change scenario does not mean, that current forest vegetation at this site is optimally adapted to the new environmental conditions. Rather the current vegetation might be poorly adapted even under today’s climatic conditions (baseline scenario) which might even result in periodical tree mortality, but does not show additional adverse effects due to the changing climate.

For this reason tree mortality in the simulated forests at the inventory plots is presented as a measure characterising how good existing forests are adapted to their specific site conditions under "no management" – conditions. Model output for the simulation years 2000 to 2050 under the baseline scenario (current climate) as well as under three climate change scenarios (scA, scB, scC) was used to identify inventory plots where the simulations indicated substantial tree mortality (Figure 5-8a-b).

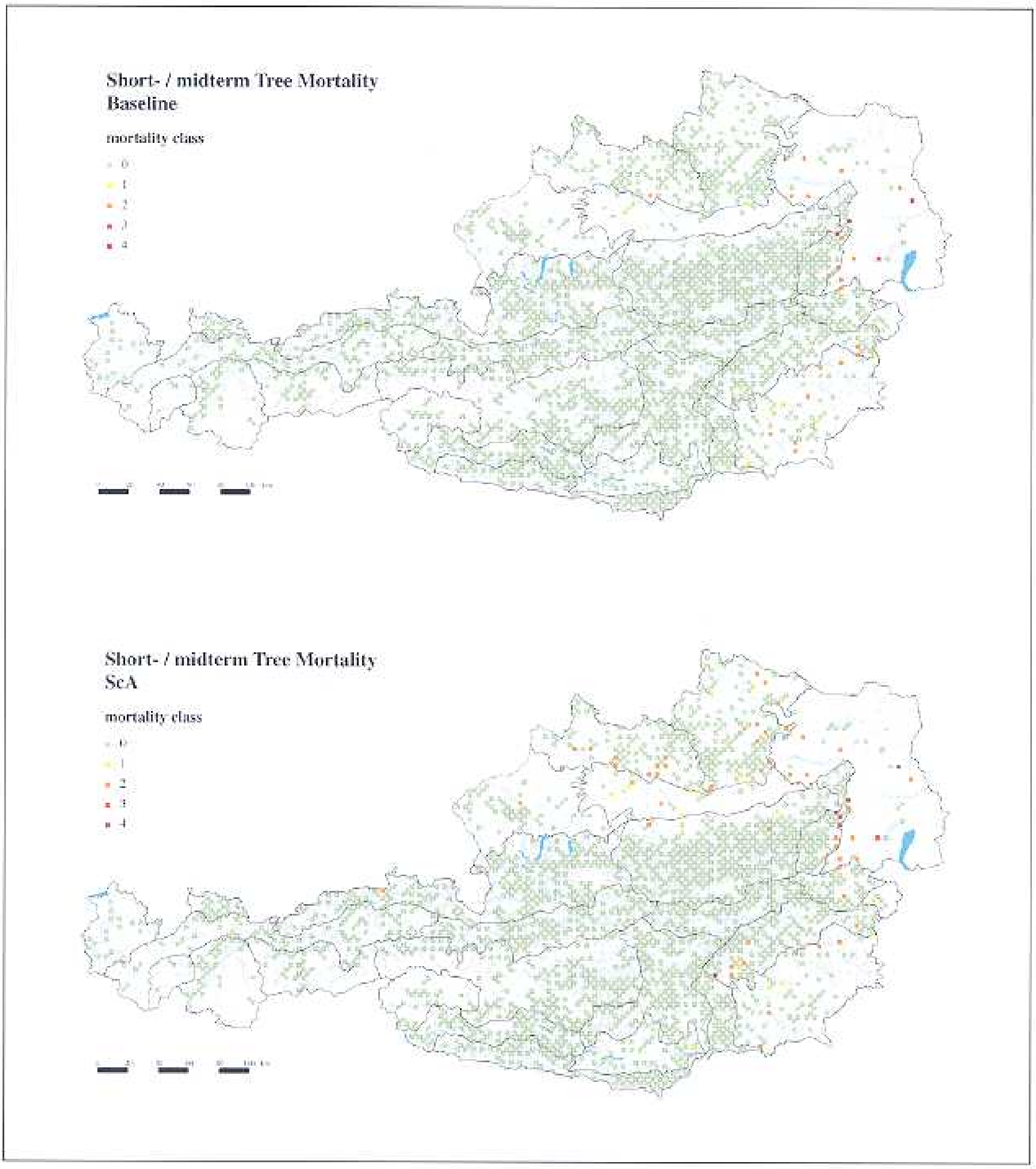


Figure 5-8a. *Sample points of the Austrian Forest Inventory with substantial simulated tree mortality during the period 2000 to 2050 under current climate (baseline scenario) [above; n = 2759] and climate change scenario scA (moderate warming) [below; n = 2778]. – Mortality class 0 = no net biomass loss within a decade; mortality class 1 = <10% biomass loss; mortality class 2 = 10-20% biomass loss; mortality class 3 = 20-50% biomass loss; mortality class 4 = 50-100% biomass loss within a decade.*

Abb. 5-8a: *Erhebungspunkte der Österreichischen Waldinventur auf denen erhebliche simulierte Baummortalität in der Periode 2000-2050 auftrat. Oben: aktuelles Klima (baseline scenario). Unten: Klimaänderungsszenario scA.- Mortalitätsklasse 0 = kein Nettobiomassenverlust innerhalb einer Dekade, Klasse 1 = <10% Nettobiomassenverlust, Klasse 2 = 10-20% Nettobiomassenverlust, Klasse 3 = 20-50% Nettobiomassenverlust, Klasse 4 = 50-100% Nettobiomassenverlust innerhalb einer Dekade.*

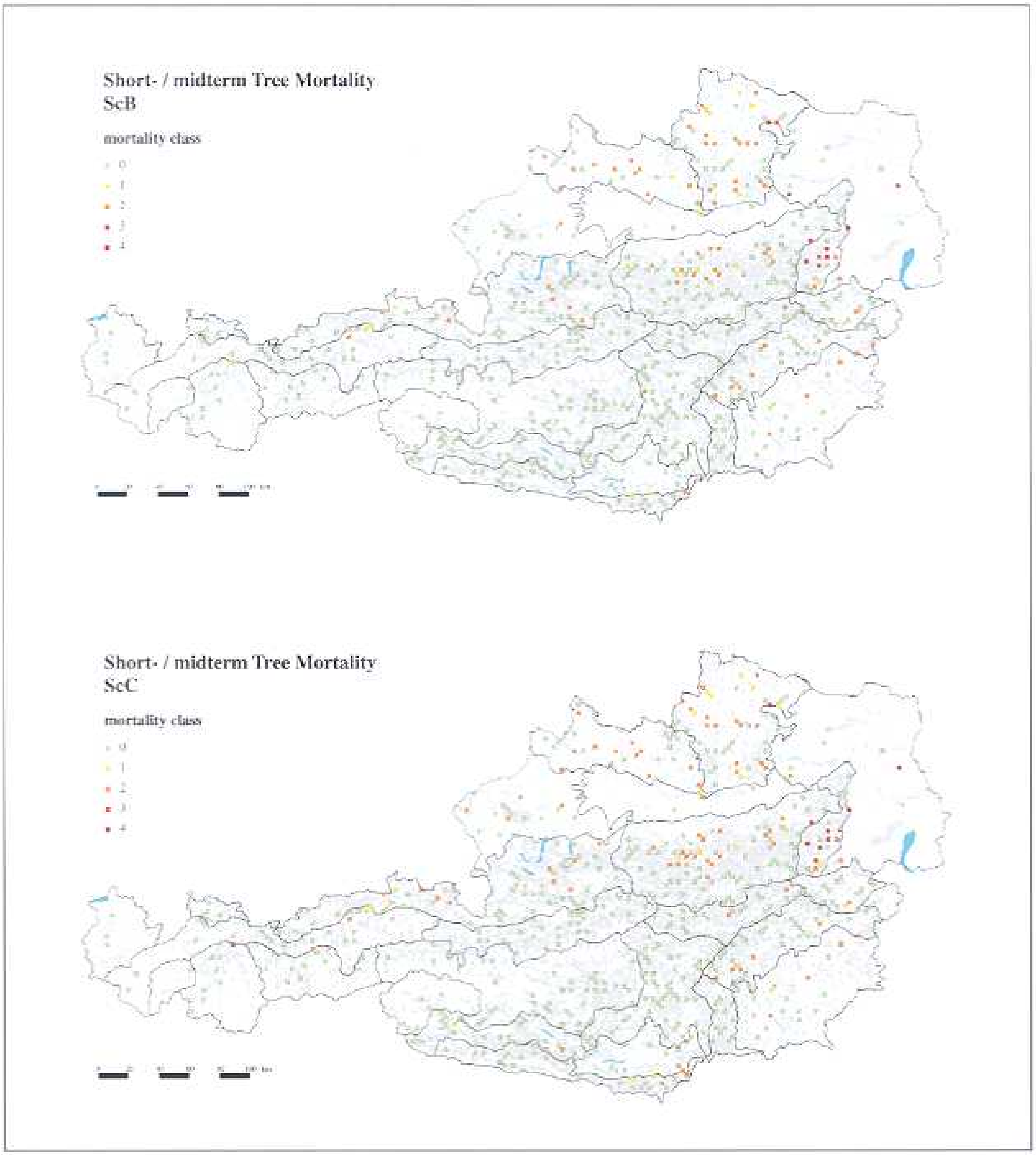


Figure 5-8b. Sample points of the Austrian Forest Inventory with substantial simulated tree mortality during the period 2000 to 2050 under climate change scenario scB (strong warming) [above; n = 699] and climate change scenario scC (strong warming, additional decrease in summer precipitation) [below; n = 701]. – Mortality class 0 = no net biomass loss within a decade; mortality class 1 = <10% biomass loss; mortality class 2 = 10-20% biomass loss; mortality class 3 = 20-50% biomass loss; mortality class 4 = 50-100% biomass loss within a decade.

Abb. 5-8b: Erhebungspunkte der Österreichischen Waldinventur auf denen erhebliche simulierte Baummortalität in der Periode 2000-2050 auftrat. Oben: Klimaänderungsszenario scB. Unten: Klimaänderungsszenario scC.- Mortalitätsklasse 0 = kein Nettobiomassenverlust innerhalb einer Dekade, Klasse 1 = <10% Nettobiomassenverlust, Klasse 2 = 10-20% Nettobiomassenverlust, Klasse 3 = 20-50% Nettobiomassenverlust, Klasse 4 = 50-100% Nettobiomassenverlust innerhalb einer Dekade.

According to Table 5-7 the percentage of inventory points where during at least one decade in the period from 2000 to 2050 a net biomass loss occurred (mortality classes 1 to 4) increased from 1.8% under current climate (baseline scenario) to about 17% under scenario scC (strong warming, additional decrease in summer precipitation). The majority of these plots was assigned to mortality class 2 indicating periodic losses of up to 20% of standing aboveground biomass. Inspection of these plots revealed that in essentially all cases tree mortality occurred in stands with Picea abies either due to direct effects of drought or due to simulated bark beetle infestations (compare Lexer and Hönninger 1998a). In general the rule holds, that the higher the proportion of Picea abies, the higher simulated tree mortality. An overlay of Figure 5-8a-b with the distribution of the soil moisture indices (compare Figure 5-6), temperature regimes (compare Figure 5-5a-b) and potential annual bark beetle life cycles (Figure 5-7a-b) uncovered the close correlation of Norway spruce mortality with these bioclimatic site indices.

Table 5-7. Percentage of investigated Austrian Forest Inventory points with substantial decenial tree mortality in the period 2000-2050 under current climate (baseline scenario) and three climate scenarios (scA, scB, scC). – Mortality class 0 = no net biomass loss within a decade, mortality class 1 = < 10% net biomass loss, mortality class 2 = 10-20% net biomass loss, mortality class 3 = 20-50% net biomass loss, mortality class 4 = 50-100% net biomass loss within a decade.

Tab. 5-7: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur mit erheblicher simulierter Baummortalität in der Periode 2000-2050 unter aktuellem Klima (baseline scenario) und drei Klimaänderungsszenarien (scA, scB, scC).- Mortalitätsklasse 0 = kein Nettobiomassenverlust innerhalb einer Dekade, Klasse 1 = <10% Nettobiomassenverlust. Klasse 2 = 10-20% Nettobiomassenverlust, Klasse 3 = 20-50% Nettobiomassenverlust, Klasse 4 = 50-100% Nettobiomassenverlust innerhalb einer Dekade.

Climate scenario	**mortality class [%]**				
	0	**1**	**2**	**3**	**4**
baseline scenario	98.2	0.5	0.9	0.2	0.2
scA	96.1	0.9	2.3	0.3	0.4
scB	85.2	3.2	9.7	0.4	1.5
scC	82.9	3.5	11.9	0.3	1.4

It is important to keep these features in mind when interpreting the presented indicators of the potential impact of climate change. If tree mortality of similar intensity occurs under both, baseline scenario and climate change scenario, the resulting differences in vegetation composition will be low. Hence assessment criteria ac_{1-5} will yield values close to 1 (high similarity), the estimated adverse effect will be low (AC_{SMS1-5} close to 0) and subsequently the short- to midterm index of forest sensitivity to climate change SMS will yield a low impact class. However, if mortality under the climate change scenario exceeded mortality under baseline conditions substantially, large differences in simulated successional dynamics between the two scenarios occurred corresponding to unfavourable index values for SMS.

5.4.1.2 Short to midterm sensitivity to scenarios of climatic change: Total represented forest

The indicator for the short- to midterm sensitivity of existing forests SMS characterised adverse climate change impacts during the transient phase of the applied climate change scenarios from year 2000 to 2050. Originally SMS was expressed continuously on the [0-1] interval, with values of 1 indicating a severe impact. This continuum was split into 5 impact categories of equal width where category 5 represents severe impact of climate change. Figure 5-9 shows the distribution of impact categories (SMS) for the total represented forest area.

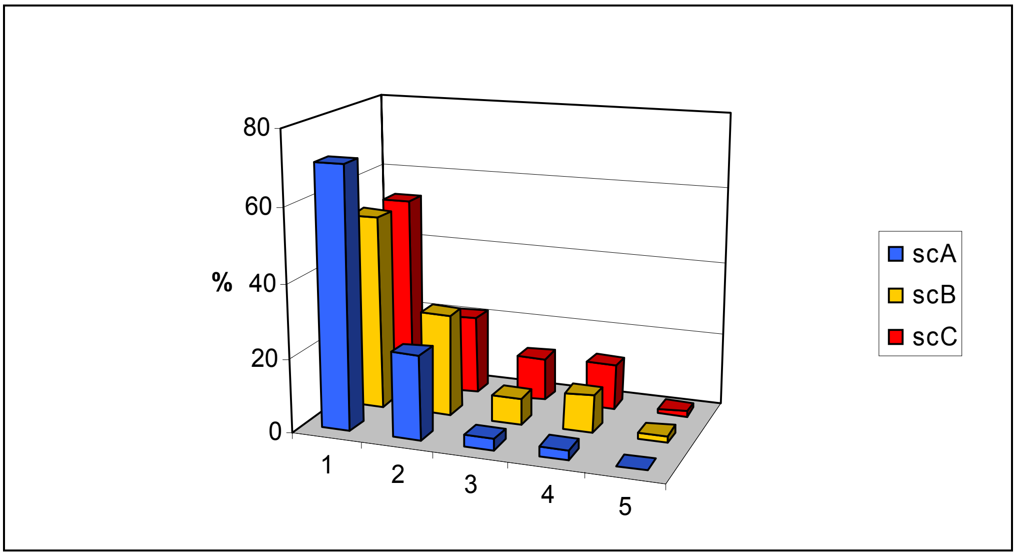


Figure 5-9. Percentage of investigated Austrian Forest Inventory sample points within the impact categories 1 - 5 of the short- to midterm sensitivity index SMS under three climate change scenarios (scA, scB, scC). – Category 5 represents severe climate change impacts.

Abb. 5-9: Anteil untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Kurz-/Mittelfristindikators SMS unter drei Klimaänderungsszenarien (scA, scB, scC).- Kategorie 5 repräsentiert starke Auswirkungen einer Klimaänderung.

The low impact classes 1 and 2 comprised between 93.8% (under scenario scA) and 74.4% (under scenario scC) with the major proportion always assigned to class 1 (compare Table 5-8). The proportion of inventory points assigned to the intermediate category 3 increased from 3.1% under scenario scA (moderate warming) to 11.9% under scenario scC (strong warming, additional decrease in summer precipitation). The categories 4 and 5 indicating substantial to severe impacts comprised between 2.7% under the moderate warming scenario scA and 13.5% under scenario scC with temperature increases of 2 °C and summer precipitation reduced by 15%. Kruskall-Wallis and Wilcoxon-Mann-Whitney tests (SAS 1990) on differences in impact categories among the climate change scenarios revealed, that SMS was significantly higher under scB and under scC respectively when compared to scA, but differed not significantly between scenarios scB and scC ($\alpha = 0.05$).

For the climate change scenario scA (moderate warming) Figure 5-10 shows that the impact categories of the short- to midterm index SMS are definitely not homogeneously distributed in geographical space.

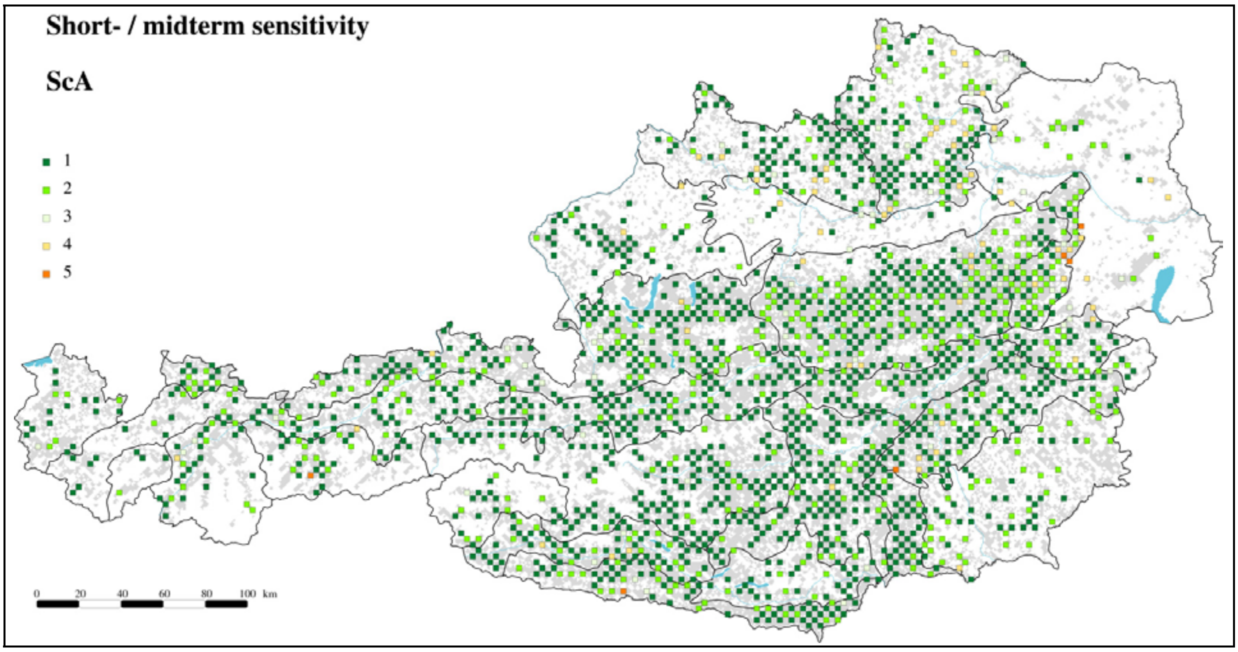


Figure 5-10. Distribution of impact categories of the short- to midterm index of forest sensitivity to climate change (SMS) at selected sample points of the Austrian Forest Inventory under the climate change scenario scA (moderate warming). Impact category 1 = very low impact, impact category 5 = severe impact.

Abb. 5-10: Räumliche Verteilung der Kategorien des Kurz-/Mittelfristindikators SMS anhand untersuchter Erhebungspunkte der Österreichischen Waldinventur unter dem Klimaänderungsszenario scA.- Kategorie 5 repräsentiert starke Auswirkungen einer Klimaänderung.

Table 5-8. Percentage of investigated Austrian Forest Inventory points within impact categories of the short- to midterm index for forest sensitivity to climate change (SMS) under three climate change scenarios (scA, scB, scC).

Tab. 5-8: Anteil untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Kurz-/Mittelfristindikators SMS unter drei Klimaänderungsszenarien (scA, scB, scC).

Impact category	**scA [%]**	**scB [%]**	**scC [%]**
1 (very low impact)	70.9	53.0	52.9
2 (low impact)	22.9	27.8	21.5
3 (moderate impact)	3.1	7.1	11.9
4 (substantial impact)	2.7	10.2	12.2
5 (severe impact)	0.4	1.9	1.5
Total	**100.0**	**100.0**	**100.0**

5.4.1.3 Short- to midterm sensitivity to scenarios of climatic change: Altitudinal zones

Whenever we refer to altitudinal zones we use the definitions given by Kilian et al. (1994) which are based on elevation above sea level and thus always refer to current climate. A detailed description of altitudinal zonation is enclosed in the annex. Figure 5-11 shows that the highest impacts of climate change during the transient phase were expected to occur in today's submontane (increases in SMS regardless of the scenario considered significant at $\alpha = 0.05$) and montane zone, the least severe impacts at high elevation sites in the subalpine and upper montane zone. This can be partly explained by increased tree mortality under conditions of warming in Picea abies stands at low elevations. A second reason is, that at lower elevations more species are eligible in the regeneration process which results in higher potential species diversity and thus larger differences between simulation runs under different scenarios.

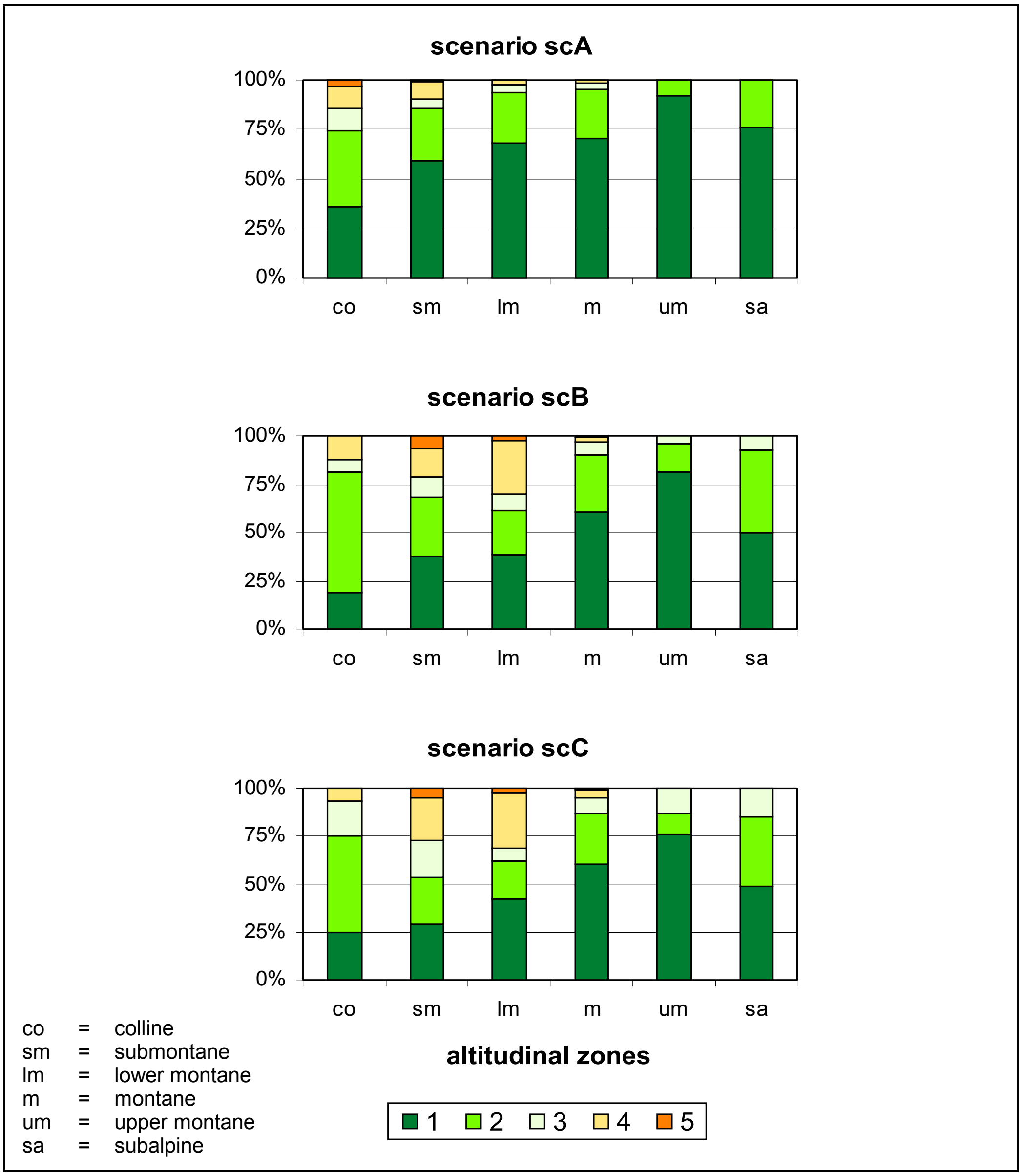


Figure 5-11. Percentage of investigated Austrian Forest Inventory points within impact categories of short- to midterm forest sensitivity to scenarios of climatic change (SMS) in altitudinal zones under three climate change scenarios (scA: n = 2778, scB: n = 699, scC: n = 701). – Impact category 5 represents severe potential climate change impact.

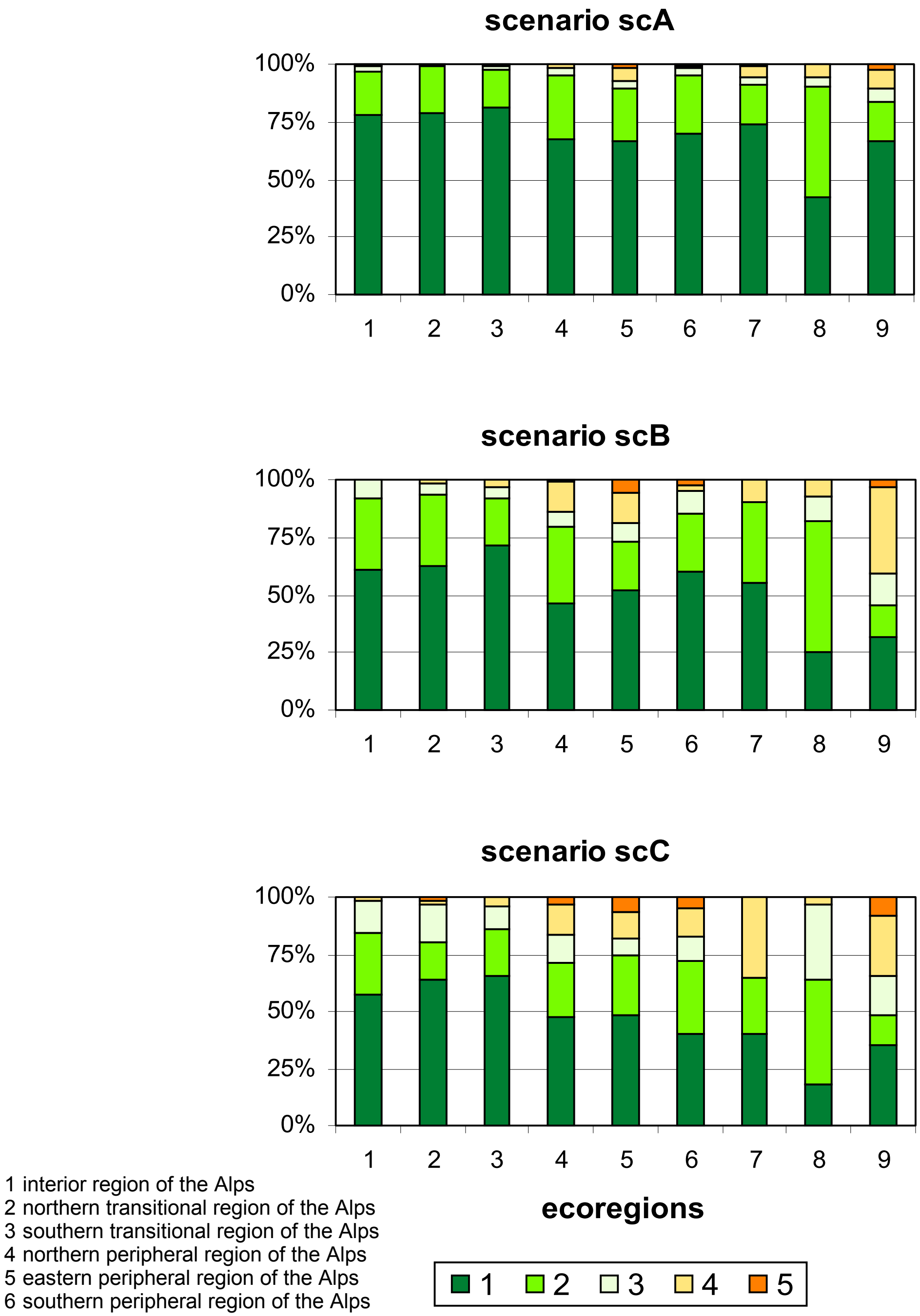
Abb. 5-11: Anteil untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Kurz-/Mittelfristindikators SMS unter drei Klimaänderungsszenarien (scA, scB, scC) gegliedert nach Höhenstufen.- Kategorie 5 repräsentiert starke Auswirkungen einer Klimaänderung.

It is interesting to note, that under the conditions of scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) no significant increase in the proportion of high impact categories occurred in today's colline zone (Wilcoxon-Mann-Whitney test, α = 0.05). This pattern origins from the fact that at colline sites trees susceptible to warm and dry conditions already died under the moderate warming scenario scA or even under baseline conditions. Small apparently inconsistent differences in the share of impact categories might occur between scenarios due to the reduced number of involved inventory points for scenarios scB (n = 699) and scC (n = 701) (compare section 4.2). Finally, under the marked warming of scenarios scB and scC high elevation sites showed a stronger response, too. As temperatures increased, more species gained competitiveness at altitudes where under current climate Picea abies was the only dominating tree species. However, under scB and scC the short- to midterm index of forest sensitivity SMS did not increase significantly (α = 0.05) in today's upper montane as well as in the subalpine zone compared to the moderate warming scenario scA.

5.4.1.4 Short- to midterm sensitivity to scenarios of climatic change: Ecoregions

In addition to the vertical strata defined by altitudinal zones the distribution of impact categories of the short- to midterm index of forest sensitivity to climate change SMS is also shown for the major ecoregions according to Kilian et al. (1994). A map of Austria's main ecoregions according to Kilian et al. (1994) is enclosed in the annex. Under scenario scA (moderate warming) the share of high impact categories 4 and 5 was confined to values between 0% and 10.1% with largest proportions occurring in ecoregion 9 (Bohemian Massif), ecoregion 8 (eastern lowlands), ecoregion 7 (northern piedmont of the Alps) and ecoregion 5 (eastern peripheral region of the Alps) (Figure 5-12). Essentially the same pattern occurred for scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation), with the extension to ecoregion 6 (southern peripheral region of the Alps) in the very south of Austria. Under these scenarios the share of the low impact category 1 was substantially reduced, whereas categories 3 an 4 increased. The share of impact category 5 increased slightly but remained at similar levels for scenarios scB and scC. Kruskall-Wallis and Wilcoxon-Mann-Whitney tests (SAS 1990) indicated no significant differences (α = 0.05) in SMS impact categories among scenarios scB and scC with the exception of ecoregion 6 (mainly due to inventory points situated in the Klagenfurt basin within the southern peripheral region of the Alps). Regardless of the climate change scenario considered, no significant differences occurred in ecoregions 2 (northern transitional region of the Alps), 3 (eastern and southern transitional region of the Alps) and 8 (eastern lowlands).

In general the results for the ecoregions correspond well with expectations. Ecoregions 6, 7, 8 and 9 are characterised by a substantial proportion of plantation-like forests mainly dominated by Picea abies ("secondary conifer forests"). Mainly due to frequently occurring drought periods these forests are susceptible to an array of insect and disease organisms even under current climatic conditions (e.g., Geburek et al. 1994). Under scenarios of warming these forests contribute the main share of inventory plots assigned to impact categories 3, 4 and 5. The relatively high proportion of categories 4 and 5 in ecoregion 5 in the eastern peripheral region of the Alps is an interesting feature which deserves some explanation. According to the data of the Austrian Forest Soil Survey (Englisch et al. 1991) rendzinas comprise a major proportion of the soil types in this ecoregion. The estimated water holding capacities (WHC) for these sites are rather low. Together with relatively low annual precipitation (appr. 700 – 1000 mm per year under current climatic conditions) this results in soil moisture regimes which in dry years are rather unfavourable for Picea abies (compare Schadauer 1999). When temperatures increase bark beetles are able to develop two or even more complete life cycles per year, thus increasing the risk of tree mortality in Picea abies stands (Schopf 1989).



1 interior region of the Alps
2 northern transitional region of the Alps
3 southern transitional region of the Alps
4 northern peripheral region of the Alps
5 eastern peripheral region of the Alps
6 southern peripheral region of the Alps
7 northern piedmont of the Alps
8 eastern lowlands
9 Bohemian Massif

Figure 5-12. Percentage of investigated sample points of the Austrian Forest Inventory within impact categories of the short- to midterm index of forest sensitivity to climate change (SMS) in the main ecoregions of Austria (Kilian et al., 1994) under three climate change scenarios (scA: n = 2778, scB: n = 699, scC: n = 701). – Impact category 5 = severe climate change impact.

Abb. 5-12: Anteil untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Kurz-/Mittelfristindikators SMS unter drei Klimaänderungsszenarien (scA, scB, scC) gegliedert nach Hauptwuchsgebieten.- Kategorie 5 repräsentiert starke Auswirkungen einer Klimaänderung.

5.4.2 The potential long-term impact of climatic change on current forests

The index LI for potential long-term impacts of climate change on current forests was based on two assessment criteria (compare section 3.1.3):

a) AC_{LI1} is the evaluated similarity of the simulated equilibrium species composition (i.e., PNV) under current climatic conditions (baseline scenario) to the PNV under a climate change scenario. Thus, AC_{LI1} can be seen as an indicator for changes in the ecological site potential. The more similar the two simulated species compositions, the smaller the impact of the climate change scenario.

b) AC_{LI2} is based on the difference between (i) the similarity of the current forest species composition at a particular inventory plot to the simulated equilibrium species composition at this site under current climate (baseline scenario), and (ii) the similarity of the current forest species composition to the simulated equilibrium species composition under a climate change scenario. If the difference between the two similarity measures is small, the divergence of the current forest composition at a site to the simulated potential natural species composition did not increase substantially under a climate change scenario.

5.4.2.1 Similarity of current forests to simulated potential natural vegetation (PNV) under current climate

To provide the benchmark in calculating the impact measure AC_{LI2} the species composition of the forests observed by the Austrian Forest Inventory was compared with the simulated potential natural vegetation (PNV) under current climate (baseline scenario) at each involved inventory point. Figure 5-13 shows the similarity of current forests to simulated PNV under the baseline scenario (current climate). Under baseline conditions the similarity of current forest composition to simulated PNV essentially characterises some type of "naturalness" of current forest tree species composition (compare Grabherr et al. 1998). From Figure 5-13 it can be seen that the lowest values for similarity of current forests to simulated PNV under today’s climate (baseline scenario) concentrate in the submontane and montane vegetation zones. In this regions Norway spruce (Picea abies) has been heavily promoted since the nineteenth century at sites supporting either mixed conifer-broadleaf or broadleaf-dominated forests as potential natural vegetation (Kilian et al. 1994). Table 5-9 summarises the findings presented in Figure 5-13. In presenting individual assessment criteria we use six categories allowing for smaller class width between values of 0.8 - 1.0. This was meant to better indicate early responses to an altered climate.

Table 5-9. Similarity of current forest tree species composition at investigated sample points of the Austrian Forest Inventory to simulated PNV under current climate (baseline scenario).– n = 2589 AFI sample points with trees > 5 cm dbh. Class 1 = quasi identical species composition, class 6 = very low similarity.

Tab. 5-9: Ähnlichkeit der aktuellen Baumartenzusammensetzung auf untersuchten Erhebungspunkten der Österreichischen Waldinventur mit simulierter PNV unter aktuellem Klima (baseline scenario).- n = 2589 Punkte mit Bäumen > 5 cm BHD. Klasse 1 = quasi idente Artenzusammensetzung, Klasse 6 = sehr geringe Ähnlichkeit.

Similarity class	class width	sample points [%]
1	1.0-0.9	12.78
2	0.9-0.8	9.82
3	0.8-0.6	21.82
4	0.6-0.4	19.89
5	0.4-0.2	16.80
6	0.2-0.0	18.89
Total	**-**	**100.00**

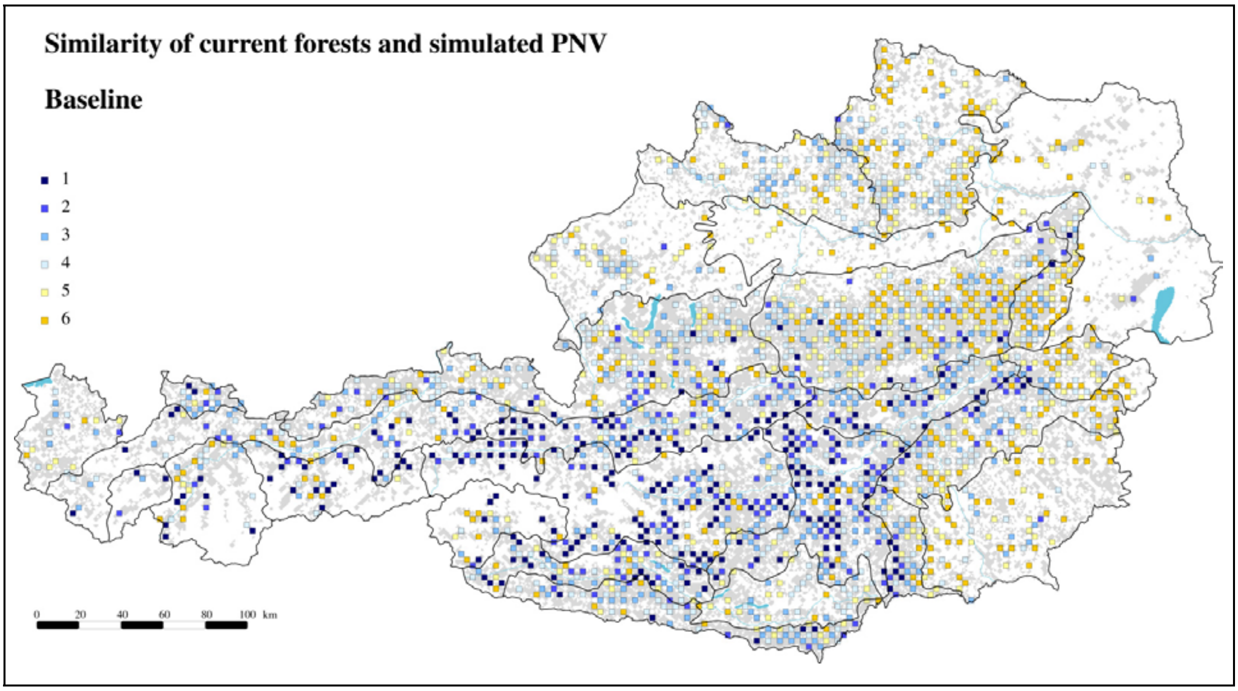


Figure 5-13. Similarity of current forests at investigated sample points of the Austrian Forest Inventory to simulated potential natural vegetation (PNV) under current climatic conditions (baseline scenario). – n = 2589 sample points with trees > 5 cm dbh. Class 1 = percentage similarity PS > 0.9 (quasi identical species composition), class 2 = 0.8<PS<0.9, class 3 = 0.6<PS<0.8, class 4 = 0.4<PS<0.6, class 5 = 0.2<PS<0.4, class 6 = PS<0.2 (very low similarity).

Abb.. 5-13: Ähnlichkeit der aktuellen Baumartenzusammensetzung auf untersuchten Erhebungspunkten der Österreichischen Waldinventur mit simulierter PNV unter aktuellem Klima (baseline scenario).- n = 2589 Punkte mit Bäumen > 5 cm BHD. Klasse 1 = quasi idente Artenzusammensetzung, Klasse 6 = sehr geringe Ähnlichkeit.

It is worth mentioning that the distribution of similarity classes in general corresponds well with the findings of a recent study on the hemeroby of Austrian forests (Grabherr et al. 1998). Figures 5-14 and 5-15 show the general pattern in more detail stratified for altitudinal zones and ecoregions respectively.

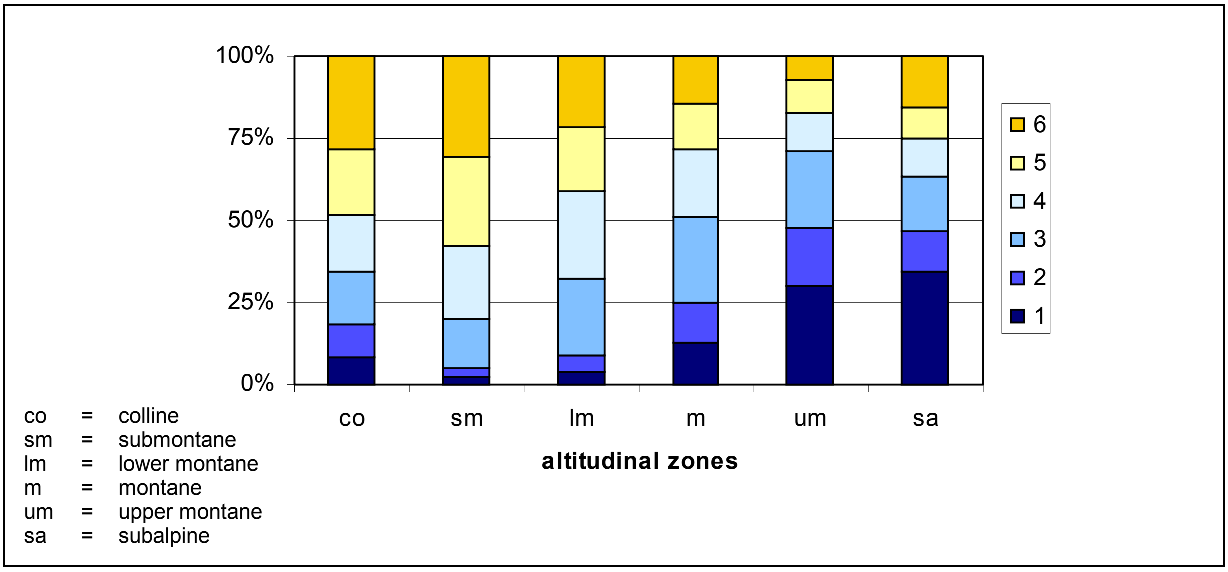


Figure 5-14. *Percentage of investigated sample points of the Austrian Forest Inventory within classes of similarity of current forest species composition to simulated potential natural vegetation (PNV) under current climatic conditions (baseline scenario) in altitudinal zones. – Class 1 = quasi identical species composition, class 6 = similarity close to zero.*

Abb. 5-14: *Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in Kategorien der Ähnlichkeit zwischen aktueller Baumartenzusammensetzung und simulierter PNV unter aktuellem Klima (baseline scenario) gegliedert nach Höhenstufen.- Klasse 1 = quasi idente Artenzusammensetzung, Klasse 6 = sehr geringe Ähnlichkeit.*

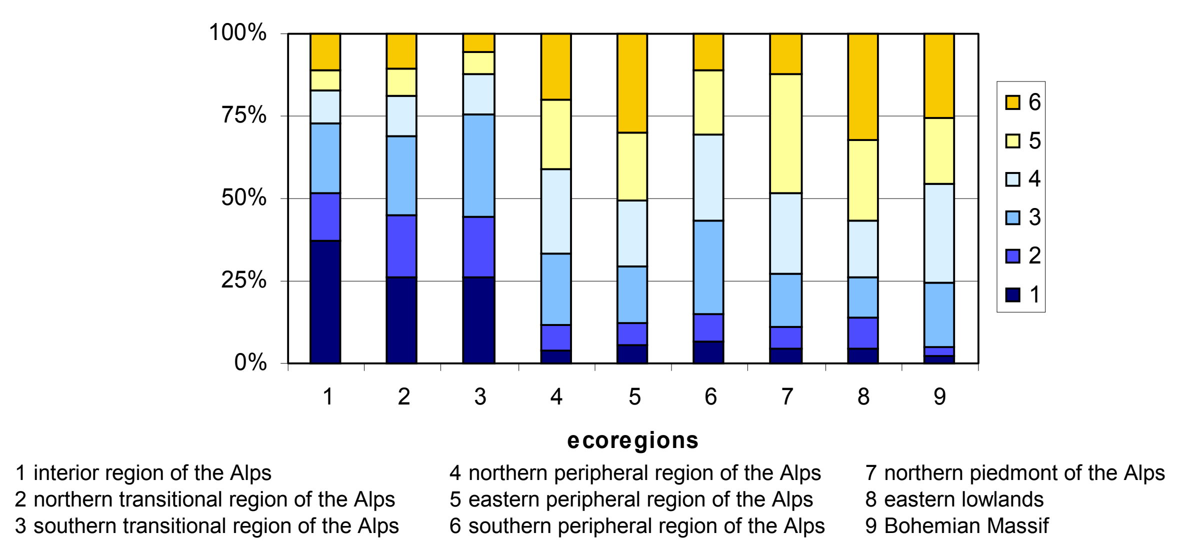


Figure 5-15. *Percentage of investigated sample points of the Austrian Forest Inventory within classes of similarity of current forest species composition to simulated potential natural vegetation (PNV) under current climatic conditions (baseline scenario) in the main ecoregions. – Class 1 = quasi identical species composition, class 6 = similarity close to zero.*

Abb. 5-15: *Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in Kategorien der Ähnlichkeit zwischen aktueller Baumartenzusammensetzung und simulierter PNV unter aktuellem Klima (baseline scenario) gegliedert nach Hauptwuchsgebieten.- Klasse 1 = quasi idente Artenzusammensetzung, Klasse 6 = sehr geringe Ähnlichkeit.*

It is important to note that the similarity measures of forest composition as recorded by the AFI and simulated PNV did only include tree species composition. No other ecosystem attributes were considered. Please note, that (a) the calculations were performed for species groups (compare Table 3-1), and (b) the similarity measure presented in Figures 5-13, 5-14 and 5-15 did not include a valuation with regard to the expected adverse effects of the divergence of observed forest composition to simulated PNV (compare section 3.1.2).

5.4.2.2 Potential long-term impact of climatic change: Total represented forest

The indicator LI characterising the potential long-term impact of a changing climate on current forests is based on the assessment criteria ac_6 and ac_7 (compare section 3.1) which after evaluation for expected adverse effects (compare Figure 3-2) give AC_{LI1} and AC_{LI2}. In the following sections we first present the results for the original assessment criteria ac_6 and ac_7 to better exemplify the effects imposed by the three climate change scenarios scA (moderate warming), scB (strong warming) and scC (strong warming, additional decrease in summer precipitation).

5.4.2.2.1 Shifts in potential natural species composition (PNV)

Independently from the species composition of currently existing forests the assessment criterion ac_6 characterised the effect of climate change on the ecological site potential by means of the similarity of simulated PNV under current climate (baseline scenario) to simulated future PNV under three climate change scenarios (scenarios scA, scB, scC). Strictly speaking ac_6 represented a shift in ecological site potential entirely due to climatic factors without considering edaphic factors or dynamic feed backs between vegetation, climate and soil characteristics. For instance, in simulating the equilibrium species composition (i.e., PNV) under the climate change scenario scA (moderate warming) the same set of soil parameters (pH-value, C/N-ratio, water holding capacity) as for the simulation under current climate (baseline scenario) is used. The response of the simulated equilibrium species composition (PNV) to three scenarios of climatic change is shown in Figure 5-16.

The moderate warming scenario scA resulted in marked but not dramatic shifts in equilibrium species composition, particularly at high elevation sites with corresponding impact categories mainly confined to classes 1 to 3 (Figure 5-17). Under scenarios scB and scC the response was much stronger including lower altitudinal zones, too. The differences in AC_{L11} under scenarios scB and scC versus scA, and scB versus scC respectively were significant at α = 0.05 (Wilcoxon-Mann-Whitney test).

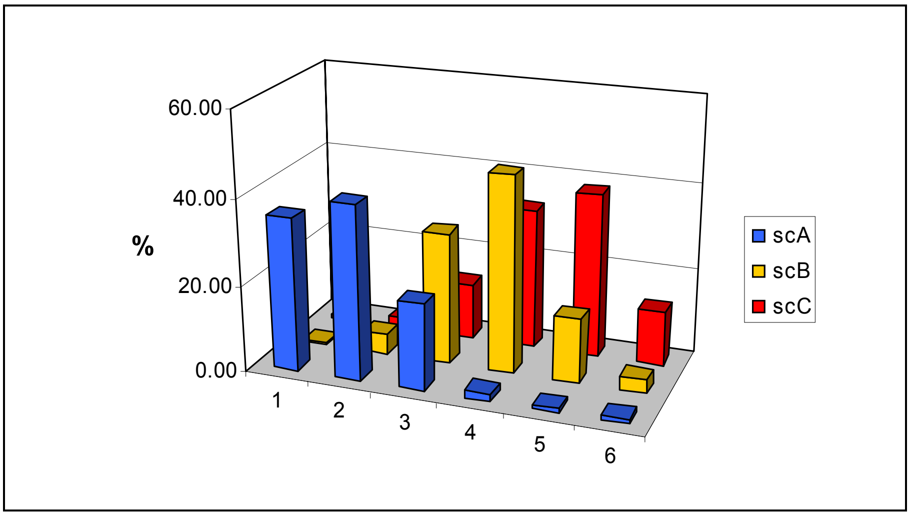


Figure 5-16. Percentage of investigated sample points of the Austrian Forest Inventory within classes of similarity of simulated equilibrium species composition (PNV) under current climate (baseline scenario) to PNV under three climate change scenarios (scA, scB, scC) (assessment criterion ac_6). Class 1 = quasi identical (PS >0.9), class 6 = very low similarity (PS <0.2).

Abb. 5-16: Anteil untersuchter Erhebungspunkte der Österreichischen Waldinventur in Klassen der Ähnlichkeit zwischen simulierter PNV unter aktuellem Klima (baseline scenario) und simulierter PNV unter drei Klimaänderungsszenarien (scA, scB, scC) (Analysekriterium ac_6). Klasse 1 = quasi ident (PS >0.9), Klasse 6 = sehr geringe Ähnlichkeit (PS <0.2).

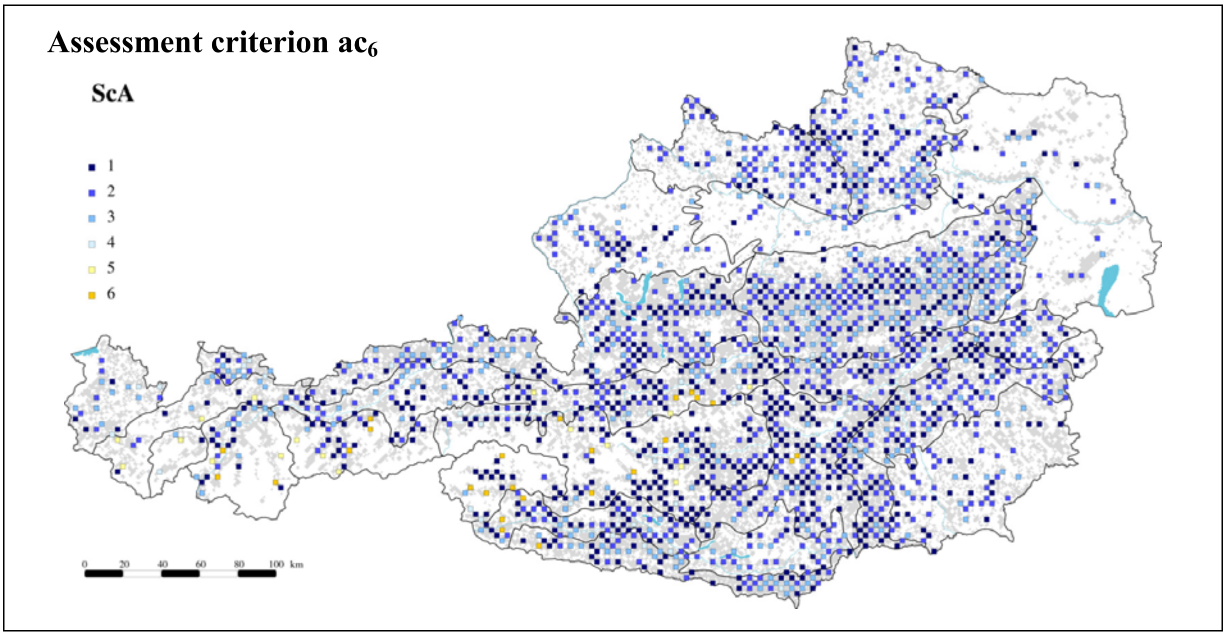


Figure 5-17. Effect of climate change scenario scA (moderate warming) on simulated equilibrium species composition (PNV) at investigated sample points of the Austrian Forest Inventory (assessment criterion ac_6 is derived from similarity of simulated PNV under current climate (baseline scenario) to the simulated PNV under the climate change scenario scA). Class 1= quasi identical (PS >0.9), class 6 = very low similarity (PS >0.2). n = 2759.

Abb. 5-17: Der Effekt von Klimaänderungsszenario scA (moderate Erwärmung) auf die simulierte Baumartenzusammensetzung der PNV für untersuchte Erhebungspunkte der Österreichischen Waldinventur (Ähnlichkeit zwischen simulierter PNV unter aktuellem Klima (baseline scenario) und simulierter PNV unter Klimaänderungsszenario scA). Klasse 1 = quasi identisch (PS >0.9), Klasse 6 = sehr geringe Ähnlichkeit (PS <0.2). n = 2759.

5.4.2.2.2 Effect of climatic change on the divergence of current forest composition to simulated PNV

With assessment criterion ac_7 we tested whether the divergence of current forest species composition at inventory points to simulated PNV increased under conditions of climatic change as defined in scenarios scA, scB and scC. From Figure 5-18 it follows that the effect of scenario scA (moderate warming) was mainly confined to categories 1 and 2 with only minor proportions of involved sample points in other categories. Under scenario scA 76.8% of the sample points had been assigned to category 1. Approximately 1.4% were distributed among classes 4 to 6 indicating substantial effect of the climate change scenario on criterion ac_7. Under the conditions of scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) a total of 26.7% and 41.9% respectively was assigned to the high impact categories 4, 5 and 6. The assessment criterion ac_7 differed significantly (Wilcoxon-Mann-Whitney test, $\alpha = 0.05$) among all simulated scenarios (scA, scB, scC).

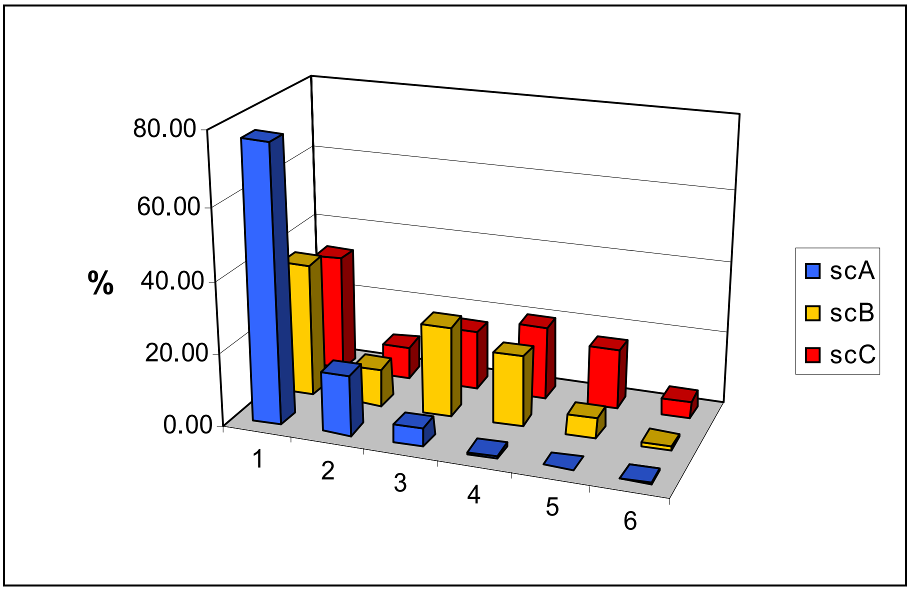


Figure 5-18. Percentage of investigated sample points of the Austrian Forest Inventory within classes of assessment criterion ac_7 (increase in divergence of current forest composition to simulated PNV under three climate change scenarios (scA, scB and scC)). Class 1 = quasi no effect (divergence <0.1), class 6 = severe effect (divergence >0.8).

Abb. 5-18: Anteil untersuchter Erhebungspunkte der Österreichischen Waldinventur in Klassen für das Analysekriterium ac_7 (Zunahme der Abweichung von aktueller Baumartenzusammensetzung zu simulierter PNV zwischen aktuellem Klima und den Klimaänderungsszenarios (scA, scB, scC). Klasse 1 = quasi kein Effekt (Abweichung <0.1), Klasse 6 = starker Effekt (Abweichung >0.8).

The spatial distribution of the criterion ac_7 under the climate change scenario scA (moderate warming) is shown in Figure 5-19.

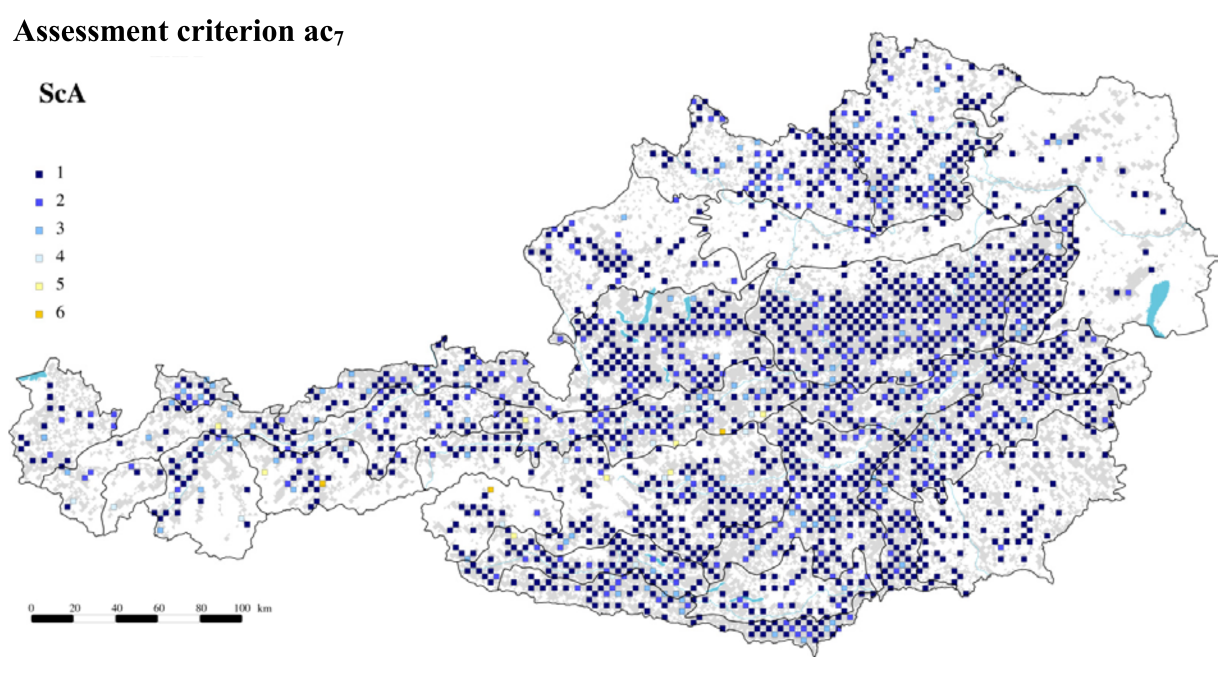


Figure 5-19. Spatial distribution of assessment criterion ac_7 (increase in divergence of current forest composition to simulated PNV under the climate change scenario scA) at investigated sample points of the Austrian Forest Inventory. Class 1 = quasi no effect(divergence <0.1), class 6 = severe effect (divergence >0.8). n = 2585.

Abb. 5-19: Räumliche Verteilung für Klassen des Analysekriteriums ac_7 (Zunahme der Abweichung von aktueller Baumartenzusammensetzung zu simulierter PNV zwischen aktuellem Klima und dem Klimaänderungsszenario scA) auf untersuchten Erhebungspunkten der Österreichischen Waldinventur. Klasse 1 = quasi kein Effekt (Abweichung <0.1), Klasse 6 = starker Effekt (Abweichung >0.8). n = 2585.

5.4.2.2.3 Indicator of the potential long-term impact of climatic change (LI)

After the assessment criteria ac_6 and ac_7 had been evaluated with regard to the expected adverse effects of a changing climate the resulting criteria AC_{LI1} and AC_{LI2} were combined to an index characterising the potential long-term impact of climatic change on current forests (compare section 3.1.3). For the whole represented forest area the distribution of this index over five impact categories under three climate change scenarios is shown in Figure 5-20. Under the conditions of scenario scA (moderate warming) approximately 92% of all involved sample points had been assigned to the low-impact categories 1 and 2. This percentage is drastically reduced to 37.9% and 30.3% respectively under the more severe climatic changes of scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation). According to the long-term index LI severe climate change impacts are expected for 1.2% (under scenario scA), 25.8% (under scenario scB) and 43.4% (under scenario scC) of all sample points (Table 5-10). The differences in LI among the scenarios scA, scB and scC were significant at α = 0.05 (Kruskall-Wallis and Wilcoxon-Mann-Whitney tests).

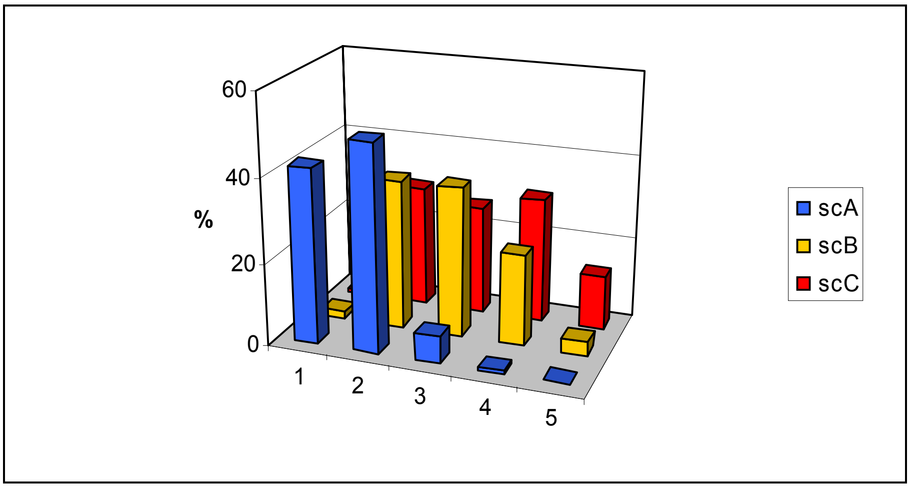


Figure 5-20. The potential long-term impact of scenarios of climatic change (scA, scB, scC) on current forests at investigated sample points of the Austrian Forest Inventory. Impact category 1 = very low impact, category 2 = low impact, category 3 = moderate impact, category 4 = substantial impact, category 5 = severe impact.

Abb. 5-20: Potentielle langfristige Auswirkung von drei Klimaänderungsszenarien (scA, scB, scC) auf aktuelle Wälder für untersuchte Erhebungspunkte der Österreichischen Waldinventur. Kategorie 1 = sehr geringe Auswirkung, Kategorie 2 = geringe Auswirkung, Kategorie 3 = mäßig starke Auswirkung, Kategorie 4 = starke Auswirkung, Kategorie 5 = sehr starke Auswirkung.

Table 5-10. Distribution of the long-term index LI for three climate change scenarios. Impact category 1 = very low impact, category 5 = severe impact.

Tab. 5-10: Verteilung der Kategorien des Langfristindikators LI. Kategorie 1 = sehr geringe Auswirkung, Kategorie = sehr starke Auswirkung.

Impact category	scA [%]	scB [%]	scC [%]
1	42.2	1.7	0.9
2	49.8	36.2	29.4
3	6.8	36.3	26.3
4	0.8	22.4	30.1
5	0.4	3.4	13.3
Total	**100.0**	**100.0**	**100.0**

5.4.2.3 Potential long-term impact of climatic change: Altitudinal zones

5.4.2.3.1 Shifts in potential natural species composition

The assessment criterion ac_6 (which represents the similarity of the simulated equilibrium species composition under current climate (baseline scenario) to the simulated equilibrium species composition under a climate change scenario) was analysed for the altitudinal zones given in Kilian et al. (1994). Figure 5-21 clearly demonstrates that the largest effects of the applied climate change scenarios on the equilibrium species composition (i.e., PNV) generally occurred at higher elevations.

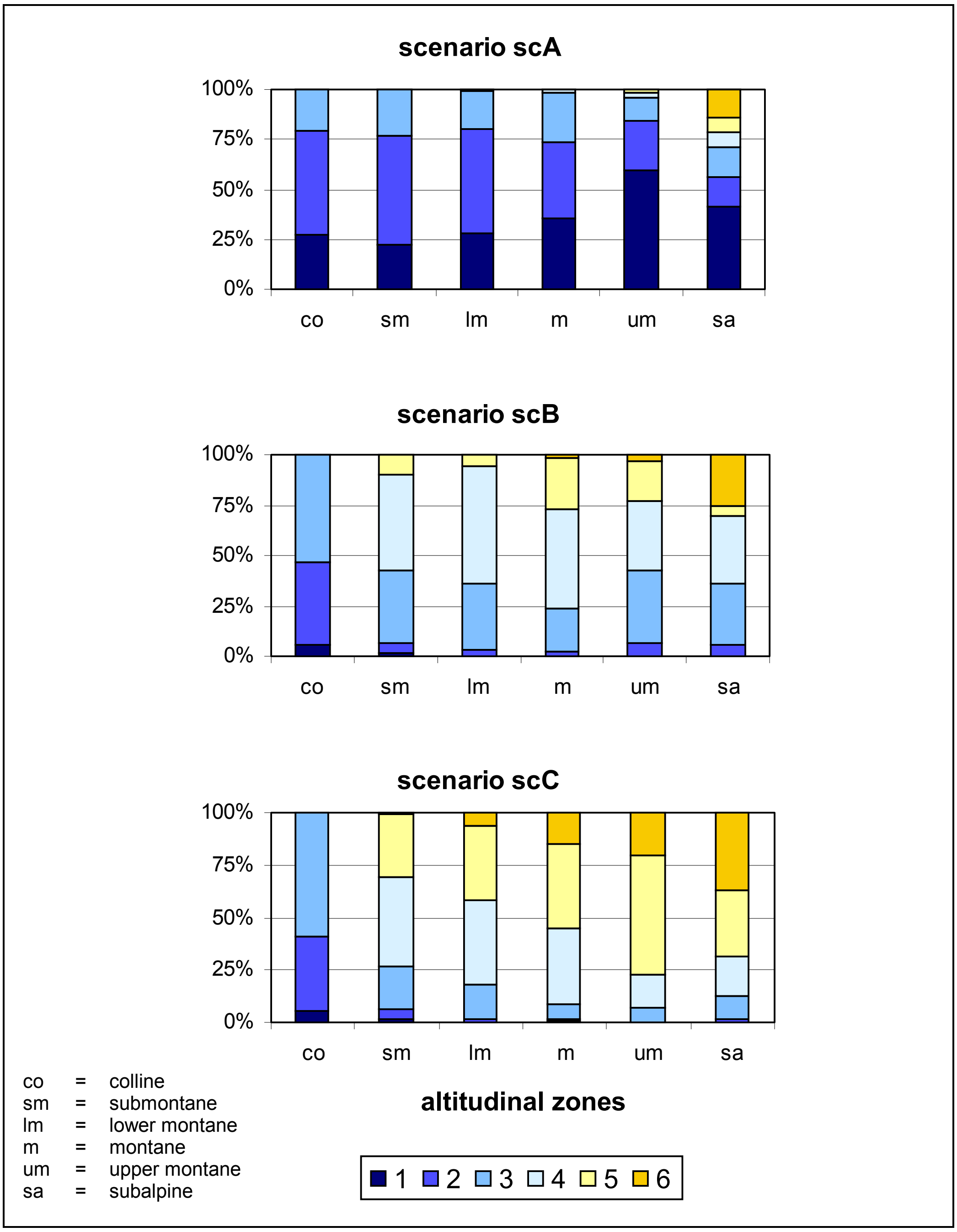


Figure 5-21. Effect of three climate change scenarios (scA, scB, scC) on simulated equilibrium species composition (PNV) at investigated sample points of the Austrian Forest Inventory (assessment criterion ac$_6$) stratified for altitudinal zones (ac$_6$ is derived from similarity of simulated PNV under current climate (baseline scenario) to the simulated PNV under the climate change scenarios). Class 1 = quasi identical (similarity >0.9), class 6 = very low similarity (similarity <0.2).

Abb. 5-21: Der Effekt von drei Klimaänderungsszenarios (scA, scB, scC) auf die simulierte Baumartenzusammensetzung der PNV für untersuchte Erhebungspunkte der Österreichischen Waldinventur gegliedert nach Höhenstufen (Ähnlichkeit zwischen simulierter PNV unter aktuellem Klima (baseline scenario) und simulierter PNV unter den Klimaänderungsszenarios). Klasse 1 = quasi identisch (PS >0.9), Klasse 6 = sehr geringe Ähnlichkeit (PS <0.2). n = 2759.

This pattern is consistent for all climate change scenarios. This may indicate that under the applied climate change scenarios at sites in the colline and submontane zone with broad-leafed-dominated potential natural vegetation types (i) the drought tolerance limits of species at oak/hornbeam sites had not yet been reached, and (ii) that today's beech forests remained under dominance of Fagus sylvatica. On the contrary at high elevation sites increasing temperatures under the climate change scenarios (scA, scB, scC) favoured the immigration of broad-leaved species with higher temperature requirements. Figure 5-21 corroborates this explanation. Under scenario scA (moderate warming) classes 4 to 6 of ac_6 indicating major shifts in simulated equilibrium species composition concentrate in regions with altitudes above approximately 1500 m a.s.l. Under scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) this response extended to lower elevations. Kruskall-Wallis and Wilcoxon-Mann-Whitney tests (SAS 1990) showed a significant decrease of ac_6 under scB and scC compared with scA with the only exception in the colline zone. No significant differences could be found between scC and scB (all tests at $\alpha = 0.05$).

5.4.2.3.2 Effect of climatic change on the divergence of current forest composition to simulated PNV

The effect of the applied climate change scenarios scA, scB and scC on the assessment criterion ac_7 shows a large-scale pattern similar to criterion ac_6 (Figure 5-22). The criterion ac_7 can be interpreted as the degree to which the "naturalness" of a given forest at a sample point of the Austrian Forest Inventory is reduced by a climate change scenario. The results show, that this effect was largest for the highest altitudinal zone. There are two reasons for this: (i) at sites in today's montane and subalpine zones existing forests are fairly close to the expected potential natural state (Grabherr et al. 1998) which in turn sets a large potential for a decrease in naturalness in case the expected potential natural vegetation composition (PNV) changes due to altered environmental conditions, and (ii) the potential for the latter case is extremely high at sites where under current climatic conditions (baseline scenario) many broadleaf species are either not competitive or even outside their fundamental niche (i.e., physiological amplitude).

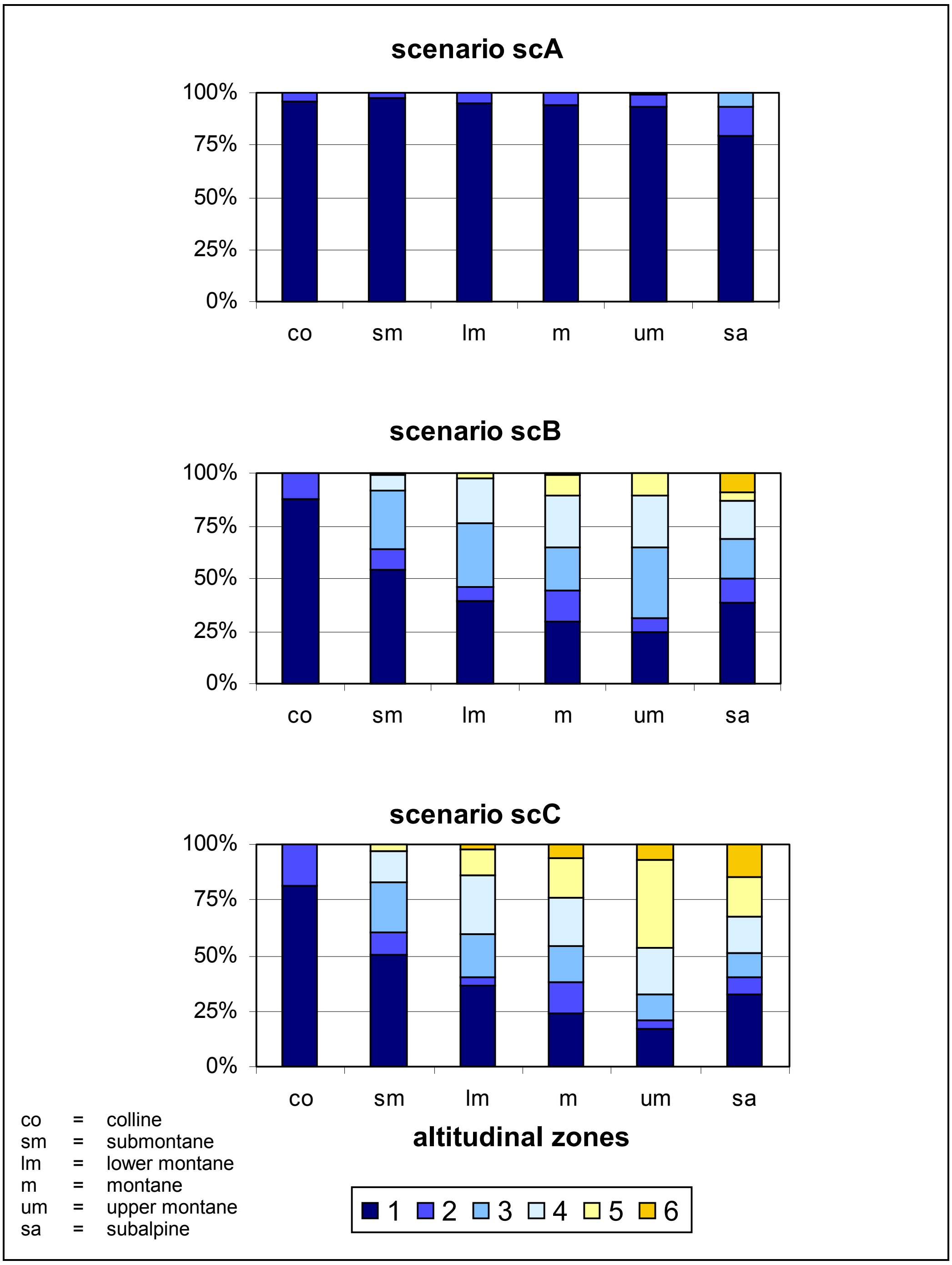


Figure 5-22. Effect of three climate change scenarios on assessment criterion ac_7 (increase in divergence of current forest composition to simulated PNV under climate change scenarios scA, scB and scC) at investigated sample points of the Austrian Forest Inventory stratified for altitudinal zones. Class 1 = divergence <0.1 (quasi no effect), class 6: divergence = > 0.8 (severe effect).

Abb. 5-22: Der Effekt von drei Klimaänderungsszenarien (scA, scB, scC) auf das Analysekriterium ac_7 (Zunahme der Abweichung von aktueller Baumartenzusammensetzung zu simulierter PNV zwischen aktuellem Klima und den Klimaänderungsszenarios) auf untersuchten Erhebungspunkten der Österreichischen Waldinventur gegliedert nach Höhenstufen. Klasse 1 = quasi kein Effekt (Abweichung <0.1), Klasse 6 = starker Effekt (Abweichung >0.8).

5.4.2.3.3 Indicator for the potential long-term impact of climatic change (LI)

Under conditions of moderate warming (climate change scenario scA) substantial to severe impacts (impact categories 4, 5) occurred in the subalpine zone exclusively due to large expected shifts in PNV (ac_6) and subsequently decreasing similarity of current forest composition to simulated future equilibrium species composition (ac_7). At all other elevations the response was mainly confined to the low impact categories 1 and 2 (Figure 5-23). Under stronger warming and eventually decreasing precipitation (scenarios scB and scC respectively) the general response pattern remained: potential long-term climate change impacts decreased with decreasing altitude showing a clear peak in the upper montane and subalpine zones. At low elevations (colline and submontane zones) just a minority of sample points was assigned to impact category 4 at the worst (submontane zone). In the colline zone no significant differences in LI among the climate change scenarios occurred. In all other altitudinal zones LI increased (indicating increasing potential risks due to climate change) under scB compared to scA as well as under scC compared to scB (except for the submontane zone) always significantly at $\alpha = 0.05$ (Wilcoxon-Mann-Whitney test on impact categories of LI).

It is interesting to note, that under the moderate climatic changes of scenario scA very similar long-term indices (LI) were calculated for all altitudinal zones with the exception of subalpine sites. Here, even small increases in temperature resulted in a marked change in ecological site conditions. In most cases the climatic conditions represented by the climate change scenarios scA (moderate warming), scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) might lead to increased net primary productivity due to longer vegetation periods and more favourable thermal conditions (compare also Hasenauer et al. 1999). At these altitudes for a few sites with very low water holding capacities scenario scC might change site conditions for the worse. Vice versa, for the low elevation sites, particularly in the colline zone, we refer to the baseline features presented in section 5.4.1.1. Relatively moderate potential long-term impacts as indicated by impact categories 1, 2 and 3 for LI do not necessarily mean that current forests in low elevation zones are not at risk in case of a possible climate change. True is, that at some sample points included in this study current vegetation is at substantial risk to suffer from catastrophic tree mortality even under current climatic conditions (baseline scenario). It is important that the different meanings of the short- to midterm indicator SMS at one side and the long-term index LI at the other side are clearly recognised.

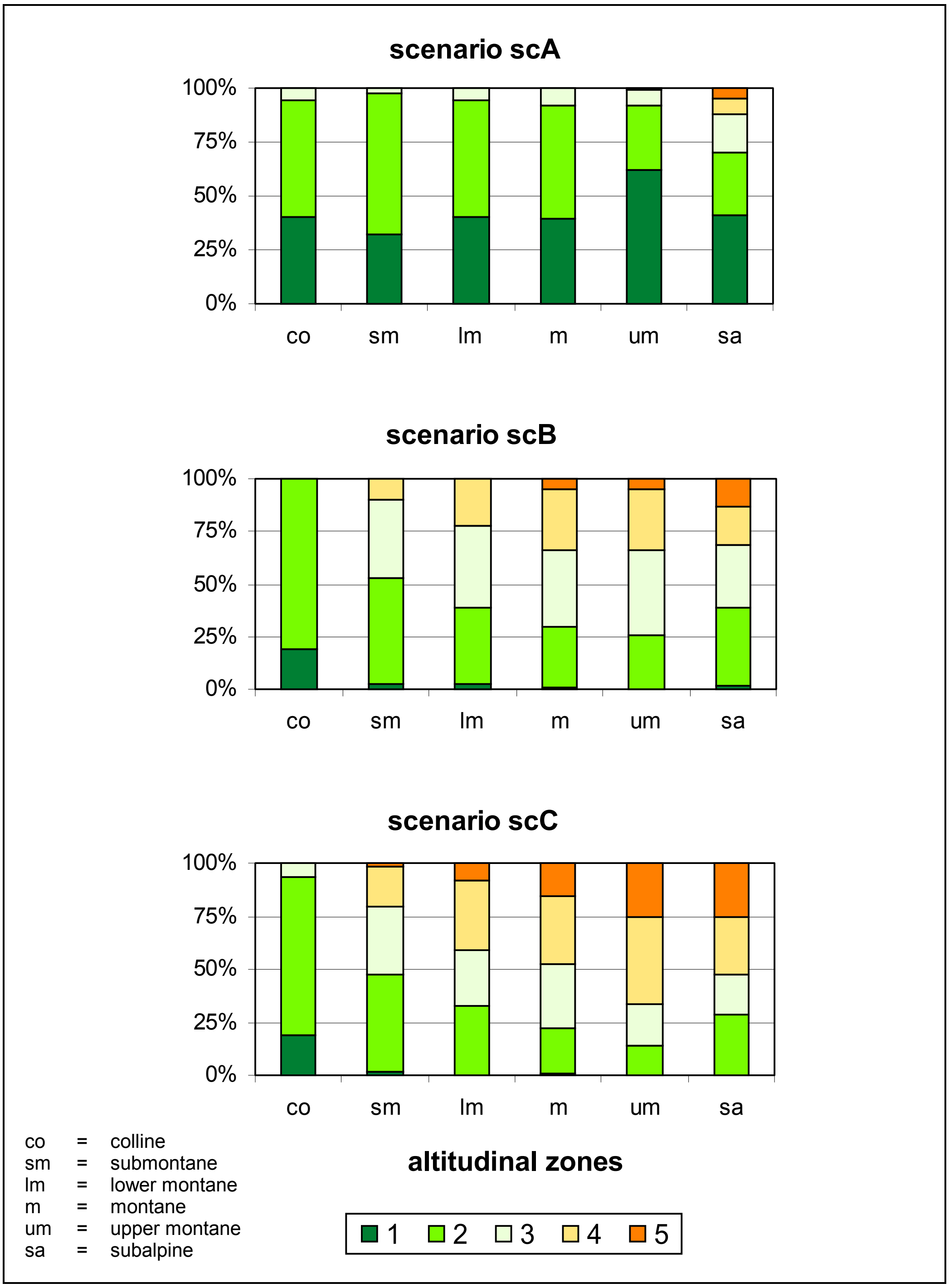


Figure 5-23. The potential long-term impact (LI) of climate change scenarios (scA, scB, scC) on current forests at investigated sample points of the Austrian Forest Inventory stratified for altitudinal zones. Impact category 1 = very low impact, category 2 = low impact, category 3 = moderate impact, category 4 = substantial impact, category 5 = severe impact.

Abb. 5-23: Potentieller Langfristeffekt (LI) von drei Klimaänderungsszenarien (scA, scB, scC) auf aktuell bestehende Wälder auf untersuchten Erhebungspunkten der Österreichischen Waldinventur gegliedert nach Höhenstufen. Kategorie 1 = sehr geringe Auswirkung, Kategorie 2 = geringe Auswirkung, Kategorie 3 = mäßig starke Auswirkung, Kategorie 4 = starke Auswirkung, Kategorie 5 = sehr starke Auswirkung.

5.4.2.4 Potential long-term impact of climatic change: Ecoregions

5.4.2.4.1 Shifts in potential natural species composition

The simulated responses of equilibrium species composition to scenarios of climatic change are shown in Figure 5-24. Because high altitude mountain sites are distributed among most of the ecoregions (with the exception of ecoregions 7, 8 and 9) the similarity classes of ac_6 indicating substantial shifts in the equilibrium species composition (PNV) under the climate change scenarios were more evenly distributed among the ecoregions with peaks in the alpine ecoregions 1 (interior region of the Alps) and 2 (northern transitional region of the Alps) under all applied climate change scenarios. Under scenario scC ecoregions 3 (eastern and southern transitional region of the Alps) and 6 (southern peripheral region of the Alps) also showed a higher-than-average level of categories 5 and 6 indicating drastically changed equilibrium species compositions (PNV) under scenario scC (strong warming, additional decrease in summer precipitation) compared with the simulated equilibrium species composition (PNV) under current climate (baseline scenario). Kruskall-Wallis and Wilcoxon-Mann-Whitney tests ($\alpha = 0.05$) showed significant decreases in similarity of simulated PNV under scB to simulated PNV under scA, and under scC when compared to scB with the exception of ecoregion 8 (eastern lowlands). According to FBVA (1995) and Kilian et al. (1994) ecoregion 8 contains a large proportion of sites with oak-dominated potential natural vegetation types. Our results showed that these oak-dominated PNV-types responded just slightly to the drier conditions of scenario scC compared to scenario scB. This means, that according to the simulation results oak forests remained within their fundamental niche even under the conditions of scenario scC (strong warming, additional decrease in summer precipitation).

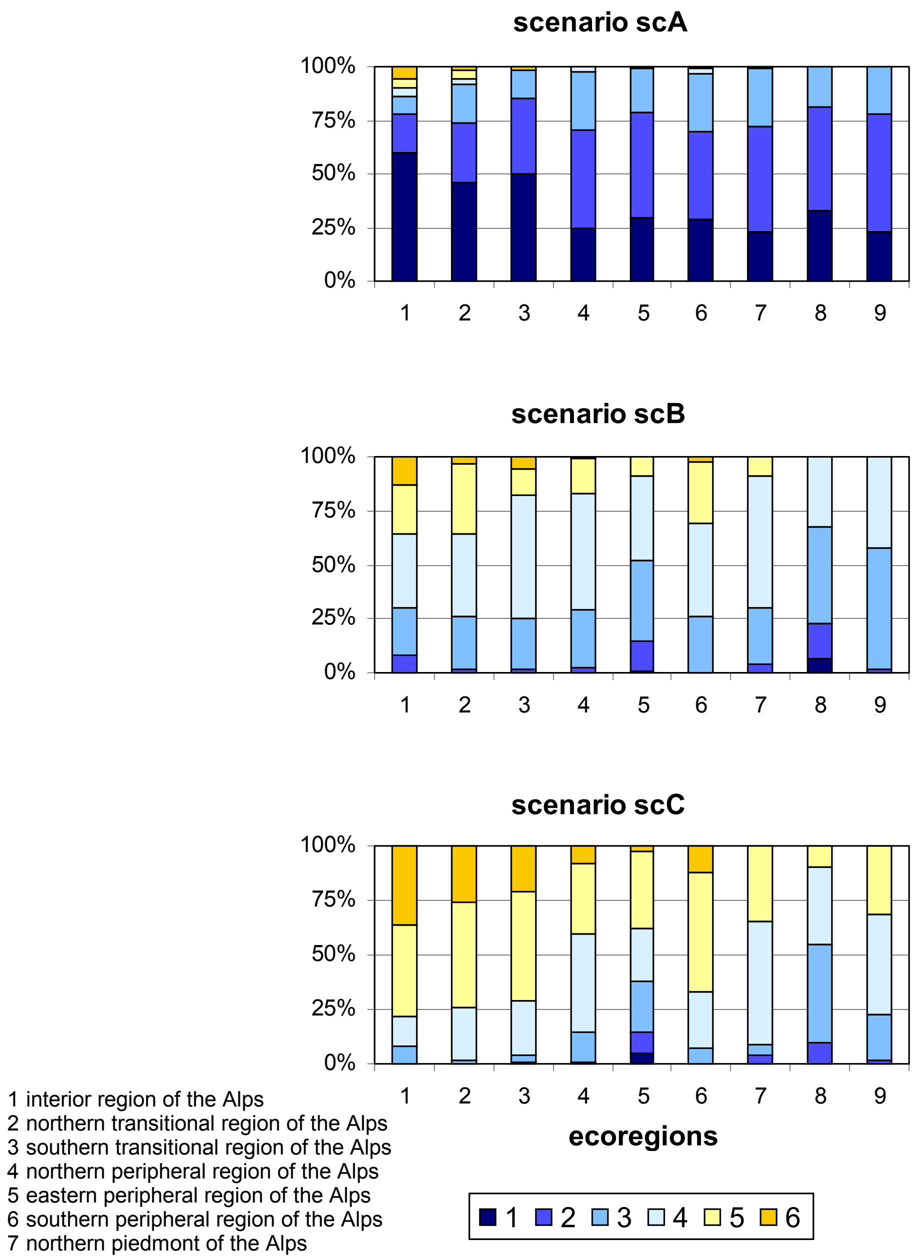


Figure 5-24. Effect of three climate change scenarios (scA, scB, scC) on simulated equilibrium species composition (PNV) at investigated sample points of the Austrian Forest Inventory (assessment criterion ac_6) stratified for the main ecoregions (ac_6 is derived from similarity of simulated PNV under current climate (baseline scenario) to simulated PNV under the climate change scenarios). Class 1: similarity > 0.9 (quasi identical), class 6: similarity < 0.2 (very low similarity).

Abb. 5-24: Der Effekt von drei Klimaänderungsszenarios (scA, scB, scC) auf die simulierte Baumartenzusammensetzung der PNV für untersuchte Erhebungspunkte der Österreichischen Waldinventur gegliedert nach Hauptwuchsgebieten (Ähnlichkeit zwischen simulierter PNV unter aktuellem Klima (baseline scenario) und simulierter PNV unter den Klimaänderungsszenarios). Klasse 1 = quasi identisch (PS >0.9), Klasse 6 = sehr geringe Ähnlichkeit (PS <0.2). n = 2759.

5.4.2.4.2 Effect of climatic change on the divergence of current forest composition to simulated PNV

In interpreting the results for the assessment criterion ac_7 (changes in the divergence of current forest composition as recorded by the Austrian Forest Inventory to simulated PNV under current climate (baseline scenario) and under climate change scenarios) it is essential to consider that a substantial load of potential adverse climate effects on current forests at lower elevations (today's colline and submontane zones) has already been anticipated under the baseline scenario (current climate) and are not explicitly indicated by assessment criterion ac_7. Figure 5-25 confirms this phenomenon with lowest impact for ecoregion 8 (eastern lowlands) and highest for the alpine ecoregions 1, 2 and 3.

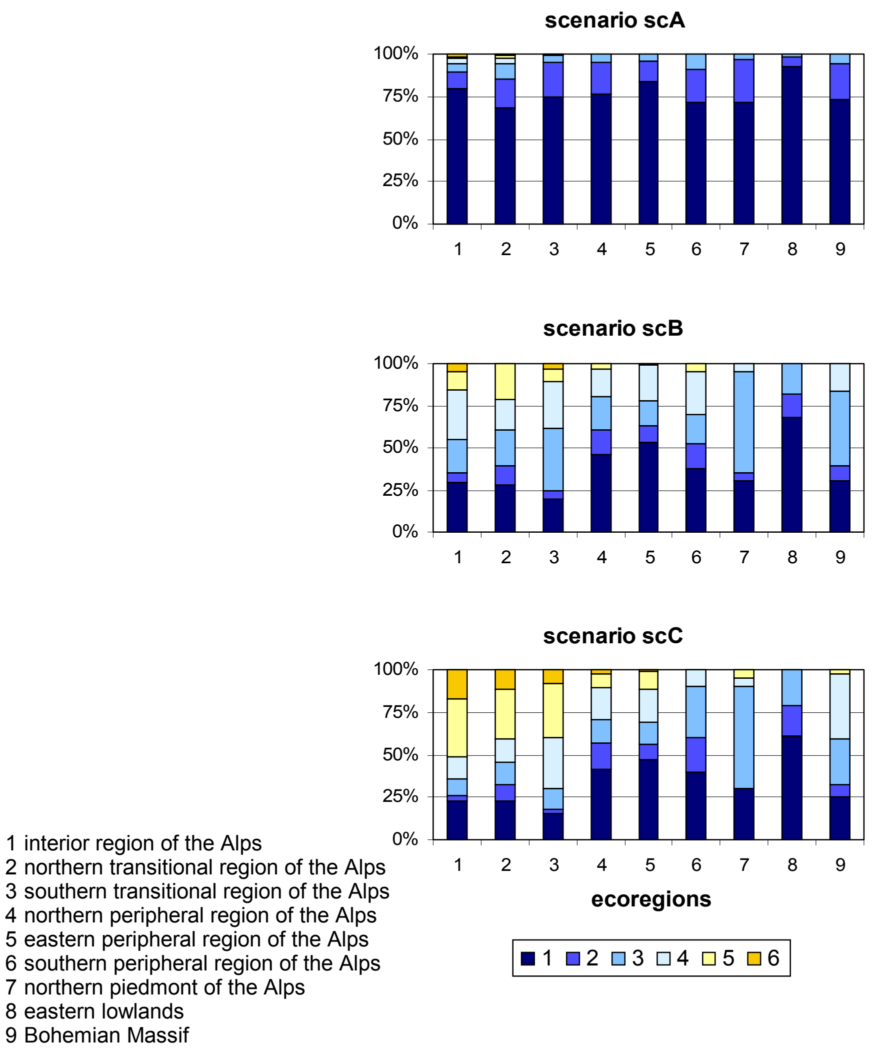


Figure 5-25. Effect of three climate change scenarios on assessment criterion ac_7 (increase in divergence of current forest composition to simulated PNV under climate change scenarios scA, scB and scC) at investigated sample points of the Austrian Forest Inventory stratified for the main ecoregions. Class 1 = divergence <0.1 (quasi no effect), class 6: divergence = > 0.8 (severe effect).

Abb. 5-25: Der Effekt von drei Klimaänderungsszenarien (scA, scB, scC) auf das Analysekriterium ac_7 (Zunahme der Abweichung von aktueller Baumartenzusammensetzung zu simulierter PNV zwischen aktuellem Klima und den Klimaänderungsszenarios) auf untersuchten Erhebungspunkten der Österreichischen Waldinventur gegliedert nach Hauptwuchsgebieten. Klasse 1 = quasi kein Effekt (Abweichung <0.1), Klasse 6 = starker Effekt (Abweichung >0.8).

5.4.2.4.3 Indicator for the potential long-term impact of climatic change

The indicator LI characterising the potential long-term impacts of climate change on current forests combines the assessment criteria ac_6 and ac_7. In general these criteria showed the same behaviour. Therefore the distribution pattern of impact categories LI corresponds largely to the pattern of ac_6 and ac_7 (Figure 5-26). The results under the climate change scenario scA (moderate warming) barely differed among the ecoregions. Just a very low share of sample points assigned to impact categories 3 and 4 occurred in the ecoregions 1 (interior region of the Alps) and 2 (northern transitional region of the Alps). Under the conditions of scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) the share of impact categories 4 (substantial impact) and 5 (severe impact) increased rather drastically. The ecoregions 7 (northern piedmont of the Alps), 8 (eastern lowlands) and 9 (Bohemian Massif) contained the lowest proportion of high-impact points under all applied climate change scenarios (scA, scB, scC). Non-parametric Wilcoxon-Mann-Whitney rank tests on impact categories of LI showed significant increases in potential long-term impact LI under scB compared to scA, and under scC compared to scB with the exception of ecoregions 5 to 8 for the latter case ($\alpha = 0.05$).

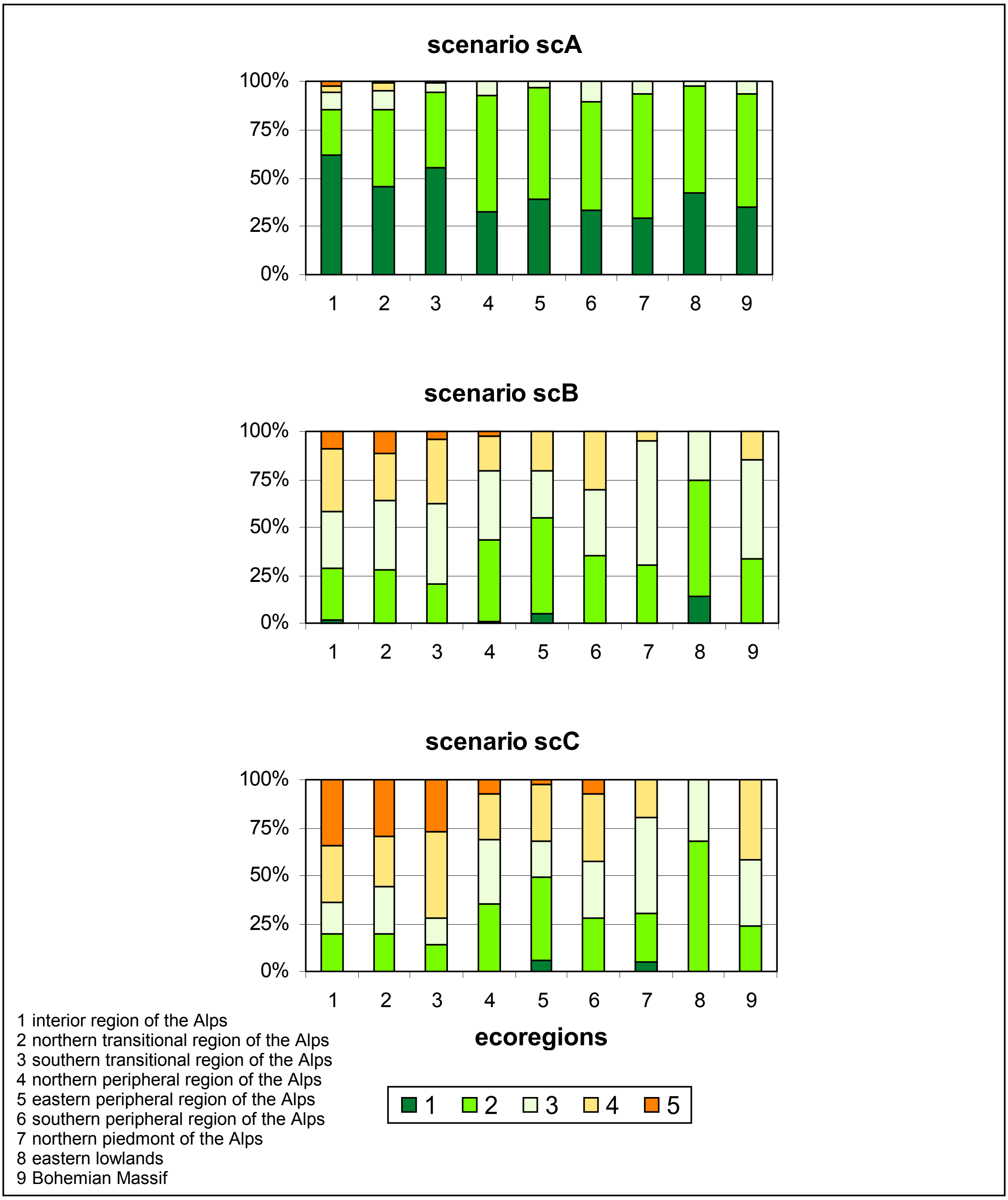


Figure 5-26. The potential long-term impact (LI) of climate change scenarios (scA, scB, scC) on current forests at investigated sample points of the Austrian Forest Inventory stratified for the main ecoregions. Impact category 1 = very low impact, category 2 = low impact, category 3 = moderate impact, category 4 = substantial impact, category 5 = severe impact.

Abb. 5-26: Potentielle langfristige Auswirkung (LI) von drei Klimaänderungsszenarien (scA, scB, scC) auf aktuell bestehende Wälder auf untersuchten Erhebungspunkten der Österreichischen Waldinventur gegliedert nach Hauptwuchsgebieten. Kategorie 1 = sehr geringe Auswirkung, Kategorie 2 = geringe Auswirkung, Kategorie 3 = mäßig starke Auswirkung, Kategorie 4 = starke Auswirkung, Kategorie 5 = sehr starke Auswirkung.

5.5 Combined assessment of potential short-/midterm and long-termimpacts

5.5.1 Total represented forest

From the short- to midterm indicator for the sensitivity of current Austrian forests to climatic changes (SMS) as well as from the indicator for the potential long-term impacts of climatic change on current Austrian forests (LI) an overall rating (CCI) was derived for each sample point. We distinguished a total of four impact classes (compare section 3.1.3).

1. Class 1 is a low-impact category where (1) on the short- to midterm range during the transient phase (2000-2050) of the applied climate change scenarios the simulations showed no additional tree mortality due to the changing climate, and (2) just minor potential long-term impacts were indicated by the index LI.
2. Class 2 represents an intermediate impact category where (1) moderate changes in species composition (i.e., effects of climatic changes on tree regeneration, fairly low additional tree mortality) during the transient phase, but (2) substantial potential long-term implications with regard to changes in the ecological site potential and an increasingly large divergence of existing forest composition to simulated future PNV were expected according to the model results.
3. Class 3 includes sample points where the simulation results showed (1) intermediate short- to mid-term response due to different successional patterns during regeneration phases or low-level tree mortality in mature stands, or (2) substantial changes with regard to PNV species composition.
4. Class 4 includes all sample points where according to the model results high-impact effects due to the changing climate were expected, either with regard to (1) additional catastrophic tree mortality under climatic change conditions and subsequently large divergence of simulated vegetation under baseline to simulated vegetation under climate change conditions during the transient phase 2000 to 2050, or (2) a combination of intermediate short- to midterm effects (additional tree mortality involved) and an almost complete replacement of the PNV species set under climate change conditions.

Figure 5-27 shows the spatial distribution of the climate change impact index CCI in Austria for each of the applied climate change scenarios.

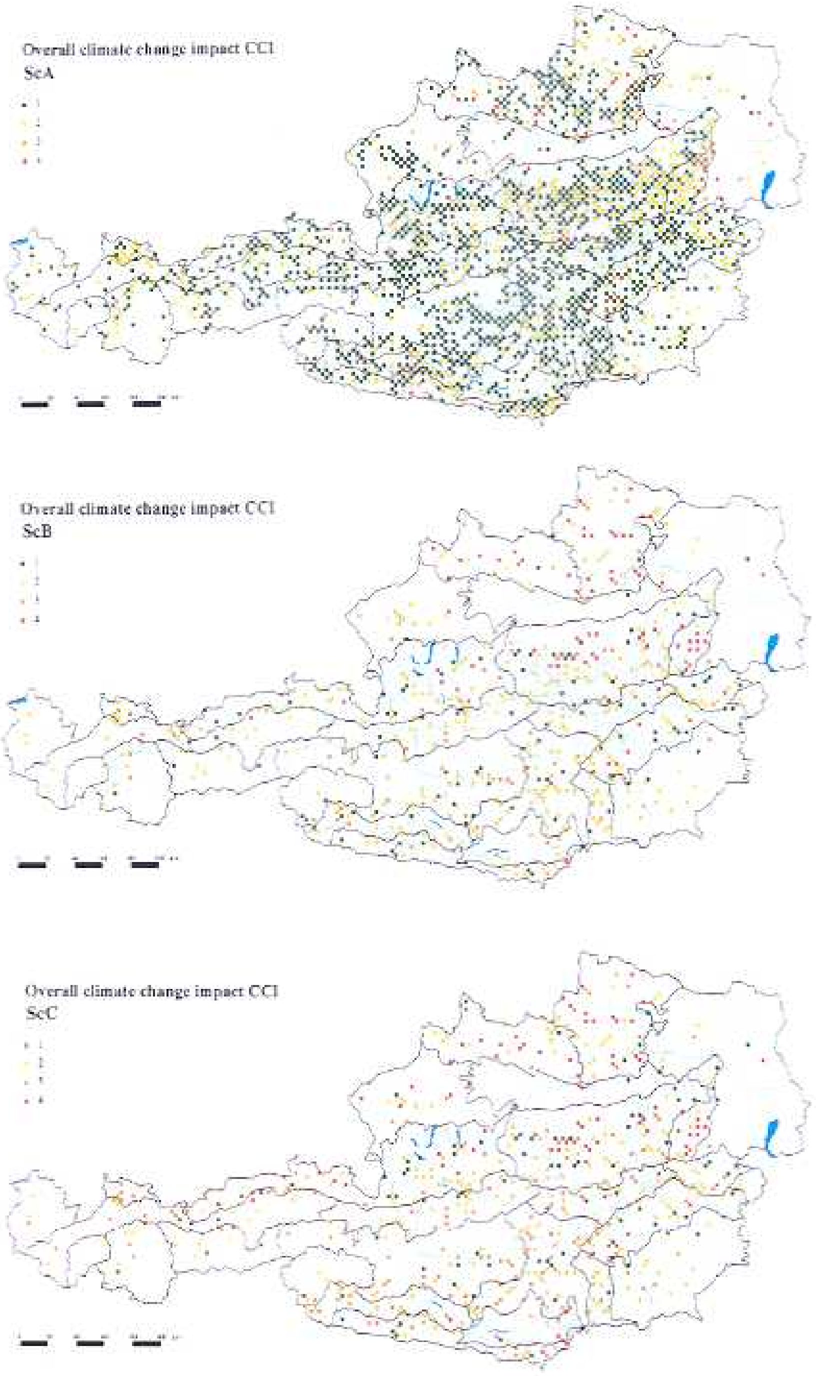


Figure 5-27. Spatial distribution of the overall climate change impact index CCI for three climate change scenarios (scA: n = 2585, scB: n = 644, scC: n = 647) at investigated sample points of the Austrian Forest Inventory. Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.

Abb. 5-27: Räumliche Verteilung des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung einer Klimaveränderung auf untersuchten Erhebungspunkten der Österreichischen Waldinventur unter drei Klimaänderungsszenarien (scA: n = 2585, scB: n = 644, scC: n = 647). Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.

For the total represented forest area the share of impact category 1 was 67.3 % under scenario scA, 18 % and 15.5 % for scenarios scB and scC respectively (Table 5-11).

Table 5-11. Percentage of investigated sample points of the Austrian Forest Inventory within the overall climate change impact categories (CCI) under the climate change scenarios scA (n = 2585), scB (n = 644) and scC (n = 647). Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.

Tab. 5-11: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung unter den Klimaänderungsszenarios scA (n = 2585), scB (n = 644) und scC (n = 647). Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.

climate change scenario	**impact category (CCI) [%]**			
	1	**2**	**3**	**4**
scA	67.3	26.1	3.5	3.1
scB	18.0	57.6	12.3	12.1
scC	15.5	44.7	25.8	14.1

This marked decrease in the low-impact category 1 goes hand in hand with a substantial increase in categories 3 and 4 indicating substantial to severe potential climate change impact. The joint categories 3 and 4 increased from 6.6% under scenario scA (moderate warming) to 24.4% under scB (strong warming), and to nearly 40% under the climatic conditions of scenario scC (strong warming, additional decrease in summer precipitation). The general increase of CCI under scenario scB as well as under scenario scC was significant at $\alpha = 0.001$ (Wilcoxon-Mann-Whitney test) (Figure 5-28).

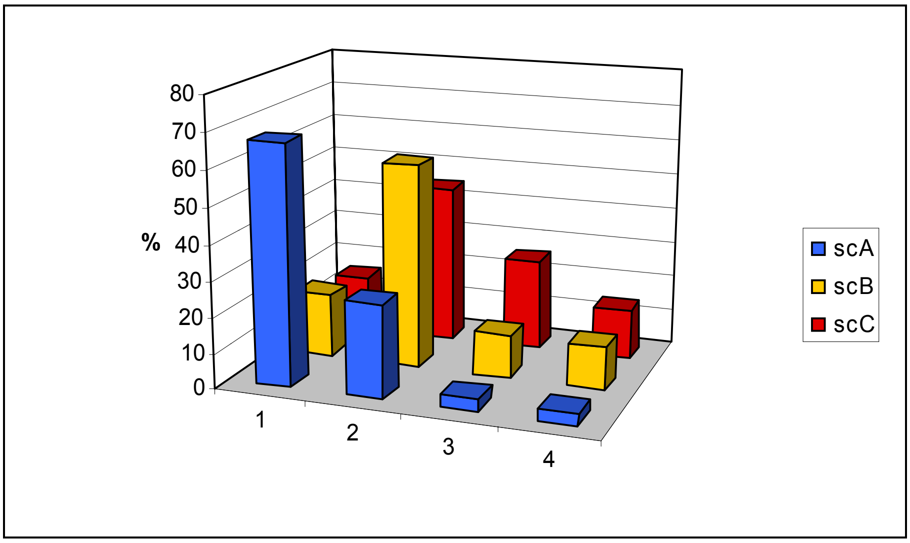


Figure 5-28. Percentage of investigated sample points of the Austrian Forest Inventory within the overall climate change impact categories (CCI) under the climate change scenarios scA (n = 2585), scB (n = 644) and scC (n = 647). Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.

Abb. 5-28: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung unter den Klimaänderungsszenarios scA (n = 2585), scB (n = 644) und scC (n = 647). Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.

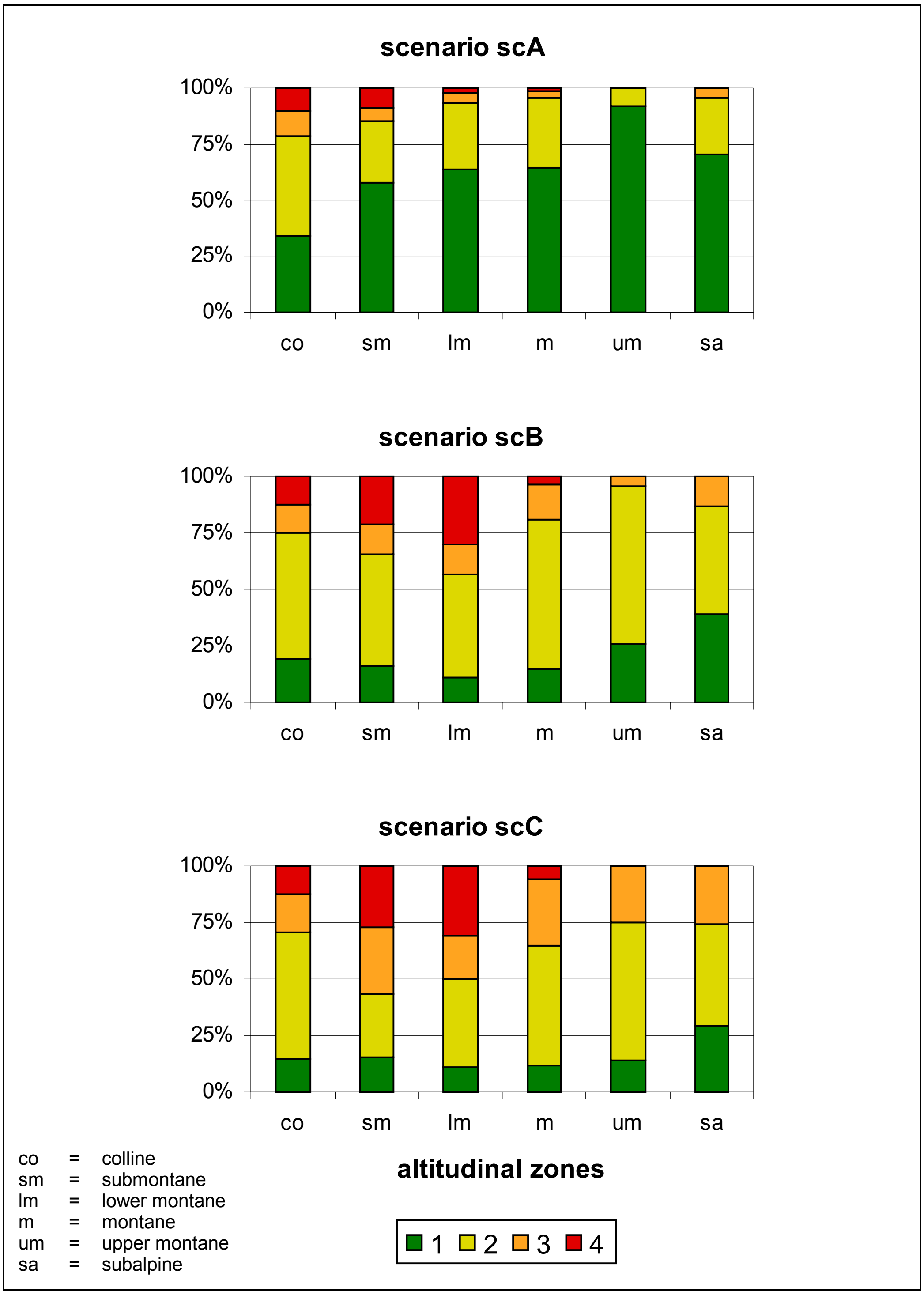
5.5.2 Altitudinal zones

Figure 5-29 and Table 5-12 show how the categories of the overall potential impact of climate change CCI on Austrian forests are distributed within altitudinal zones. The general result was, that categories indicating substantial or severe climate change impact (CCI categories 3 and 4) were mainly confined to lower elevations, extending from colline and submontane zones under scenario scA (moderate warming) higher up into montane regions under scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation), without major differences between the latter two scenarios. In the upper montane and subalpine zones no sample point was assigned to category 4 (severe impact) under any of the applied climate scenarios. A striking feature of Figure 5-29 is the marked shift of sample points which under scenario scA had been assigned to impact category 1 (low impact) into category 2 (moderate impact) at higher elevations under the conditions of scenarios scB and scC. In the colline zone no significant differences existed among the scenarios (Kruskall-Wallis test, $\alpha = 0.05$). Scenario scB yielded significantly higher impact categories than scenario scA in all other altitudinal zones (Wilcoxon-Mann-Whitney test, $\alpha = 0.05$). Scenario scC yielded a significant increase in CCI when compared to scenario scB for the montane and upper montane zone only.

Table 5-12. Percentage of investigated sample points of the Austrian Forest Inventory within overall potential climate change impact categories (CCI) under three climate change scenarios (scA, scB, scC) within altitudinal zones. Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.

Tab. 5-12: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung unter drei Klimaänderungsszenarien (scA, scB, scC) gegliedert nach Höhenstufen. Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.

Altitudinal	**scA**				**scB**				**scC**			
zone	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
colline	34.3	44.0	11.4	10.3	18.8	56.5	12.3	12.4	15.0	55.3	17.2	12.5
submontane	57.7	27.6	5.9	8.8	16.2	49.6	12.8	21.4	15.7	27.9	29.1	27.3
lower montane	63.7	29.9	3.9	2.5	11.0	45.5	13.2	30.3	10.8	38.9	19.3	31.0
montane	64.4	31.0	3.3	1.3	14.6	66.5	15.5	3.4	12.1	52.6	29.3	6.0
upper montane	92.1	7.7	0.2	0	25.5	69.8	4.7	0	14.1	60.6	25.3	0
subalpine	70.1	25.4	4.5	0	38.9	48.1	13.0	0	29.1	45.5	25.4	0



co = colline
sm = submontane
lm = lower montane
m = montane
um = upper montane
sa = subalpine

Figure 5-29. Percentage of investigated sample points of the Austrian Forest Inventory within overall potential climate change impact categories (CCI) under three climate change scenarios (scA, scB, scC) within altitudinal zones. Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.

Abb. 5-29: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in Kategorien des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung unter drei Klimaänderungsszenarien (scA, scB, scC) gegliedert nach Höhenstufen. Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.

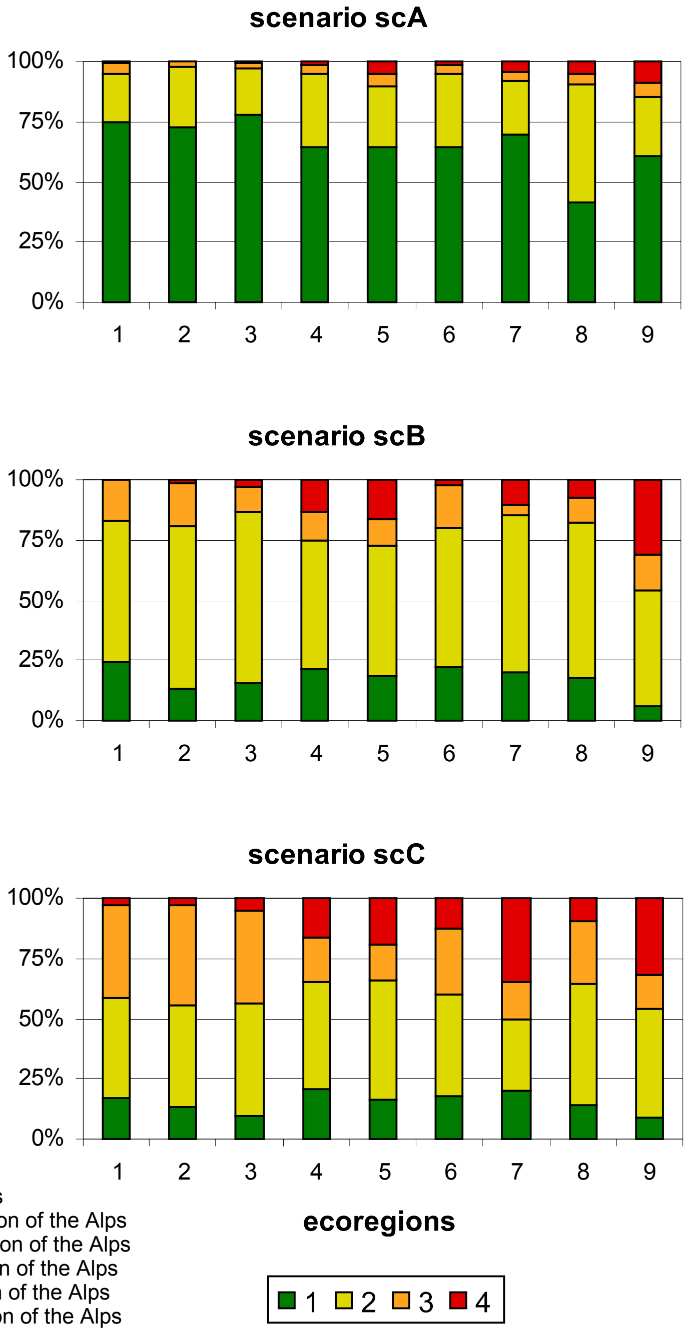
5.5.3 Ecoregions

The results for the main ecoregions according to Kilian et al. (1994) revealed that in addition to the expected problem areas due to frequent plantation-like Norway spruce forests in ecoregions 7 (northern piedmont of the Alps), 8 (eastern lowlands) and 9 (Bohemian Massif) under climate change conditions of scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) the share of sample points with substantial to severe potential impact also occurred in ecoregions 4 (northern transitional region of the Alps), 5 (eastern and southern peripheral regions of the Alps) and 6 (Klagenfurt basin within the southern peripheral region of the Alps) (Table 5-13 and Figure 5-30). In essentially all ecoregions (with the exception of ecoregion 1 under scenario scB) a low number of inventory points assigned to overall impact category 4 (severe impact) occurred under each of the three applied climate change scenarios (scA, scB, scC). With the exception of ecoregion 8 (eastern lowlands) the overall climate change impact index CCI was generally significantly higher under scenario scB than under conditions of scenario scA (α = 0.05). The increase of CCI under scenario scC compared to scenario scB was significant in ecoregions 1 (interior region of the Alps), 2 (northern transitional region of the Alps) and 3 (eastern and southern transitional region of the Alps) only (α = 0.05).

Table 5-13. Percentage of investigated sample points of the Austrian Forest Inventory within overall potential climate change impact categories (CCI) under three climate change scenarios (scA: n = 2585, scB: n = 644, scC: n = 647) within the main ecoregions. Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.

Tab. 5-13: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung unter drei Klimaänderungsszenarien (scA, scB, scC) gegliedert nach Hauptwuchsgebieten. Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.

Ecoregion (Kilian et al., 1994)	**scA**				**scB**				**scC**			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
interior region of the Alps	75.1	19.7	4.2	1.0	24.7	58.4	16.9	0	17.1	41.4	38.6	2.9
northern transitional region of the Alps	72.3	25.2	2.5	0	13.2	67.2	18.0	1.6	13.1	42.6	41.0	3.3
southern transitional region of the Alps	78.0	19.2	1.7	1.1	15.6	70.8	10.5	3.1	9.4	46.9	38.5	5.2
northern peripheral region of the Alps	64.8	30.0	3.6	1.6	21.3	53.8	11.3	13.6	20.7	44.4	18.3	16.6
eastern peripheral region of the Alps	64.1	25.6	4.9	5.4	18.4	54.0	11.2	16.4	16.1	49.5	14.9	19.5
southern peripheral region of the Alps	64.5	30.3	3.9	1.3	22.5	57.5	17.5	2.5	17.5	42.5	27.5	12.5
northern piedmont of the Alps	69.3	22.7	3.5	4.5	20.0	65.0	5.0	10.0	20.0	30.0	15.0	35.0
eastern lowlands	41.4	48.6	4.6	5.4	17.9	64.3	10.7	7.1	14.3	50.0	26.1	9.6
Bohemian Massif	61.1	24.0	6.1	8.8	6.1	47.9	15.2	30.8	9.2	44.7	14.5	31.6



1 interior region of the Alps
2 northern transitional region of the Alps
3 southern transitional region of the Alps
4 northern peripheral region of the Alps
5 eastern peripheral region of the Alps
6 southern peripheral region of the Alps
7 northern piedmont of the Alps
8 eastern lowlands
9 Bohemian Massif

Figure 5-30. Percentage of investigated sample points of the Austrian Forest Inventory within overall potential climate change impact categories (CCI) under three climate change scenarios (scA: n = 2585, scB: n = 644, scC: n = 647) within the main ecoregions. Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.

Abb. 5-30: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur in den Kategorien des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung unter drei Klimaänderungsszenarien (scA, scB, scC) gegliedert nach Hauptwuchsgebieten. Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.

The share of overall impact category 4 indicating severe potential impacts due to the underlying climate change scenario within the ecoregions increased substantially under scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) from a few percent under scenario scA to more than 30% under scenario scC (ecoregions 7 and 9) (compare Table 5-13). The fairly low share of inventory points assigned to overall impact category 4 in ecoregion 8 (eastern lowlands) with the warmest and driest forest sites in Austria might attract some attention. This phenomenon is entirely due to two reasons: (1) currently existing off-site conifer stands (mainly Picea abies) are already severely affected under current climate (baseline scenario) due to frequently occurring drought years, and (2) the drought tolerance thresholds of species dominating current PNV apparently are not exceeded under the applied climate change scenarios. Thus, the additional impact of climate change with increasing temperatures and eventually decreasing precipitation (scenario scC) is barely represented by the calculated indices expressing the difference (i.e., the impact of climatic changes) between baseline scenario and a climate change scenario (compare section 3.1.1).

5.5.4 Sensitivity of Norway spruce forests

The major crop species in Austria is Norway spruce (Picea abies). According to Schieler et al. (1995) this species comprises 61% of total standing volume in Austria's forests. Norway spruce has been heavily promoted since the 19th century and planted far beyond its natural distribution area (cf. Mayer 1974). Considerable portions of these "secondary" plantation-like conifer forests are prone to frequently recurring biotic (bark beetles, root fungi) and abiotic damages (wind, snow). The vulnerability of Norway spruce to drought periods and subsequent infestations by phloem feeding bark beetles increases the risk of this species under warmer and eventually drier climates substantially. Figure 5-31 shows the distribution of overall climate change impact categories (CCI) under three climate change scenarios for all sample points included in the present study where Picea abies comprised more than 50% of aboveground standing biomass.

Under scenario scA (moderate warming) the overall climate change impact category 4 (severe impact) occurred in the colline (55.5%), the submontane (19.8%) and in the lower montane zone (2.8%). Under conditions of scenario scC (strong warming, additional decrease in summer precipitation) the percentage of plots with severe potential climate change impact increased to 66.7% (colline zone), 54.2% (submontane zone) and 43.8% (lower montane zone). In the colline zone the potential impact of a changing climate on Picea abies stands is so severe, that it seems prohibitive to favour this species any longer at such sites. According to the results of the present study even under the relatively moderate warming conditions of scenario scA a substantial share of Norway spruce dominated stands in the submontane zone had been assigned to overall climate change impact category 4 (severe impact). This share increased substantially under scenarios scB and scC indicating the sensitivity of such stands to higher temperatures and limited water supply. Under the climatic conditions of scenarios scB and scC the zone with large proportions of overall impact categories 3 and 4 extends further up into the lower montane zone. The portions of overall impact category 3 in the upper montane and in the subalpine zones were largely due to expected long-term impacts due to changes in the simulated equilibrium species composition (PNV) (compare section 3.1.3).

Figure 5-31. *Percentage of investigated sample points of the Austrian Forest Inventory with a share of Picea abies >50% of aboveground standing biomass within overall potential climate change impact categories (CCI) under three climate change scenarios (scA: n = 1719, scB: n = 420, scC: n = 420) within altitudinal zones. Impact category 1 = low impact, category 2 = moderate impact, category 3 = substantial impact, category 4 = severe impact.*

Abb. 5-31: *Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur mit Fichtenanteil >50% [oberirdische stehende Biomasse] in den Kategorien des Indikators CCI für die kombinierte kurz-/mittelfristige und langfristige Auswirkung unter drei Klimaänderungsszenarien (scA: n = 1719, scB: n = 420, scC: n = 420) gegliedert nach Höhenstufen. Kategorie 1 = geringe Wirkung, Kategorie 2 = mäßig starke Wirkung, Kategorie 3 = starke Wirkung, Kategorie 4 = sehr starke Wirkung.*

5.5.5 Evaluation of current regeneration

Regarding the adaptation potential of current forests to changing climatic conditions it is interesting to compare current regeneration with the set of species expected under the conditions of the applied climate change scenarios (i.e., PNV) because of the importance of juvenile trees for a possible transition process of today's forests. To evaluate whether currently available regeneration at a sample plot of the Austrian Forest Inventory meets specific silvicultural minimum requirements with regard to its expected potential for stand transition we defined a threshold value based on two considerations. First, the dominating tree species in a simulated future equilibrium species assemblage (corresponding to the climate of the year 2050 according to a particular climate change scenario) should be considered. Therefore we selected all species which together comprised at least 70% of aboveground standing biomass. Second, we had to define a minimum requirement for the decision whether existing regeneration was sufficiently abundant at a plot. To accomplish this task we used a table with silvicultural tree number requirements for different tree species in four different height classes included in the field instruction manual of the Austrian Forest Inventory (FBVA 1995). The given numbers are rather high to grant future crop stands of sufficient quality. Therefore we assumed 10% of the given stem numbers over all height classes (compare Annex 2) as a minimum requirement for the evaluation of the adaptation potential of current forest regeneration. Please note, that AFI provided detailed data on tree regeneration for stands only which were judged to require regeneration (approximately 16% of all sample points included in the present study). In Table 5-14 the percentage of sample points which met the defined regeneration requirement under three scenarios of climatic change is shown.

Table 5-14. Percentage of sample points of the Austrian Forest Inventory with regeneration data which meet the regeneration requirement regarding similarity of current regeneration to simulated PNV under four climate scenarios (baseline scenario: n = 446, scA: n = 444, scB: n = 121, scC: n = 120).

Tab. 5-14: Anteile untersuchter Erhebungspunkte der Österreichischen Waldinventur mit vorhandenen Verjüngungsdaten, die ausreichend Verjüngung in bezug auf die simulierte PNV unter vier Klimaszenarien aufweisen (baseline scenario: n = 446, scA: n = 444, scB: n = 121, scC: n = 120).

climate scenario	**sample points with current regeneration adapted to future climate [%]**
baseline scenario	76.7
scA	75.2
scB	66.1
scC	45.8

The moderate warming scenario scA essentially had no effect on the share of sample points where today's regeneration included the defined minimum share of species of "tomorrows" species set. Under scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) this percentage decreased drastically to as far as about 45% (scC). This share might be considered rather low. The presence of species expected in a future PNV indicates merely the chance of a transition of currently existing forests to species mixtures better adapted to the prevailing site conditions without artificial regeneration of climax species and does not indicate the risk of a forest breakdown. A detailed analysis showed that the majority of sample points with insufficient regeneration according to the definition above was located at sites where due to the simulation experiments a transition from today's Norway spruce dominated forests to stand types naturally dominated by beech had been expected.

6 DISCUSSION

Climate change impact assessments share at least one of the following objectives: (i) the assessment of ecosystem sensitivity to climatic changes, (ii) the assessment of magnitude and rate of change for those ecosystems which appear vulnerable, and (iii) to develop treatment plans to mitigate the adverse effects of a changing climate. The present study aims at the former two of these objectives. The presented methodology seemed particularly suitable to address the first task of the "classical" problem solving sequence (Rauscher 1999): problem identification. However, before drawing final conclusions based on results of the simulation experiments in this study possible limitations of the presented methodology will be discussed.

Core of the approach is the newly developed 3D-patch model PICUS v1.2 which was applied to simulate forest vegetation development at sample points of the Austrian Forest Inventory starting from today's species composition and structure as recorded by the Austrian Forest Inventory. This approach bears several advantages compared to earlier climate change impact studies:

(1) PICUS is a dynamic model of forest vegetation development which is based on individual trees as the basic modelling entity. Thus, contrary to static community models PICUS accounts for the individualistic nature in the formation of forest communities (Gleason 1927) and avoids the extrapolation of today's hypothetical potential natural vegetation to environmental conditions which might have no analogue in today's landscapes (Austin and Smith 1989). Furthermore, with a dynamic model the transient response of forests to a changing climate can be explored, a feature not accounted for by equilibrium models (e.g., Kienast et al. 1996).

(2) The internal structure of PICUS allows for the initialisation of currently existing forests according to standard forest inventory data. Thus, in initialising PICUS composition and structure of a forest can be considered depending on the degree of detail of available stand data. However, the use of "real" inventory data in combination with a fairly complex general ecological model such as PICUS v1.2 bears several problems. First, forests grown strictly within the algorithmic frame of PICUS may differ from "real" forests with regard to attributes such as accumulated biomass and structural details such as vertical leaf area distribution within a stand. Subsequently this mismatch may result in unrealistic growth pattern of simulated stands which are initialised with real data in the early phase of a simulation. In the present study this unwanted eventual behaviour was taken into consideration by employing a baseline simulation as a control run relating each simulation under a climate change scenario to this benchmark.

(3) Regarding the employed model it is important to note, that in PICUS v1.2 species performance at super-optimal temperatures is not restricted by temperature per se (compare Bugmann and Solomon 2000). To enhance the science-based parameterisation scheme of earlier patch-models an extensive data set combining information from large-scale forest inventories, soil and meteorological data bases had been employed to estimate species-specific parameters for environmental response functions used within PICUS (compare Lexer and Hönninger 1998b, Lexer and Hönninger 2000a). Replacing the often criticised parabola in modelling tree response to temperature derived from today's observed geographical distribution limits avoids the unrealistic "truncation" of species occurrence under warming scenarios (Schenk 1996). Nevertheless, there is a potential drawback to this model modification. Extrapolation to temperature conditions far beyond the conditions observed for a species under current climate may introduce bias due to neglected effects such as respiration. In the present study this potential problem was avoided by restricting temperature increases in the climate change scenarios to a maximum of +2.0 °C. Under such conditions the oak species considered in PICUS are

well within their known ecophysiological limits and the risk of simulating a forest under conditions where according to literature a forest should not grow is minimised.

(4) The evaluation of PICUS v1.2 as presented in this study prior to its application for a climate change impact assessment can be considered rather restrictive. The percentage of 40% correctly classified PNV-types according to the scheme used within the Austrian Forest Inventory may seem rather low. However, several points have to be considered: First, the expert classification of PNV used as an evaluation object essentially is another model open to debate. Second, the climate data required to drive the model at spatially explicit sites in heterogeneous alpine landscapes are surely a potential source of error (compare Scheifinger and Kromp-Kolb 2000). Similar arguments hold true for the soil data required to initialise PICUS (see Lexer et al. 1999). Third, classification of a simulated species assemblage into a particular PNV-category might be due to a rather subjective definition of species thresholds. For instance, sensitivity analyses of the classification scheme employed for this task showed, that decreasing the threshold for Abies alba required for a classification into the spruce/fir-type from 15% to 10% aboveground biomass increased the percentage of sample points correctly classified into that PNV-category by approximately 15%. Thus, even a misclassified simulated forest might be very close to the expected species composition. From the evaluation exercise we conclude that in general PICUS v1.2 is capable of producing a plausible pattern of expected potential natural vegetation (PNV) for alpine landscapes. The spatially explicit point-specific initialisation of the model, however, did not provide for a "smoothed" response of the model output as for instance presented by Lindner et al. (1997) where the soil parameters required to initialise the model runs had been lumped at a scale of 10 x 10 km^2 (see also Bugmann et al. 2000).

A new approach to evaluate the sensitivity of current forests to changing climatic conditions at regional scale had been employed in combining short- to midterm transient behaviour with the potential long-term impact derived from PNV. A decenial sequence of anomalies in tree species composition and accumulated biomass from 2000 to 2050 under current climate and a climate change scenario was condensed to an indicator for the short- to midterm sensitivity of current forests. No human interventions were assumed. The latter assumption may seem unduly when dealing with managed forests. However, this "no management" assumption is a prerequisite to identify forest conditions vulnerable to a changing climate. Species compositions which are well adapted to the site conditions evolving under climate change scenarios will show no signs of abrupt diebacks and rather maintain forest functions without management interventions. This "natural" behaviour of forests would be blurred by the effect of management operations.

In addition to the transient response of current forests a further indirect approach is employed to assess the potential impact of climatic change. The "classical" approach in Central European silviculture to derive the aptitude of tree species at a given site by utilising the species composition of the potential natural vegetation (PNV sensu Tüxen 1956) as a benchmark for species suitability is employed to derive an estimate of "long-term" impacts on current forests due to climatic changes. In accordance with Kienast et al. (1996) this approach alone would provide a rather crude classification of a current forest's risk in case of climatic change because today's absence of naturally dominating tree species under climate change conditions may not result in a forest breakdown. However, the greater the shift in the ecological site potential and the larger the divergence to the current species composition the more likely is an adverse effect of climatic change on forest functioning, and the more intense the required management operations to maintain forest functions. It is important to note, that with the presented approach the current forest is matched with PNV which is generated by a dynamic vegetation model for each site specifically. Thus, the postulation of species proportions for syntaxonomic PNV-formations (e.g. Ellenberg 1996, Mucina et al. 1993) which essentially can rarely be found in the forest landscapes of Central Europe was avoided.

One essential feature of the approach employed in the present study is the explicit formulation of baseline conditions ("control run"). By doing so we strictly stay within the implicit boundary conditions for vegetation development as defined in the forest model and avoid mixing up "virtual" with "real" data in deriving indicators of forest sensitivity to changing climate. Nevertheless, this is also a crucial point that has to be considered for the proper interpretation of the presented risk assessment results. The presented impact indicators SMS (short- to midterm), LI (long-term) and CCI (overall climate change impact) quantify the potential impacts of a changing climate on forest vegetation by relating simulated vegetation response under climate change conditions to simulated response under current climate (baseline scenario). The anomaly of vegetation development under both scenarios is the impact of climate change. However, this simple but consistent concept (in similar form employed in global climate modelling) trades off its advantages against the problem, that the risk assessment indices will not indicate the response of currently existing forests to today's climate. Thus, a region with no indication of climate change impact as indicated by the indicators SMS, LI and CCI might well be a problem area even under current climate (baseline scenario). To circumvent this limitation simulated tree mortality under current climate is presented to indicate potential short- to midterm problems, and simulated PNV under current climate is matched with today's forest composition to indicate eventual adverse long-term consequences of existing forests under current climate.

The assessment criteria ac(i) calculated from the model output strictly quantified similarity of two species sets at one point in time and do not include any explicit valuation with regard to adverse effects. To provide this information the eigenvalue method as proposed by Saaty (1977) was employed. Based on this technique asymptotic transfer functions were constructed which subsequently were used to calculate the "impact value" for each realisation of an assessment criterion with respect to climatic change. The coefficients in the additive functions used to combine assessment criteria to the indices SMS and LI respectively (i.e., the weights for involved criteria) were also estimated with Saaty's method and thus are based on subjective judgements. Sensitivity tests showed that within the plausible range of weights effects on the output were small. The matrix of logical combinations of classes for SMS and LI used to estimate the overall climate change impact CCI is admittedly intuitive. However, we feel confident in the definition of CCI impact categories 1 (low impact) and 4 (severe impact). The intermediate categories 2 (moderate impact) and 3 (substantial impact) attempt to differentiate among cases where the current forest showed either intermediate adverse short-/midterm response to climate change (period 2000-2050), or considerable dissimilarity with regard to (1) simulated equilibrium species composition (PNV) under current climate and corresponding future PNV, and (2) increasing divergence of current forest composition to simulated PNV under current climate and climate change scenario. A recent study by Lasch et al. (1999) corroborated the difficulties in comparing directly simulated short-/midterm indices and long-term indices derived from PNV. Long-term impact measures did not necessarily correlate with short- to midterm measures.

In a large-scale assessment with hundreds to thousands of sample points involved it is admittedly impossible to consider each single observation (i.e., sample point) separately. For instance, a calculated similarity of zero represents the same impact value irrespectively of the involved species and location of the site. The consideration of this fact is of particular importance when interpreting long-term indices such as LI. A value for LI indicating a possible severe long-term impact of climate change at a subalpine site will have a different meaning than the identical value at a colline site. In other words, forest response to changing environmental conditions has to be interpreted with regard to absolute environmental conditions. A small response close at the ecophysiological limits of involved tree species is of higher relevance than the very same numerical response well within the species' limits. This feature is also the main motivation behind the separate identification of impact indices for sample points where Picea abies currently is the dominating species.

Finally, it is important to recognise the uncertainties involved with climate change scenarios. Although it is very probable that due to increased loading of the atmosphere with green house gases climate will change, direction and in particular magnitudes and rates of change are not yet clear. In the present study substantial efforts have been devoted to the construction of regionalized climate change scenarios. However, driving an ecosystem model with a climate change scenario by definition will result in a scenario of forest ecosystem development. In addition there is no reason to assume that climate change will come to a halt in 2050 as assumed in this assessment.

7 CONCLUSIONS

Considering the limitations of the presented approach as discussed above we conclude, that the potential impacts of climatic change on forests in Austria strongly depend on the magnitude of climatic changes. Under a moderate warming scenario with an average increase in temperatures of about +0.8 °C by the year 2050 (scenario scA) the simulated impacts were relatively low. However, under the assumptions of a temperature increase of +2.0 °C (scenario scB) and an eventual additional decrease in precipitation during the summer season of 15% by the year 2050 (scenario scC) the simulated impacts were substantially larger.

Under current climate (corresponding to average conditions of the period 1961-1995) 1.8% of all included sample points showed periodical tree mortality events where the magnitude of tree mortality by far exceeded “natural” tree mortality expected from self thinning. This percentage increased under scenarios of climatic change to 3.9% (scenario scA), 14.8% (scB) and 17.1% (scC) respectively. One major reason for this severe increase was due to improved biophysical conditions for bark beetle development on one side, and to decreasing soil moisture supply on the other side. The vulnerability of Picea abies to both, the insect and limited water supply, makes this species unsuitable as a crop species at elevations below today’s lower montane vegetation belt under conditions of scenarios scB and scC.

Closely related to the risk of increased tree mortality is the short- to midterm index SMS. The interpretation of the short- to midterm index SMS is relatively straightforward. Given that no management interventions occur, high-impact categories 4 and 5 indicate that currently existing forests are not well adapted to the prevailing site conditions, and are neither at their physiological nor ecological optimum. According to the model results it is highly probable that under climatic change conditions at such sites currently existing forests will not be able to meet societal demands. High short- to midterm impact on current Austrian forests due to climate change was expected to occur at 3.1% (scA), 12.1% (scB) and 13.7% (scC) of all included sample points respectively. Once more the marked increase in forest susceptibility from scenario scA (moderate warming) to scenario scB (strong warming) is obvious. The proportion of sample points with no considerable indications of climate change impact during the transient period 2000-2050 decreased from 70.9% under conditions of scenario scA to approximately 53% under scenarios scB and scC respectively. Almost all inventory points assigned to SMS categories 4 (substantial impact) and 5 (severe impact) occurred in today’s colline, submontane and lower montane altitudinal zones. Under climate change conditions of scenario scA (moderate warming) the ecoregions with the highest proportion such high-impact points were ecoregions 9 (Bohemian Massif), 7 (northern piedmont of the Alps) and 8 (eastern lowlands). Under conditions of scenarios scB (strong warming) and scC (strong warming, additional decrease in summer precipitation) sample points with indications of high short-/midterm impact expanded to ecoregions 6 (southern peripheral region of the Alps), 5 (eastern peripheral region of the Alps) and 4 (northern peripheral region of the Alps).

When compared with the simulated potential natural vegetation (PNV) under current climate approximately 50% of all species compositions at sample points as recorded by the Austrian Forest Inventory yielded a similarity value <0.5 (species grouped). Similar to the findings of a field-based study on the hemeroby of Austrian forests (Grabherr et al. 1998) similarity of current vegetation to simulated PNV under current climate (baseline scenario) increased with increasing altitude. This postulated "naturalness" of currently existing forests was substantially affected under conditions of a changing climate. Particularly under scenarios scB and scC at more than 60% of all involved sample points similarity was substantially decreased (reduction in similarity of one class width minimum). The proportion of sample points assigned to categories of the long-term index LI which indicated substantial to severe potential long-term impact of climatic changes increased from 1.2% under scenario scA to 25.8% under scenario scB and finally to 43.4% under conditions of scenario scC. These large percentages arose from the significant effect of increased temperatures at higher altitudes where according to the simulation results broad-leaved species were expected to play a substantial role in the natural species assemblage. Although unfavourable impact categories regarding the index LI do not mean that these forests will suffer from a breakdown as was indicated as corresponding high-impact categories of the short- to midterm index SMS, LI has the potential to reveal the eventually altered competitive status of tree species under altered climate which in turn might be used to adapt silvicultural strategies accordingly. Particularly at higher altitudes the silvicultural decision space increased substantially with regard to eligible tree species as well as to suitable natural regeneration systems. The increasing complexity of silvicultural decision making under conditions of a possible climate change increases the need for sound site-specific silvicultural planning methods. Though this study concentrated on possible adverse effects of climate change, simulation results indicated, that part of the involved inventory plots – in particular sites in today's montane vegetation zone with excellent water supply – might benefit from a warmer climate and showed increased biomass increment rates.

Although SMS and LI can be valuable indicators on their own, we combined both to an overall climate change impact index CCI. Within the overall impact index CCI higher weight was given to the short-/midterm response of the simulated forests. The percentage of sample points assigned to the least favourable overall climate change impact category 4 (severe impact) increased from 3.1% under scenario scA (moderate warming) to 12.1% under scenario scB (strong warming), and finally to 14.1% of all considered sample points under conditions of scenario scC (strong warming, additional decrease in summer precipitation). Such sites were particularly concentrated in the submontane (under both scB and scC) and in the lower montane zone (under scenario scC) where they comprised between 20% and 30% of all considered sample points. Within this group most forests as recorded by the Austrian Forest Inventory showed species compositions with dominating Norway spruce (Picea abies (L.) karst.). Similar increases were found for overall climate change impact category 3 (substantial impact). A comparison of regeneration data provided by the Austrian Forest Inventory for a subset of all involved sites with the simulated equilibrium species composition under conditions of climate change (i.e., possible future PNV) showed, that for the majority of sites with unfavourable overall impact ratings the currently available sapling pool is not sufficient for a transition to forests with broad-leaved tree species adapted to the site conditions. The share of sample points showing either none or low overall climate change impact (CCI impact category 1) decreased from 67% under conditions of scenario scA to 18% under scB, and finally to about 15% under conditions of scenario scC. Comparison of simulated forest responses under the three climate change scenarios indicated, that climate change conditions as represented by scenario scA (moderate warming) seemed to characterise a threshold beyond which the severity of potential climate change impacts might increase substantially.

Finally there are two important points to be addressed when interpreting the results of the present study. Firstly, it is important to recognise the uncertainties involved with climate change scenarios. Driving an ecosystem model with climate change scenario data by definition will result in a scenario of forest ecosystem development. In addition there is no reason to assume that climate change will come to a halt in 2050 as assumed in deriving the long-term impact indices in this study. Secondly, several sources of uncertainty in the employed forest model have to be considered (model structure, model parameters) when interpreting the simulation results. From this we might conclude that climate change impact studies do not have predictive value but rather are sensitivity tests of how a forest ecosystem might respond under a range of specified conditions which may never occur in reality (Bugmann 1997). However, beyond this reminder the presented approach is well suited to identify regions and conditions where the impacts of a changing climate might be severe. The development of mitigation strategies for regions/conditions were severe impact of climatic change is probable remains a challenging task. To develop optimised management strategies within a multiple-purpose forestry under uncertain future climatic conditions requires (1) the consideration of models that are responsive to both, environmental changes and forest management interventions, (2) the consideration of spatial scales beyond the stand level, and (3) multiple criteria decision making techniques to model the trade-offs between conflicting objectives based on the preferences of the involved decision makers.

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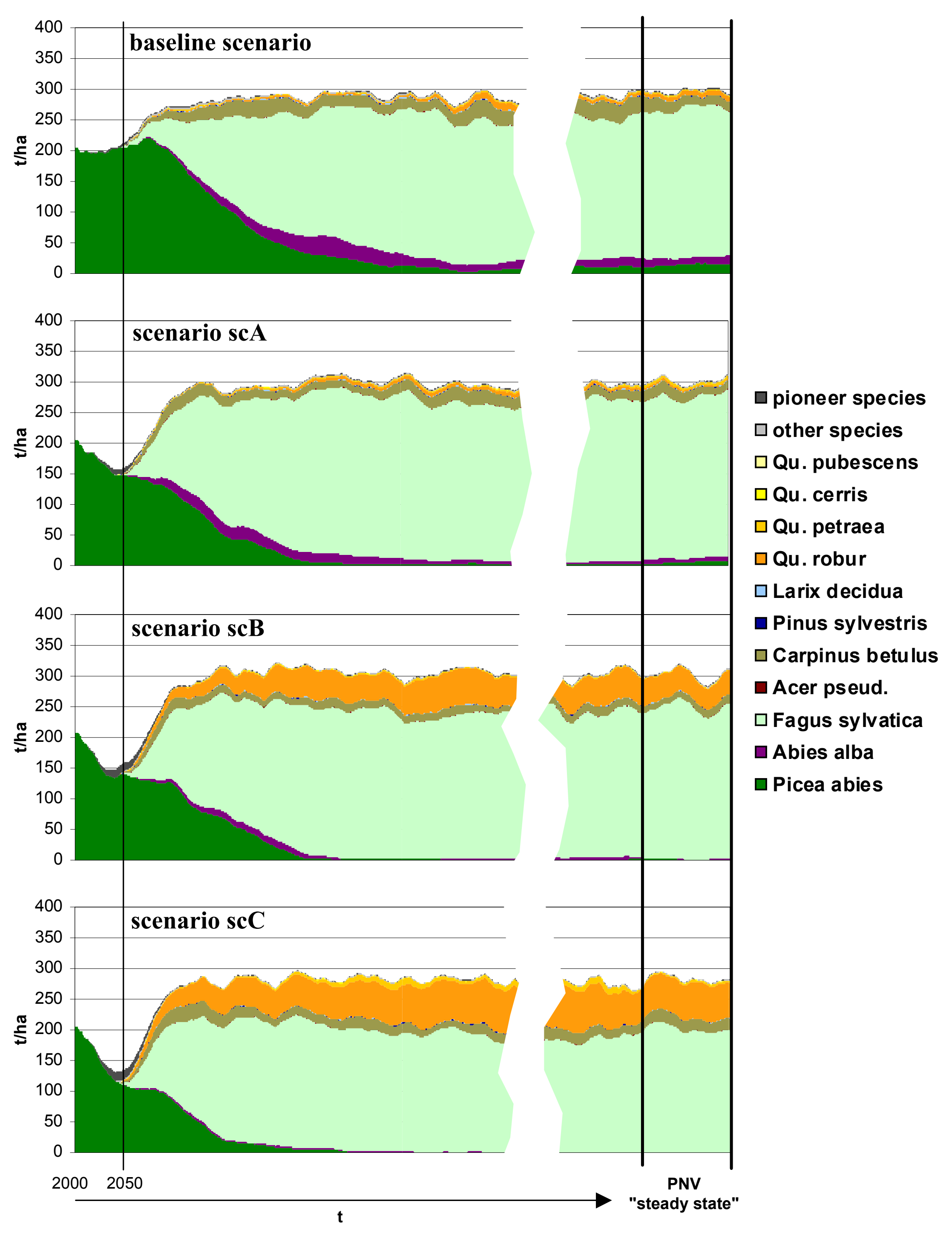
Annex 1

Enclosed are 6 examples to demonstrate the concept applied within the present study to analyse the potential impacts of climatic change on current forests. Each example consists of a series of 4 Figures each showing the simulated vegetation development under current climate (baseline) and three climate change scenarios (scA, scB, scC) starting from current stand composition as recorded by the Austrian Forest Inventory. In Table A1-1 the corresponding impact indices as employed in the presented study are shown.

Table A1-1. Climate change impact indices SMS (short- to midterm), LI (long-term) and overall climate change impact index CCI for 6 demonstration examples (Figures A1-1-6).

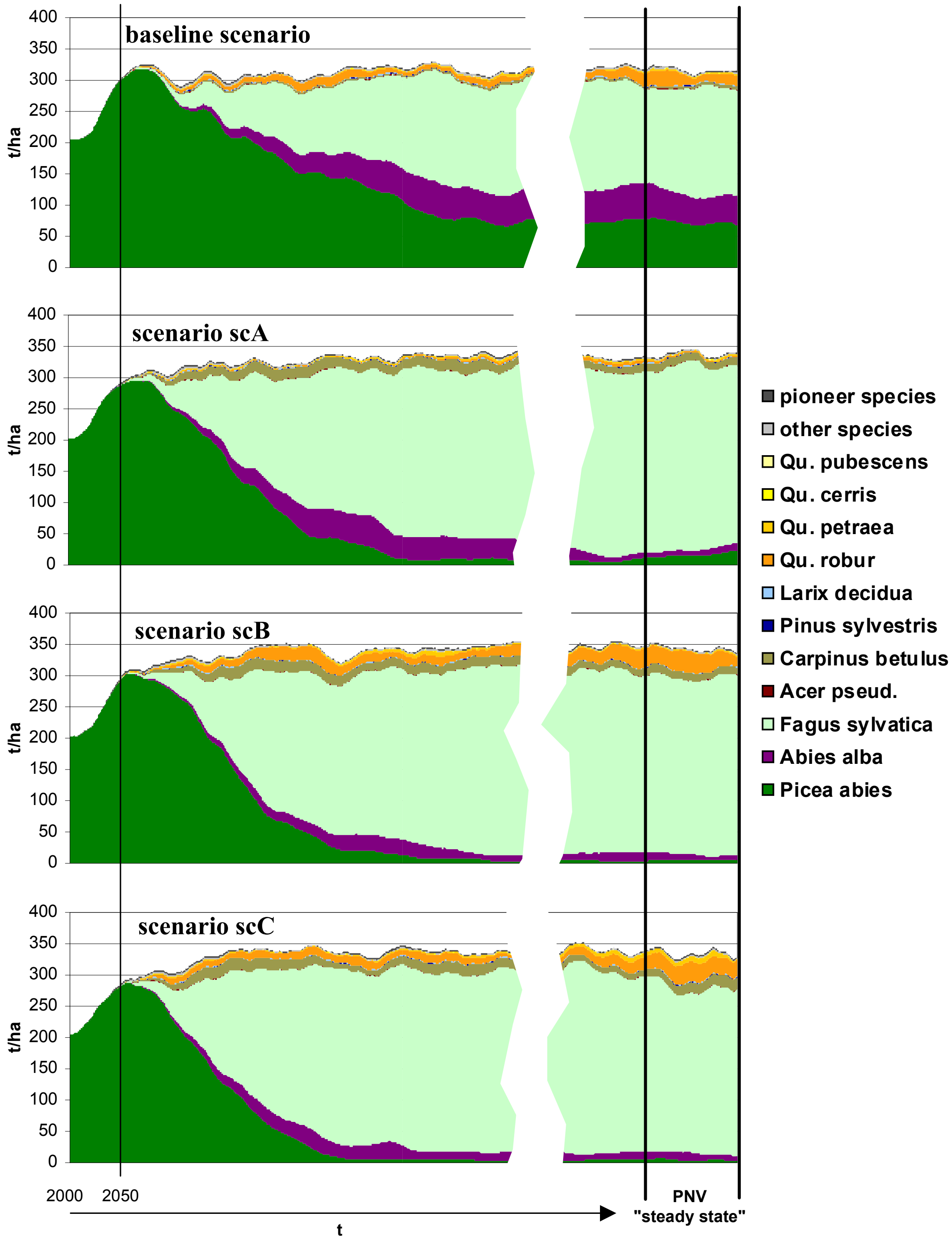
Tab. A1-1: Indikatoren für den Effekt von Klimaänderungsszenarios SMS (kurz-/mittelfristig), LI (langfristig) und allgemeiner Klimafolgenindikator CCI für die 6 Demonstrationsbeispiele (vgl. Abb. A1-1 bis A1-6).

Example No.	**scA**			**scB**			**scC**		
	SMS	**LI**	**CCI**	**SMS**	**LI**	**CCI**	**SMS**	**LI**	**CCI**
1	3	1	3	4	2	4	4	2	4
2	1	2	1	1	3	2	1	3	2
3	1	2	1	1	2	1	1	3	2
4	1	2	1	1	3	2	1	3	2
5	1	2	1	1	3	2	1	3	2
6	1	2	1	1	3	2	1	4	2



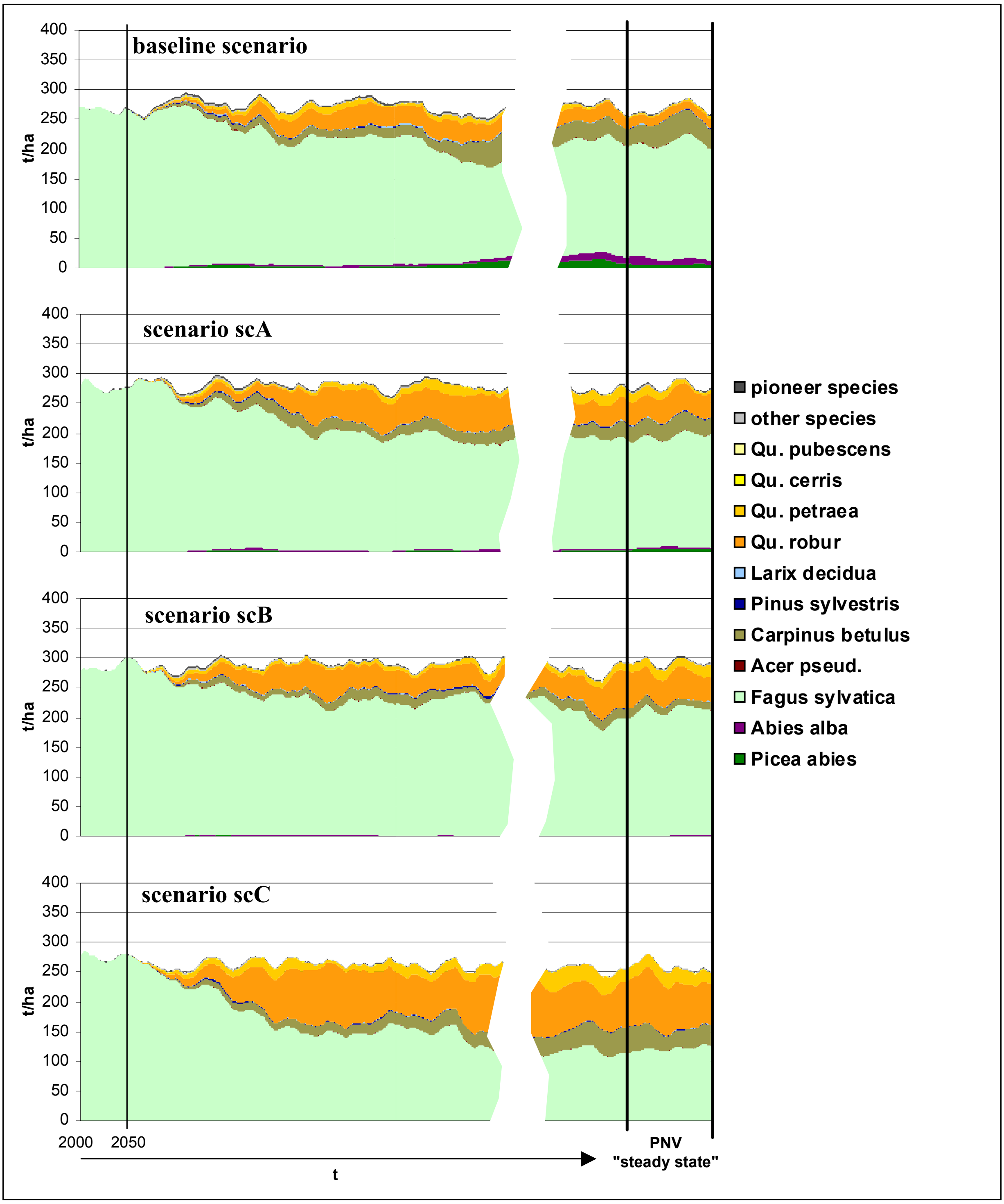
Example A1-1. Simulated secondary Norway spruce stand in the submontane zone in ecoregion 7 according to Kilian et al. (1994) (northern piedmont of the Alps) under current climatic conditions (baseline scenario) (top) and three climate change scenarios (scA, scB, scC).

Beispiel A1-1: Simulierter sekundärer Fichtenwald in der submontanen Höhenstufe (Hauptwuchsgebiet 7) unter aktuellem Klima und drei Klimaänderungsszenarios (scA, scB, scC).



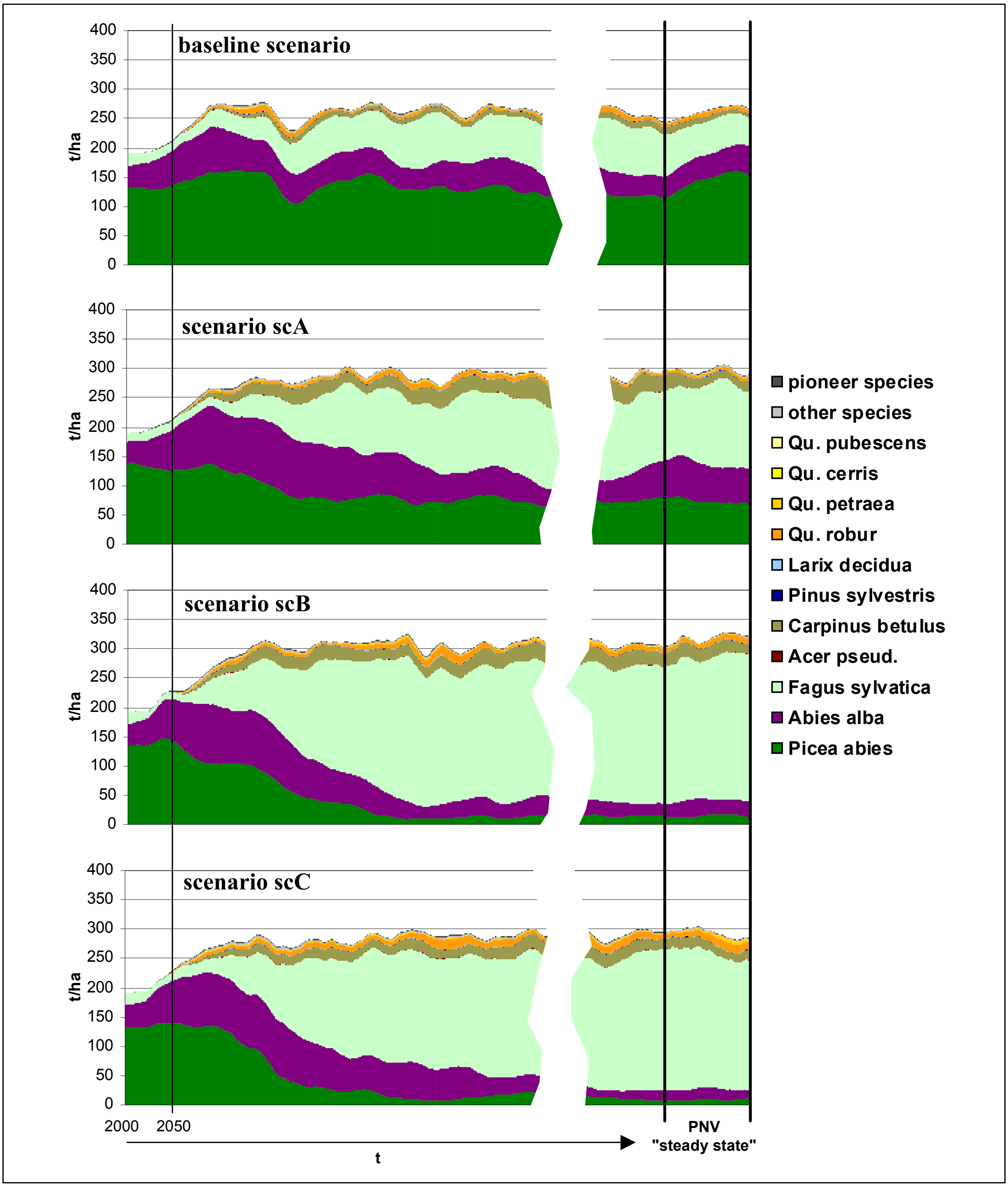
Example A1-2. Simulated secondary Norway spruce stand in the lower montane zone at a site in ecoregion 4 according to Kilian et al. (1994) (northern peripheral region of the Alps) under current climatic conditions (baseline scenario) (top) and three climate change scenarios (scA, scB, scC).

Beispiel A1-2: Simulierter sekundärer Fichtenwald in der tiefmontanen Höhenstufe (Hauptwuchsgebiet 4) unter aktuellem Klima und drei Klimaänderungsszenarios (scA, scB, scC).



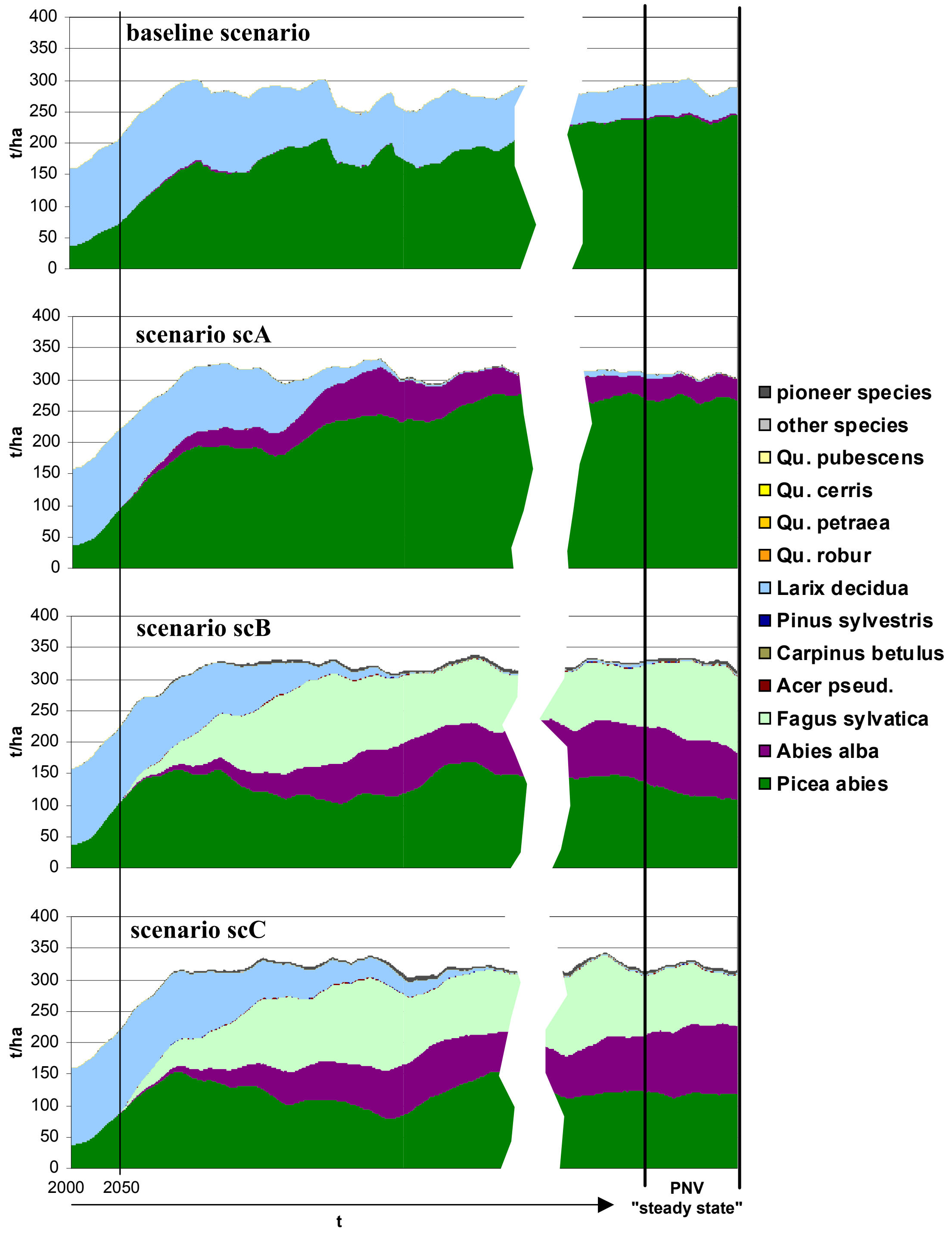
Example A1-3. Simulated beech stand in the submontane zone in ecoregion 4 according to Kilian et al. (1994) (northern peripheral region of the Alps) under current climate (baseline scenario) (top) and three climate change scenarios (scA, scB, scC).

Beispiel A1-3: Simulierter Buchenwald in der submontanen Höhenstufe (Hauptwuchsgebiet 4) unter aktuellem Klima und drei Klimaänderungsszenarios (scA, scB, scC).



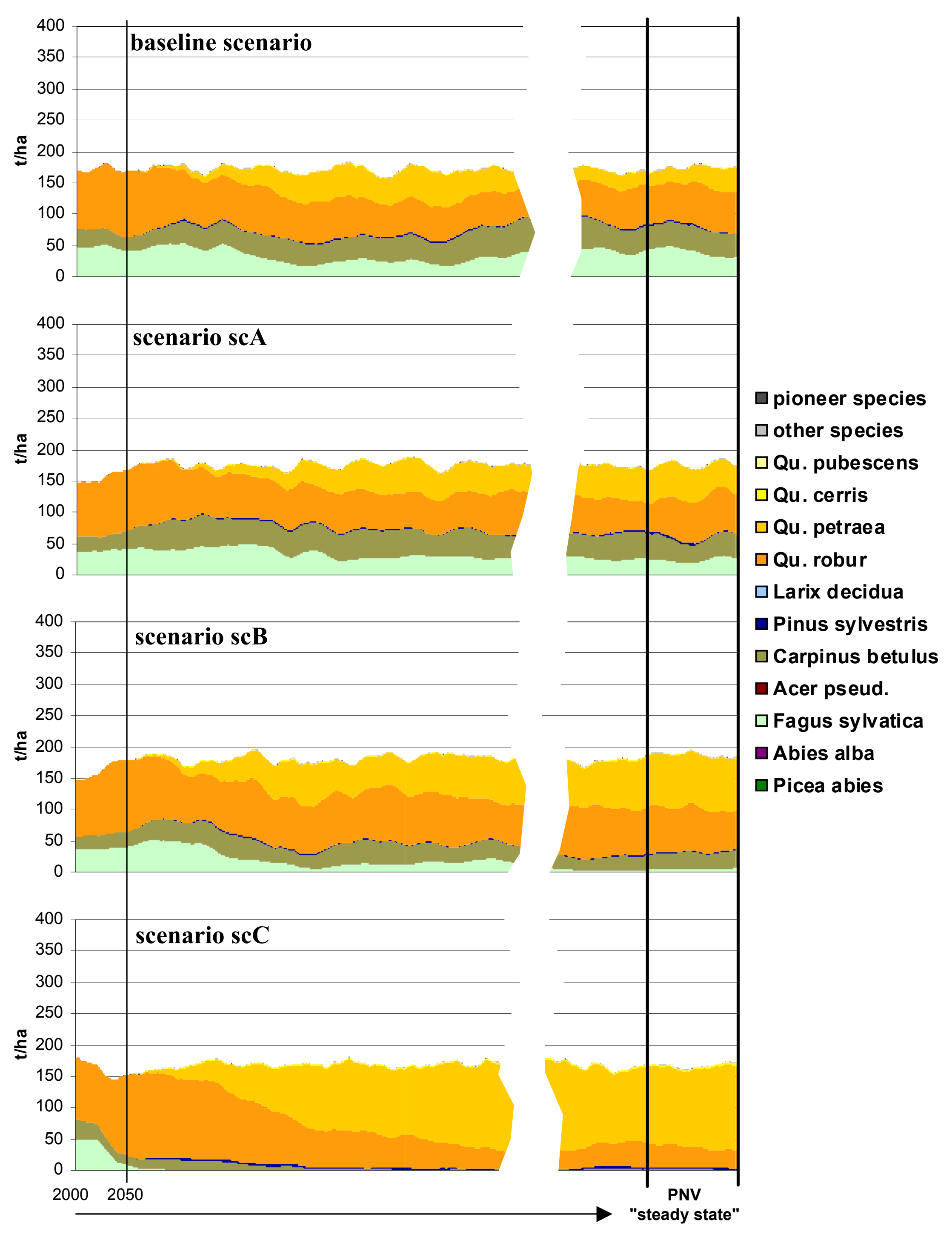
Example A1-4. Simulated "close to nature" mixed spruce/fir/beech-stand in the montane vegetation zone in ecoregion 4 according to Kilian et al. (1994) (northern peripheral region of the Alps) under current climate (baseline scenario) (top) and three climate change scenarios (scA, scB, scC).

Beispiel A1-4: Simulierter "naturnaher" Fichten/Tannen/Buchenwald in der montanen Höhenstufe (Hauptwuchsgebiet 4) unter aktuellem Klima und drei Klimaänderungsszenarios (scA, scB, scC).



Example A1-5. Simulated larch/spruce – stand in the lower subalpine zone in ecoregion 2 according to Kilian et al. (1994) (northern transitional region of the Alps) under current climate (baseline scenario) (top) and three climate change scenarios (scA, scB, scC).

Beispiel A1-5: Simulierter sekundärer Fichtenwald in der unteren subalpinen Höhenstufe (Hauptwuchsgebiet 2) unter aktuellem Klima und drei Klimaänderungsszenarios (scA, scB, scC).



Example A1-6. Simulated "close to nature" mixed oak/hornbeam stand in the colline vegetation zone in ecoregion 8 according to Kilian et al. (1994) (eastern lowlands) under current climate (baseline scenario) (top) and three climate change scenarios (scA, scB, scC).

Beispiel A1-6: Simulierter "naturnaher" Eichen/Hainbuchenwald in der kollinen Höhenstufe (Hauptwuchsgebiet 8) unter aktuellem Klima und drei Klimaänderungsszenarios (scA, scB, scC)

Annex 2

Table A2-1. Modified table for regular densities of regeneration based on Table 7.6.4 in FBVA (1995).

Tab. A2-1: Richtgrößen für waldbaulich erforderliche Mindestpflanzenzahlen nach FBVA (1995, Tabelle 6.6.4) (modifiziert).

Species	Height class 10-50 cm [N/100 m^2]	Height class 50-130 cm [N/100 m^2]
Picea abies	35	30
Abies alba	35	30
Larix decidua	25	20
Pinus sylvestris	60	55
Fagus sylvatica	120	100
Quercus spp.	120	100

Annex 3

Table A3-1. The main ecoregions (i.e., growth districts) of Austria based on Kilian et al. (1994).

Tab. A3-1: Die Hauptwuchsgebiete in Österreich nach Kilian et al. (1994).

main ecoregion No.	description
1	interior region of the Alps
2	northern transitional region of the Alps
3	southern transitional region of the Alps
4	northern peripheral region of the Alps
5	eastern peripheral region of the Alps
6	southern peripheral region of the Alps
7	northern piedmont of the Alps
8	eastern lowlands
9	Bohemian Massif

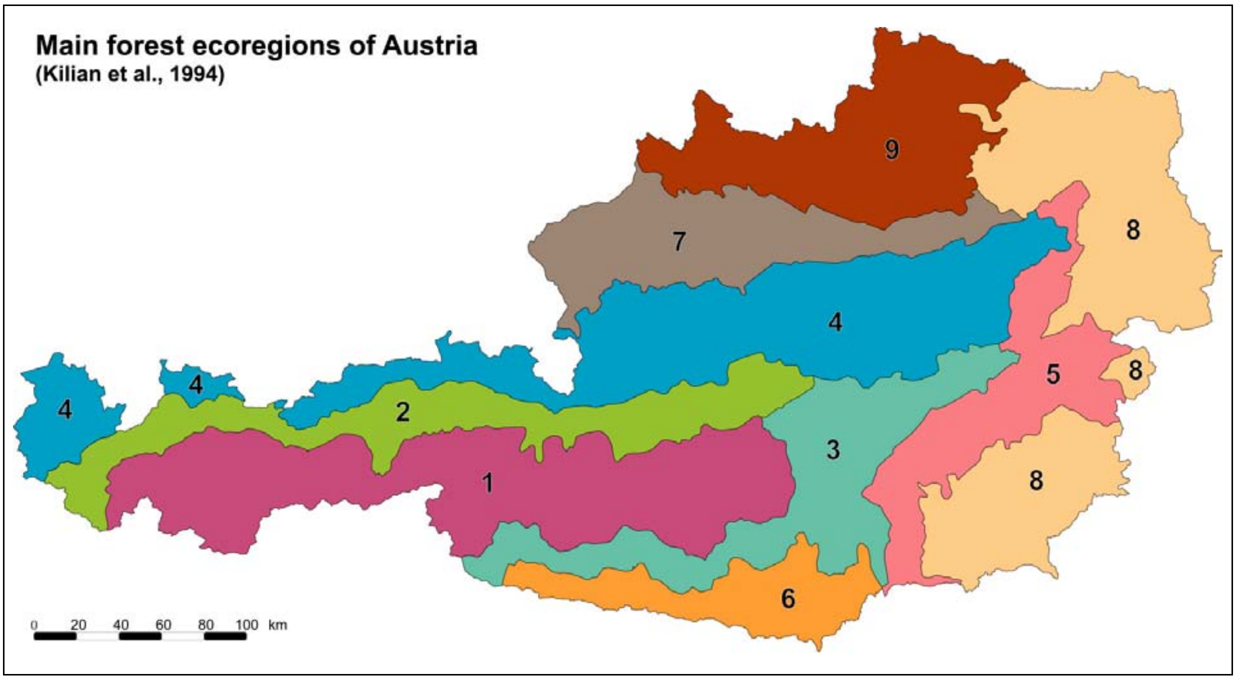


Figure A3-1. The main ecoregions of Austria according to Kilian et al. (1994). For explanation see Table A3-1.

Abb. A3-1: Die Hauptwuchsgebiete in Österreich nach Kilian et al. (1994). Für Erklärung siehe Tabelle A3-1.

Annex 4

Table A4-1a. Altitudinal zones in the main ecoregions in Austria according to Kilian et al. (1994) (modified).

Tab. A4-1a: Höhenstufengliederung in den Hauptwuchsgebieten Österreichs (nach Kilian et al. 1994, verändert).

ecoregion	altitudinal zone	elevation [m]	
		from	to
1	colline	-	-
	submontane	600	1000
	lower montane	850	1150
	montane	1100	1400
	upper montane	1400	1850
	subalpine	1500	2300
2	colline	-	-
	submontane	500	850
	lower montane	700	1000
	montane	900	1400
	upper montane	1100	1600
	subalpine	1400	2150
3	colline	-	-
	submontane	450	950
	lower montane	650	1300
	montane	900	1450
	upper montane	1200	1800
	subalpine	1400	2200
4	colline	-	-
	submontane	400	700
	lower montane	550	1000
	montane	700	1400
	upper montane	1100	1600
	subalpine	1300	2000
5	colline	200	400
	submontane	300	700
	lower montane	600	1000
	montane	800	1200
	upper montane	1100	1500
	subalpine	1400	2050
6	colline	-	-
	submontane	350	800
	lower montane	700	1100
	montane	1000	1300
	upper montane	1250	1700
	subalpine	1500	2100
7	colline	200	300
	submontane	250	550
	lower montane	600	800
	montane	-	-
	upper montane	-	-
	subalpine	-	-

Table A4-1b. Altitudinal zones in the main ecoregions in Austria according to Kilian et al. (1994) (modified).

Tab. A4-1b: Höhenstufengliederung in den Hauptwuchsgebieten Österreichs (nach Kilian et al. 1994, verändert).

ecoregion	**altitudinal zone**	**elevation [m]**	
		from	**to**
8	colline	100	400
	submontane	250	700
	lower montane	-	-
	montane	-	-
	upper montane	-	-
	subalpine	-	-
9	colline	200	350
	submontane	200	700
	lower montane	500	950
	montane	600	1100
	upper montane	1000	1300
	subalpine	1100	1400