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Evaluating thermal treeline indicators based on air and soil temperature using an air-to-soil temperature transfer model ☆

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ABSTRACT

In recent research, both soil (root-zone) and air temperature have been used as predictors for the treeline position worldwide. In this study, we intended to (a) test the proposed temperature limitation at the treeline, and (b) investigate effects of season length for both heat sum and mean temperature variables in the Swiss Alps. As soil temperature data are available for a limited number of sites only, we developed an air-to-soil transfer model (ASTRAMO). The air-to-soil transfer model predicts daily mean root-zone temperatures (10 cm below the surface) at the treeline exclusively from daily mean air temperatures. The model using calibrated air and root-zone temperature measurements at nine treeline sites in the Swiss Alps incorporates time lags to account for the damping effect between air and soil temperatures as well as the temporal autocorrelations typical for such chronological data sets. Based on the measured and modeled root-zone temperatures we analyzed the suitability of the thermal treeline indicators seasonal mean and degree-days to describe the Alpine treeline position. The root-zone indicators were then compared to the respective indicators based on measured air temperatures, with all indicators calculated for two different indicator period lengths. For both temperature types (root-zone and air) and both indicator periods, seasonal mean temperature was the indicator with the lowest variation across all treeline sites. The resulting indicator values were 7.0 °C ± 0.4 SD (short indicator period), respectively 7.1 °C ± 0.5 SD (long indicator period) for root-zone temperature, and 8.0 °C ± 0.6 SD (short indicator period), respectively 8.8 °C ± 0.8 SD (long indicator period) for air temperature. Generally, a higher variation was found for all air based treeline indicators when compared to the root-zone temperature indicators. Despite this, we showed that treeline indicators calculated from both air and root-zone temperatures can be used to describe the Alpine treeline position.

1. Introduction

It has long been recognized that the position of the climatic treeline is primarily temperature driven with other factors operating as modulating agents rather than as the main determinants (Körner, 1998; Körner and Paulsen, 2004). Early in the 20th century treeline research already found the position of the treeline to be related to temperature and defined tree-

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line indicators such as mean air temperature of the warmest month of ca. 10 °C (Brockmann-Jerosch, 1919; Köppen, 1919) or number of days with means of air temperatures above 5 °C (Ellenberg, 1963). Later, research concentrated on investigating the processes and mechanisms that underlie the correlations between environmental factors and the treeline, and in general also found the thermal regime to be the most powerful explanation for the potential treeline position (Körner, 1998; Jobbagy and Jackson, 2000). Current research focuses on the sink hypothesis, stating that growth is limited by meristem activity which declines at low temperatures (Körner, 1998; Hoch et al., 2002). Several studies have shown that tree growth is constrained by air temperature, with a growth inhibition temperature threshold varying between 3 and 10 °C, but concentrating on the band from 5.5 to 7.5 °C (Körner, 1998, 2003). The latter is also most commonly associated with seasonal means of air temperature at treeline positions (Körner, 1998). But also soil temperature limitations for tree growth have been documented in experiments (for references see Holtmeier, 2003; Körner and Paulsen, 2004). Körner and Paulsen (2004) suggested a soil temperature based indicator to explain the potential treeline, and found a seasonal mean of 6.7 °C ± 0.8 SD for the root-zone temperature to best correspond to the treeline position worldwide. Overall, findings from these studies suggest that air and soil temperatures are physically limiting tree growth at the treeline. Disentangling the individual effect of both temperature types on the vegetation is difficult, because of their close relationship with general meteorological conditions such as solar radiation. Moreover, as meristems occur both below- and above-ground, temperature limitations could indeed stem from one or both air and soil temperature.

Hence, it is important to understand the relationship between air and soil temperature at the treeline as well as its consequence for potential treeline indicators. To analyze such temperature relationships, large-scale soil and air temperature data is needed. While air data can be spatially interpolated from nearby meteorological stations, e.g. using interpolation algorithms such as implemented in DAYMET (Thornton et al., 1997, 2000), PRISM (Precipitation elevation Regressions on Independent Slopes Model; Daly et al., 1994) or ANUSPLIN (Hutchinson, 1995), interpolating soil temperature data to achieve regional coverage is difficult. This is mainly due to (a) the absence of a universal physical model that would allow for easy data interpolation like altitude lapse rates for air temperature (Green and Harding, 1980; Richardson et al., 2004), and (b) the general lack of spatially distributed soil measurements. A promising alternative to extensive field measurement campaigns is thus to develop and apply an air-to-soil temperature transfer model to calculate soil temperature from the more easily available average daily air temperatures. This would allow using continuously measured climatic data from permanent weather stations to estimate soil temperatures. Up to now, only few attempts have been made to derive soil temperatures from air temperatures alone. Most existing models use several additional parameters such as soil surface energy balance, precipitation, topography, surface cover, soil thermal diffusivity, or forest stand characteristics (Thundholm, 1990; Yin and Arp, 1993; Kang et al., 2000; Paul et al., 2004; Bond-Lamberty et al., 2005). Measuring or deriving these additional variables across a larger area is costly and laborious and consequently, these models are less suited for wide-area coverage. Toy et al. (1978) have used air temperature exclusively to estimate mean annual, seasonal and monthly soil temperatures. But while their model accurately calculates mean values, it does not allow the estimation of temperature variation needed to describe ecosystem processes at shorter, e.g. daily intervals. More recently, Brown et al. (2000) have predicted daily mean soil temperatures using mean air temperatures of the previous day, thereby considering the time-lag effect of air on soil temperatures. However, none of these models have accounted for the strong temporal correlation of the chronological temperature data, with the resulting model errors diminishing the model quality and accuracy.

A further difficulty relevant for temperature based treeline modeling is the definition of the measurement period, i.e. the time span used to calculate potential indicator values. As soil temperatures below 0 °C bear less biological meaning (Körner and Paulsen, 2004) the growing season can be defined as the snowfree period. Körner and Paulsen (2004) have defined the beginning of the season as the date at which the soil temperatures exceed 3.2 °C in spring and the end as the date at which the soil temperature sinks below 3.2 °C for the first time in autumn. According to their analysis, these soil temperatures correspond to a weekly mean canopy air temperature of 0 °C. Schmitt et al. (2004) based their observations of growth limitations on a much shorter period than what is perceived as the growing season. They investigated cambium dynamics of pine and birch at the northern Boreal treeline and found that wood formation was finished as early as by the beginning of August (birch), respectively within the first half of August (pine). This corresponds to earlier results of Zumer (1969) who found wood formation in pine to begin with a slight delay as altitude increased, whereas it stopped simultaneously for all monitored trees independently of their altitude. Kirdyanov et al. (2003) also concluded that besides the date of snow melt, the early summer temperatures are the most important factor defining seasonal growth and tree-ring structure, and Vaganov et al. (1999) identified a period of a few weeks after snowmelt to have the highest correlation with diameter increments in Boreal treeline trees. All these results suggest that whereas the beginning of wood formation is depending on temperature development, the end may not be as dynamic, potentially allowing a simplified approach to model treeline indicators. Yet, climatic treeline position may not fully follow the same drivers as radial tree growth. Additional processes may influence its position, such as maturing of wood cells and hardening of cells for the winter season (for references see Plomion et al., 2001), or higher level processes such as regeneration cycles (Zackrisson et al., 1995; Holtmeier, 2003).

The purpose of our study was threefold. First, we intended to develop a new air-to-soil temperature transfer model to calculate daily mean soil temperatures from daily mean air temperatures optimized for treelines. To allow for time-lag effects between air and soil temperatures, the model was set up to include current as well as past air temperatures, and to handle temporal autocorrelation statistically correctly. Second, we aimed at evaluating the usability of several thermal treeline indicator values calculated based on air and soil temperatures, derived from eight daily temperature measurements rather than from monthly means. Third, we wanted to

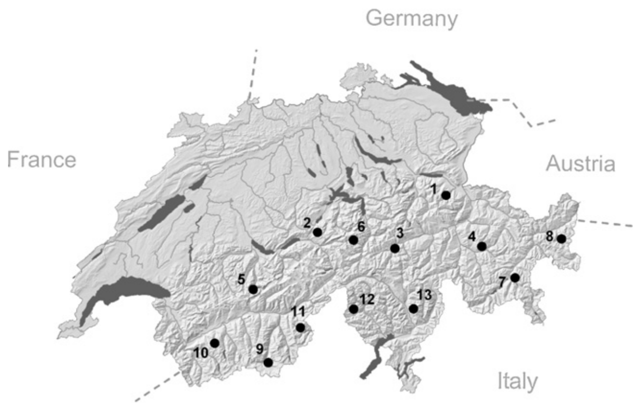

Fig. 1 – Location of study sites in the Swiss Alps. Numbers refer to sites described in Table 1.

compare several season lengths used for the calculation of the thermal treeline indicators.

2. Material and methods

2.1. *Study sites*

In this study, we focused on climatic treelines. In accordance with Körner and Paulsen (2004) we used two criteria to identify treelines that have reached their climatic potential. Specifically, we selected (1) the highest position of treeline stands in a region and (2) stands, where trees showed a rapid reduction in size along elevational gradients. The regionally highest forest patches were selected by GIS analyses. Based on the 1:25,000 pixel maps of Switzerland, we calculated the treeline by identifying the highest forest areas in a quadratic 900 m × 900 m moving search window (Paulsen and Körner, 2001; Gehrig-Fasel et al., 2007). The resulting positions were then compared with the Swiss land use statistics GEOSTAT (SFSO, 2001), and treelines with buildings or intensive agricultural use in the neighborhood were eliminated as non-climatic treelines. We additionally excluded areas where the highest forest patches reached the very tops of peaks or ridges or where they bordered directly to rock areas above. The remaining treeline positions were presumed to be of climatic nature. From these climatic treeline areas, we chose 13 study sites in four different climatic regions of Switzerland: the Northern Prealps, the Northern Transition zone, the Central Alps, and the Insubrian Southern Alps. Since the Southern Swiss Alps lack mountain systems reaching above the potential treeline, two sites in the transition zone between the Central and the Southern Alps were selected to at least partly represent this climatic domain. The geographic locations of the selected sites and their characteristics are shown in Fig. 1 and Table 1.

2.2. *Temperature measurement*

In order to measure air and soil (root-zone) temperatures at the climatic treeline, a total of 400 electronic miniature temperature loggers (iButton Thermachron® DS1921-L) were placed at the 13 sites. The iButton loggers measure temperature in a range from −20 to +80 °C with a 0.5 °C resolution. The accuracy of these loggers was tested by Gehrig (2004) by comparing their recordings to the data of an automatic meteorological station operated by the Swiss Federal Research Institute WSL. He analyzed the temperature gradient by using correlation analyses and spectral analytical methods and found the loggers to be suitable for local temperature measurements. The iButtons' compact size (1.7 cm diameter, 0.6 cm thickness) and their low cost allow for locally high density spatial measurement in the field. With the sensor enclosed in a waterproof stainless steel case and an internal battery lasting for up to 10 years (manufacturer's specifications), long-term observations on a local level are possible. We recorded data from fall 2003 to fall 2005, measuring in 3-h time intervals allowing for maximum resolution with the lim-

Table 1 – Characteristics of selected study sites

Climate sector	Site no.	Elevation (m)	Aspect (°)	Tree species at treeline	Recording period (y/m/d; from – to)
Northern Prealps					
Weisstannen: Chämmli	1	2019	180	*Picea abies*	2004/07/23–2005/09/23
Lungern: Güpfi	2	1961	180	*Picea abies*	2003/09/29–2005/09/27
Northern Transition Zone					
Disentis: Stavel Sura	3	2161	210	*Picea abies*	2003/10/14–2005/09/15
Alvaneu: Era da Mulain	4	2181	160	*Picea abies*, *Pinus mugo*	2003/10/12–2005/09/16
Spittelmatte: Sagiwald	5	2126	270	*Pinus cembra*, *Larix decidua*	2003/10/03–2005/09/10
Susten: Wielesch	6	1943	220	*Picea abies*, *Larix decidua*	2003/10/17–2005/09/24
Central Alps					
Pontresina: Laviner	7	2341	220	*Pinus cembra*, *Larix decidua*	2003/09/24–2005/09/20
S-charl: Mot Madlain	8	2349	190	*Pinus cembra*	2003/09/23–2005/09/21
Zermatt: Grüensee	9	2423	350	*Larix decidua*, *Pinus cembra*	2003/10/05–2005/09/14
Nendaz: L'Arpette	10	2325	300	*Pinus cembra*, *Larix decidua*	2003/10/13–2005/09/28
Simplon: Spilbode	11	2288	280	*Larix decidua*	2003/09/27–2005/09/13
Insubrian Southern Alps					
Bosco Gurin: Stavel Crastu	12	2119	156	*Picea abies*, *Larix decidua*	2003/09/26–2005/09/30
Cresciano: Cima di Piancra bella	13	2177	45	*Picea abies*, *Larix decidua*	2004/10/25–2005/10/01

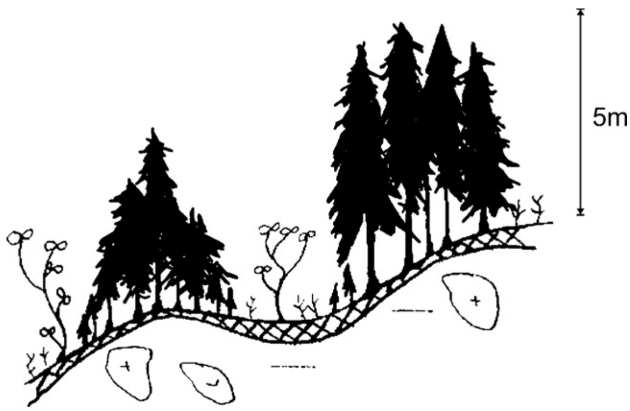

Fig. 2 – Illustration of tree clusters, modified after Ott et al. (1997).

ited memory space of the iButton loggers. Twice a year, the data from all loggers was downloaded through an interface to a handheld computer.

A series of loggers were positioned at each selected treeline location. We defined the treeline as the line which connects the highest tree clusters. Tree clusters are small groups of trees growing very closely together, usually surrounded by smaller trees with low reaching crowns and branches (Fig. 2). As these groups slowly expand, depending on (local) climatic conditions, they potentially develop into larger forest patches. We chose sample trees with a minimum height of 5 m because we observed this to be the typical size of such tree clusters. Trees with a height of less than 5 m were observed to generally grow alone, unprotected against strong wind, snow, and temperature extremes, thus representing the "combat zone" above the tree clusters. The height of these trees declined rapidly with increasing altitude, finally forming krummholz only.

For our temperature measurements on each site, we selected trees inside a cluster. Where no clusters were available, free-standing trees were used. Per site, three trees were selected along elevation contours at the potential treeline. Two loggers were placed at each tree: one buried 10 cm below the soil surface to capture the root-zone temperature of the trees (Körner and Paulsen, 2004) and one in the outer canopy, attached to a branch approximately 2 m above ground, to record the air temperature. All loggers were attached or buried on the north facing side of the trees to avoid direct sunlight as far as possible.

2.3. Data analysis

The recorded temperature data was screened for potential direct sunlight exposure leading to peaks in measured temperature. None of the root-zone temperature loggers showed any signs of excessive heating whereas a few air temperature loggers showed peaks in single measurements that may be attributable to direct sunlight influence. To minimize effects of such local measurement biases, daily mean values based on eight measurements (3 h time intervals) were calculated and averaged over three trees for each study site and used in the following analyses.

From the originally 13 sites, 2004 data from four sites was not used in the soil-to-air transfer model fitting process due to missing data (Cresciano and Weisstannen) or technical measurement biases (Bosco and S-charl). Consequently, we used daily mean values of the remaining nine study sites for model fitting and further analyses. However, for the soil-to-air model evaluation, we were able to apply the model to the complete soil data of all 13 sites for 2005.

2.4. Developing an air-to-soil transfer model (ASTRAMO)

Temperature data measured over time often displays trends and strong temporal correlations, which normally prevent direct regression modeling of such data series. With time series analysis and regression methods, however, these problems can be circumvented. In the following paragraphs, we describe the reasoning and methodological basics behind our approach to an air-to-soil transfer model.

To build a reliable time series regression model, the data series should be stationary, i.e. the mean values as well as variance and autocorrelation structures must be constant over time (Chatfield, 2004). This allows modeling of the data series relationships without the disturbing influences of trends or inconsistent variances. A simple way to mitigate trends is to subtract a smoother from the input data that is later added again to the model output (as an empirical parameter in the regression model; Fig. 3: steps 1 and 5). In our approach, we investigated different empirical smoothers to find the one which best described the seasonality of the air temperature data. The trend curve, after being temporarily removed from the input data for the regression modeling, can be added to the fitted data afterwards to reproduce the seasonal rise and fall of the temperature data (Fig. 3: step 5).

A further characteristic of regression modeling between time series is the general implication that the model errors are autocorrelated., e.g. temperatures do not change arbitrarily from measurement to measurement but rather display a continuous progression. This leads to the effect that positive deviations from a model value are most likely followed by more positive deviations. Consequently, as uncorrelated errors are a prerequisite for statistical least square calculation, the variance of model estimators as well as confidence intervals and significances for autocorrelated data are unreliable in this case. To eliminate short-term autocorrelations, the model input data (both the explanatory and response variables) can be transformed into first differences (Fig. 3: step 2, Chatfield, 2004; Huerzeler, 2004): instead of modeling each data value T_t in time, the model is built on the value difference between the current and the next day:

$$\mathrm{diff}(T_t) = T_{t+1} - T_t \qquad (1)$$

where: T = daily mean temperature; t = current day, $t+1$ = following day.

The resulting data usually shows a lower degree of periodicity and can thus be used for time series regression modeling (Fig. 3: step 3). The output from such a time series regression model represents estimates for first differences of the original response variable. These values can then be re-transformed

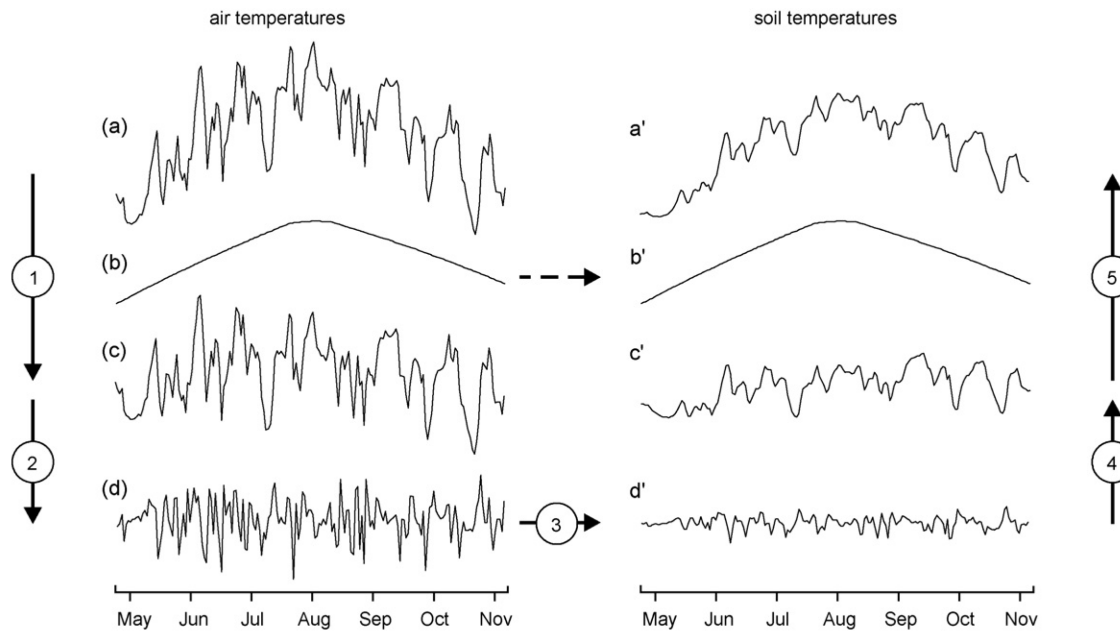

Fig. 3 – Air-to-soil transfer model approach: step (1) seasonal trend decomposition; step (2) transformation to first differences; step (3) time series regression modeling (Eq. (2)); step (4) re-transformation of first differences to non-differentiated values; step (5) reproduction of seasonal trend by adding original smoother curve. (a) Measured daily mean air temperatures; (b) seasonal trend of air temperature; (c) residuals (air-trend); (d) first differences (see Eq. (1)), (a′) modeled daily mean soil temperatures; (b′) = (b) seasonal trend of air temperature; (c′) re-transformed daily mean soil temperature values (without trend); (d′) modeled first differences of daily mean soil temperatures.

to the non-differentiated form corresponding to the original input data by cumulatively adding the output values to a start value (Fig. 3: step 4). In our case, we used a linear regression model to calculate a soil temperature start value.

Using the above methods to improve the time series regression model, we were able to fit an air-to-soil transfer model using daily mean values of air and soil temperatures in 2004 from nine treeline sites. The following paragraphs describe the model building process in detail with references to the visualization in Fig. 3.

First, we removed seasonal trends from the input temperature data (air and soil) by subtracting an empirical trend curve (Fig. 3a–c). Different smoothers were tested to describe the seasonal trend: locally weighted linear scatter plot smoothers (lowess and stl), and a cubic spline interpolation (for references see Hastie and Tibshirani, 1990). These smothers were all calculated based on the daily mean air temperature data averaged over nine treeline sites for the period from May to November 2004, with a stiff lowess smoother best describing the seasonal trend (Fig. 4). In order to also investigate a smoother independent from the measured data of the year 2004, we also calculated a “historic” lowess smoother based on 2 m above-ground air data of 18 Swiss meteorological stations in the treeline range from the years 1961 to 2005. This smoother described the seasonal trend of the year 2004 surprisingly well, though with a slightly lower fit than when using the smoother of the year 2004 only. To develop the air-to-soil transfer model, we therefore used a lowess smoother from the year 2004 with a stiffness (smoother span)

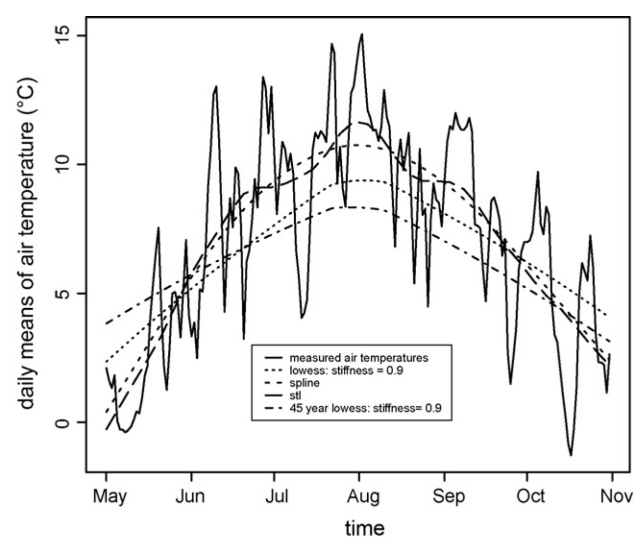

Fig. 4 – Measured daily mean air temperatures averaged over nine treeline sites for the period of Mai to November 2004 with different kind of smoothers representing the seasonal trend of the data. Lowess, spline and stl smoothers were calculated based on the measured 2004 air data of nine treeline sites, the 45-year lowess smoother was calculated based on air data from 18 Swiss meteorological stations from 1961 to 2005. The single year lowess smoother with a stiffness 0.9 (dotted line) was used in the air-to-soil transfer model.

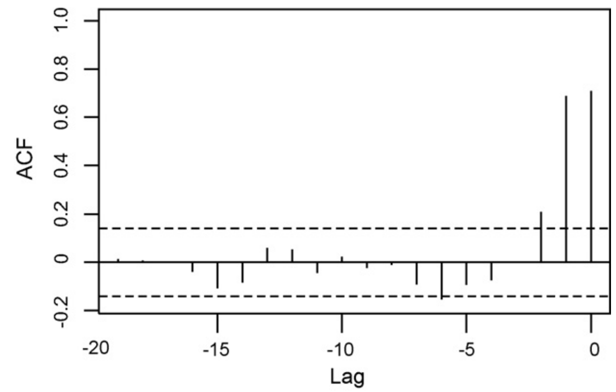

Fig. 5 – Cross-correlogram of the first difference values of 2004 daily mean temperatures, showing the temporal relationship between soil and air temperatures. Lag = time lag in days between the two data values. ACF = autocorrelation function, indicating temporal autocorrelation to respective lag. Dashed lines represent confidence bounds. Autocorrelation coefficients clearly outside of these bounds are considered significantly different from zero at the 5% level. The cross-correlogram shows that the soil data is lagged by up to 2 days behind the air data.

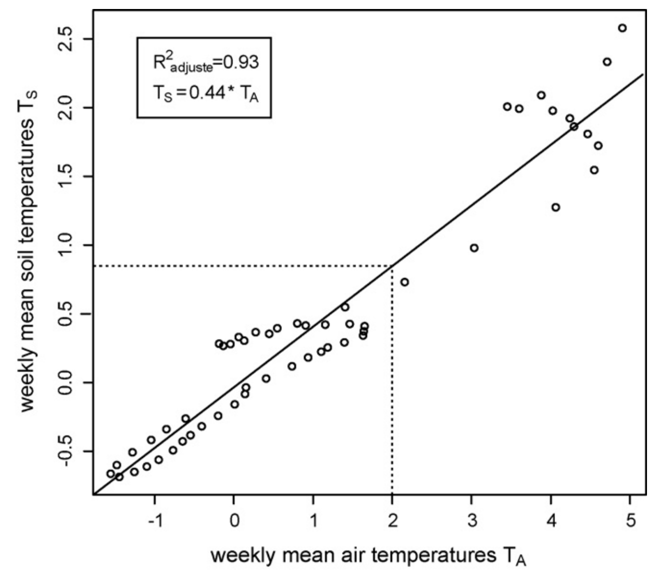

Fig. 6 – Relationship between weekly mean temperatures of soil and air for the period April 1 to May 31, 2004 averaged over nine treeline sites. The solid line represents the regression line. The $R^2_{adjusted}$ may be biased as the residuals are autocorrelated. The dashed lines represent the weekly mean air temperatures indicating that the soil is no longer frozen or covered by snow.

of 0.9 to remove the seasonal trend of the air and soil data (Fig. 3c).

In the second step, we eliminated temporal autocorrelations within our measured temperature time series by transforming the data to first differences (Eq. (1), Fig. 3d).

Third, we fitted a time-lagged regression model to calculate the soil temperature values (first differences) from the differentiated air temperature data (Fig. 3: step 3). The cross-correlogram of the input data showed that the soil data lag behind the air data by up to 2 days (Fig. 5). This means that the air temperature of day t not only influences the soil temperature of the same day but also the soil temperature of days $t+1$ and $t+2$. As a consequence, we incorporated a 2-day lag into the model by adding air temperatures from the two previous days as two additional explanatory variables (Eq. (2)).

$$\mathrm{diff}(\mathrm{Ts}_t) = c_1 * \mathrm{diff}(\mathrm{Ta}_t) + c_2 * \mathrm{diff}(\mathrm{Ta}_{t-1}) + c_3 * \mathrm{diff}(\mathrm{Ta}_{t-2}) + c_4 \quad (2)$$

where: Ts = daily mean root-zone temperature; Ta = daily mean air temperature; $c_{1\text{–}4}$ = coefficients; t = current day; t − 1 = previous day; t − 2 = 2 days past; diff(x) = first differences (see Eq. (1)).

The fourth step was to derive the soil temperature start value. This value is needed to re-transform the resulting first differences of daily mean soil temperatures (Fig. 3d′) back into non-differentiated daily mean soil temperatures (Fig. 3c′). The soil temperature start value was calculated by fitting a linear regression to the spring data of 2004, using weekly mean air and soil temperatures for the period April to May (Fig. 6). We used weekly mean instead of daily mean values in order to increase the regression robustness towards short-term temperature fluctuations. Since parameters of a regression model are unbiased in spite of autocorrelated residuals (Huerzeler, 2004), we used the value 0.44 directly from the regression model (cf. Fig. 6). However, as this relation is only true for non-frozen soil (melting period indicated by soil temperature buffered at 0.5 °C below 2 °C air temperature in Fig. 6), a threshold value of 2 °C air temperature was defined. In short, to calculate the needed soil starting value, we first screened the weekly mean air temperature data for the first value being equal or higher than 2 °C. The identified value was then transformed into the soil starting value using the 0.44 relationship factor.

In the fifth and final step, we reproduced the seasonal trend of the soil temperature values by adding the original seasonal trend of the air temperature data (Fig. 3: step 5, c′–a′).

The above steps were aggregated into an air-to-soil transition model using 2004 daily mean air temperatures to model daily mean soil temperatures. To evaluate this model, we compared the modeled daily mean soil temperatures with the measured 2004 daily mean soil temperatures for nine treeline sites. To test the generality of the model more independently, we applied it to the measured 2005 daily mean air temperatures of all 13 treeline sites (of which three were not used for the model development). Thus, modeled 2005 soil temperatures (calculated using the model calibrated for 2004) were then compared to the measured 2005 soil temperatures. The model prediction error was quantified through the mean absolute error (=average of the absolute values of the residuals; MAE) and the bias (mean of all residuals).

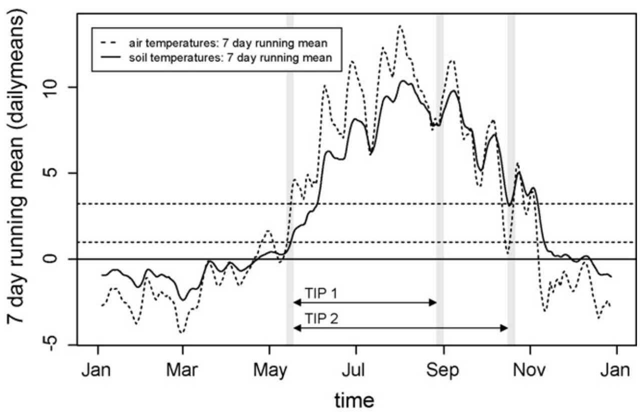

Fig. 7 – Length of thermal indicator periods used to calculate treeline indicator values. Dashed lines represent 3.2 °C and 1 °C lines of 7-day running mean. Arrows between grey bars indicate length of thermal indicator periods TIP1 and TIP2 (from top to bottom).

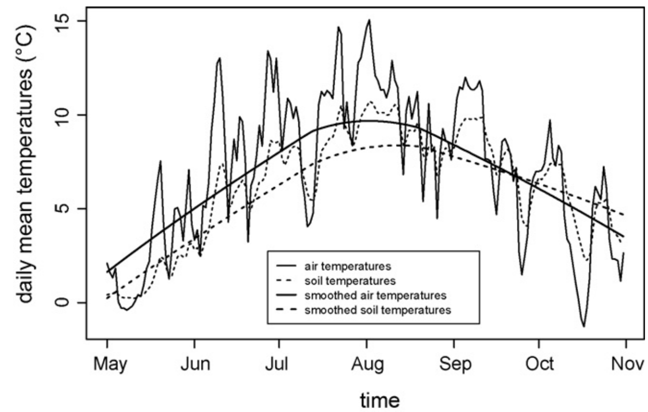

Fig. 8 – Daily means of measured soil (root-zone, 10 cm below surface) and air temperatures averaged over nine sites for the months Mai to November 2004 with smoothed values (lowess with stiffness of 0.9) for both temperature types.

2.5. *Calculate specific thermal treeline indicators*

In our study we evaluated seasonal mean temperature (hereafter *smt*), degree-days above 0 °C (sum of daily values above 0 °C, hereafter *ddg0*), and degree-days above 5 °C (sum of daily values above 5 °C, hereafter *ddg5*) for both the root-zone and the air temperature as treeline indicator values. All values were calculated based on two different thermal indicator periods (hereafter TIP; Fig. 7). Both TIPs started when the weekly mean soil temperatures exceeded 1 °C in spring (ground is snowfree, see Fig. 6). The first TIP ended by the end of August (TIP1), approximating the end of the cambial activity period of treeline trees (see Section 1), whereas the second one ended dynamically at the date where the weekly mean soil temperatures fell under the 3.2 °C mark for the first time in autumn (TIP2), representing the weekly mean air temperatures of 0 °C (Körner and Paulsen, 2004). The fact that we used a 1 °C soil temperature to delineate the start of the thermal indicator period is a slight deviation from the approach used by Körner and Paulsen (2004). It reflects the fact that the mean spring soil temperatures lag behind mean air temperatures by more than a week, which can be seen in Fig. 7. Based on the two thermal indicator seasons and temperature types (air and soil), the indicators were calculated and evaluated for variance across all treeline sites. The lower the variance of the indicators, the better we considered the suitability of the indicators to describe the treeline position for the Swiss Alps.

3. Results

3.1. *Modeling soil temperatures*

The time series graph of the soil and air temperature averaged over nine sites shows distinct patterns (Fig. 8). Overall, the air temperature data is characterized by higher amplitudes while the soil data reveals a damped response. Both curves show an almost identical pattern of peaks and dips, and a typical seasonal trend: temperatures increase from the beginning of May until they reach their highest values in the first days of August, then decrease until the end of November. Soil temperatures lag behind air temperatures and show lower values than air temperatures for most of spring and early summer, while in late fall, mean soil temperatures are above air temperatures (as is represented by the smoothed temperature curves in Fig. 8). In the winter months (not illustrated), the patterns are different: the soil data measured under the snow is quite stable whereas the air data shows peaks and dips according to the weather situation. This shows that temperature behavior in the snowfree and the snow-covered period differs fundamentally. As soil temperatures below zero do not bear much biological meaning (Körner and Paulsen, 2004) our models and indicators are based on temperature data from May to November only.

For this time, our air-to-soil temperature transfer model ASTRAMO (model development see Section 2) produced a good fit. Fig. 9 shows the modeled soil temperatures fitted according to Eq. (3) compared to the measured soil temperatures. The model revealed an adjusted R-squared of 0.88, with a mean absolute error MAE (testing the prediction against the calibration data set) of 0.36 °C, a bias of −0.04 and a maximum deviation of 1.1 °C. Comparing model MAE and bias for the two indicator period lengths TIP1 and TIP2 (Table 2) showed a high similarity. And with no autocorrelations and a normal distribution, model residuals also fulfilled all statistical requirements. In the resulting differentiated regression

Table 2 – Model mean absolute error (MAE) and model bias for 2004 and 2005 data across nine treeline sites for the two thermal indicator periods TIP1 and TIP2

	TIP1	TIP2
2004 MAE (°C)	0.35	0.36
2004 bias (°C)	−0.18	−0.04
2005 MAE (°C)	0.37	NA
2005 bias (°C)	−0.18	NA

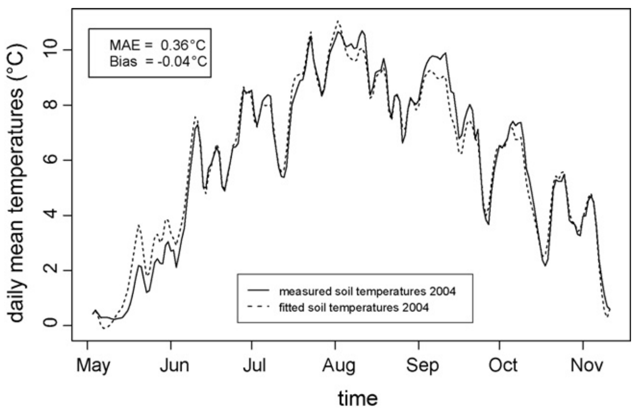

Fig. 9 – Measured and fitted daily mean soil temperature values for the period of May 3 to November 12, 2004 averaged over nine sites. The fitted soil temperatures were calculated from daily mean air temperatures using the air-to-soil transfer model ASTRAMO. Model errors: MAE (mean absolute error) = 0.6 °C, bias (mean error) = 0 °C.

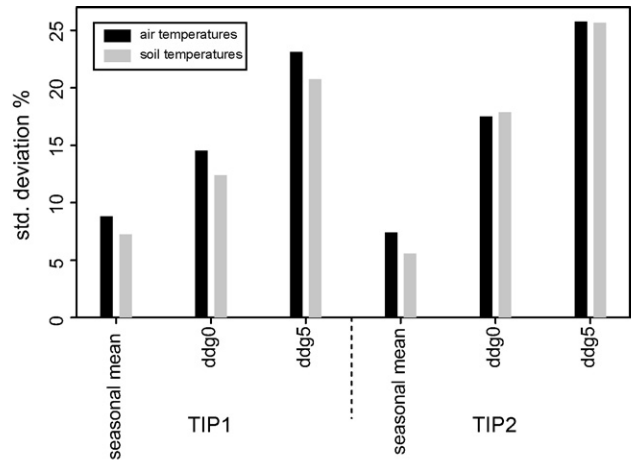

Fig. 11 – Standard deviation of treeline indicators in percent of the 2004 values for the thermal indicator periods TIP1 and TIP2 based on air and soil temperatures.

model, all three variables (Ta_t, Ta_{t-1}, Ta_{t-2}) were highly significant, with the exception of the intercept (Eq. (3)). However, in order to avoid a systematic shift while transforming the fitted first differences into non-differentiated values the intercept needs to remain in the model.

$$\mathrm{diff}(Ts_t) = 0.015 + 0.204 * \mathrm{diff}(Ta_t) + 0.174 * \mathrm{diff}(Ta_{t-1}) + 0.065 * \mathrm{diff}(Ta_{t-2}) \quad (3)$$

where: Ts = daily mean root-zone temperature; Ta = daily mean air temperature; t = current day; $t-1$ = previous day; $t-2$ = 2 days past; diff(x) = first differences (see Eq. (1)).

Results from the verification approach by applying the model to 2005 soil temperatures are shown in Fig. 10. The model also correctly predicted the soil temperature pattern for the year 2005, with a mean absolute error of 0.37 °C, a bias of −0.18 °C (Table 2), and a maximum deviation of 0.9 °C. These values closely correspond to the test results using the 2004 calibration data only, and demonstrate the robustness of the method.

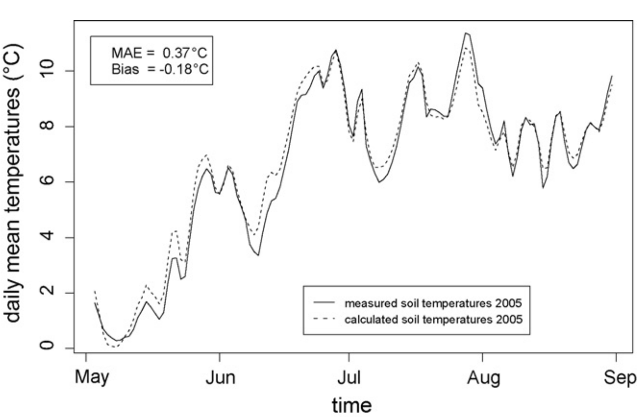

Fig. 10 – Measured and predicted daily mean soil temperature values for the period of May 3 to August 31, 2005 averaged over all 13 study sites. The predicted soil temperatures were calculated based on daily mean air temperatures using the air-to-soil transfer model ASTRAMO. Model errors: MAE (mean absolute error) and bias (mean error).

3.2. *Treeline indicators calculated from recorded data*

Table 3 shows the 2004 and 2005 treeline indicator values for nine study sites based on the measured air and root-zone temperature. While the indicator values do not differ significantly between 2004 and 2005 (paired t-test, only tested for TIP2), a difference is obvious between the two temperature types. Seasonal mean temperature is 1–2 °C higher for air temperature as compared to soil temperature. Consequently, degree-day indicators also show significantly higher values for air than for soil temperatures for all indicator periods.

Comparing the indicators for different thermal indicator periods showed varying results. While different period lengths showed no significant difference in seasonal mean temperatures, a significant increase of degree-days with growing period length (TIP2) was recorded (paired t-test).

To compare the suitability of the different air respectively soil temperature based treeline indicators, we normalized each indicator's standard deviation by calculating the respective standard deviation in percent of its mean value (Fig. 11). Relative standard deviations of air and soil temperature based indicators were very similar, irrespective of the indicator period length. Seasonal mean temperature (*smt*) was the indicator with the lowest relative standard deviation. The standard deviations were between 7.4 and 8.8% for air *smt*, respectively 5.6 and 7.3% for soil *smt*. Degree-days above 0 °C (*ddg0*) was the indicator with the second lowest variation, revealing a standard deviation between 14.5 and 17.5% (air temperature), respectively 12.4 and 17.9% (soil temperature). Degree-days above 5 °C (*ddg5*) showed variations too high to be suitable as a treeline indicator.

Table 3 – 2004 and 2005 treeline indicator values averaged over nine study sites with standard deviations based on measured air (left), and soil (root-zone, temperature 10 cm below surface; right) for the two thermal indicator periods TIP1 and TIP2

	Air temperature		Soil temperature	
	TIP1	TIP2	TIP1	TIP2
2004 *smt* (°C)	8.8 ± 0.8	8.0 ± 0.6	7.1 ± 0.5	7.0 ± 0.4
2004 *ddg0* (degree-days)	904.3 ± 131.3	1276.1 ± 223.6	728.6 ± 90.5	1110.9 ± 198.4
2004 *ddg5* (degree-days)	424.6 ± 98.2	562.9 ± 145.0	259.7 ± 53.9	377.8 ± 96.9
2005 *smt* (°C)	8.7 ± 0.8	NA	7.1 ± 0.3	NA
2005 *ddg0* (degree-days)	960.0 ± 146.5	NA	777.5 ± 100.9	NA
2005 *ddg5* (days)	447.2 ± 117.9	NA	271.4 ± 65.0	NA

NA = missing values; *smt* = seasonal mean temperature; *ddg0* = degree-days above 0 °C; *ddg5* = degree-days above 5 °C.

3.3. *Bias in predicting treeline indicators*

Using our air-to-soil temperature transfer model, we calculated the treeline indicators *smt* and *ddg0* from the modeled root-zone temperatures in 2004 and in 2005. The comparison of these indicators to the indicators based on measured root-zone temperatures revealed the model bias, indicating possible over- or under-estimation. The bias with its standard deviations for nine sites is presented in Table 4. Overall, the bias was comparably small and did not differ significantly from zero (Wilcoxon test).

4. Discussion

4.1. *Air-to-soil transfer model*

Our results show that daily mean air temperatures can be used to accurately predict the corresponding daily mean soil temperatures (10 cm below surface) for the whole growing season at treeline locations across Switzerland without using additional parameters. This is in agreement with Brown et al. (2000) who also used daily mean air temperature values exclusively to calculate the seasonal soil temperature run. This result is rather remarkable with respect to the complexity of soil temperature due to the geological variability and respective thermodynamic influences. However, as our temperature transfer model was calibrated for the uppermost treeline positions in the Swiss Alps, we effectively limited the variability of soil structure and texture. If the temperature transfer model were to be used for predicting soil temperatures at other positions than the ones specified, it would most certainly need a corrective site index variable to account for differences in soil texture and overlay.

In addition, our research has confirmed that in order to develop a reliable time series model, several elements have to be considered. Similar to Brown et al. (2000), we removed the seasonal trend from the data to avoid over and underestimation of soil temperatures. However, in our analysis an empirical trend of the actual year of the data proved best whereas Brown used a deterministic approach. To account for the damping effect of the top soil we additionally incorporated time lags of 1 and 2 days into our model. The significance of these variables reveals the importance of time-lagged models when daily soil temperatures are modeled rather than longer-term soil temperature means. By considering the strong temporal correlation of the chronological data often neglected in other studies, we were able to estimate the true model errors, thereby increasing the model's value for temperature prediction. The reliability of the model has been proven by testing it against 2005 temperature data not used in the model calibration. Even with these data, the model produced correct results with errors no larger than the model tests with 2004 calibration data. A further indication of the model robustness and accuracy is the fact that treeline indicators based on the modeled soil temperature values did not show any significant bias.

While the model has proven well to transform air-to-soil temperatures, the usefulness for simplified treeline indicators such as *smt* may be debated. On the one hand, the calculated *smt* indicator based on the modeled soil temperatures outperformed all other treeline indicators. On the other hand, the time consuming calculations required for the air-to-soil transfer model impede its application across large spatial scales. For such applications, an *smt* indicator based directly on air temperature may therefore be more efficient.

Table 4 – Bias (modeled indicators versus calculated indicators) with its standard deviation of treeline indicator values 2004 and 2005 averaged over nine study sites for the two thermal indicator periods TIP1 and TIP2

	TIP1	TIP2
2004 *smt* (°C)	0.2 ± 0.7	0.4 ± 1.0
2004 *ddg0* (days)	6.5 ± 64.1	23.4 ± 120
2005 *smt* (°C)	0.1 ± 0.4	NA
2005 *ddg0* (days)	10.3 ± 78.2	NA

smt = seasonal mean temperature, *ddg0* = degree-days above 0 °C.

4.2. *Treeline indicators and thermal indicator periods*

As expected, the treeline indicator values investigated in this paper have shown distinctly different behaviors concerning their overall variance, as well as their robustness against different indicator period lengths and temperature data bases. With the smallest variance for both indicator period lengths as well as both temperature types (soil or air), the seasonal mean temperature value (*smt*) is considered the most robust indicator for the position of the treeline. The observed root-zone *smt* value of 7.0 °C with a standard deviation of ±0.4 °C for the long indicator period (TIP2), as well as the 7.1 ± 0.5 °C for the short indicator period (TIP1), are both within the root-zone temperature range identified by Körner and Paulsen (2004) to describe the position of the treeline on a global scale. Comparing our results with Körner and Paulsen's measurements from their 12 Alpine treeline sites (located along a W–E gradient), our *smt* value for TIP2 does not significantly differ from their results. Consequently we can confirm their findings also for an N–S gradient, spanning across different alpine climate zones. Both of our *smt* values also correspond to the 7 °C mean for soil temperatures considered already by Walter and Medina (1969) and Walter (1973) for Alpine treeline positions of the Andes Mountains and the Alps. This result is an indirect proof that even in the heavily managed landscapes of the Swiss Alps natural treelines can be found.

Our results for air temperature, with an overall *smt* value of 8.0 °C ± 0.6 °C standard deviation for TIP2 and 8.8 ± 0.8° for TIP1, are clearly higher than the 5.5 to 7.5 °C air temperature range described by Körner (1998). These discrepancy appears less strong if one considers the fact that Körner's air based indicators describe the treeline position on a global scale. If compared to the four Alpine sites (Mt. Patscherkofel, Austria) in Körner and Paulsen's worldwide temperature measurements (2004), our results correspond to their findings (8.2 °C ± 0.2). Yet, an additional temperature increasing effect of direct sunlight exposure on our measurements cannot be completely excluded. However, we expect this effect to be less than 1 °C due to the smoothing of short-term peaks through the use of averaged data across several measuring points (trees), as well as consolidation to daily mean values for the indicator calculation. Thus, the indicator values appear robust enough to tolerate limited measurement artifacts such as direct sunlight exposure. However, as root-zone based indicators are less prone to such artifacts, they may still provide more reliable predictions.

Concerning the influence of the thermal indicator period length, the absence of a significant difference between the two periods (for both temperature types) can be explained by the underlying data structure: With a roughly symmetric temperature "arc" across the growing season, using only half the chronological data (e.g. the increasing part of the "arc" from spring to late summer) will result in similar mean values as using the complete season's data. For reasons of robustness, though, we suggest to use the longer measurement period to calculate mean values.

The degree-days above 0 and 5 °C indicators (*ddg0, ddg5*) showed generally higher variations than the *smt* indicator. This was expected since degree-days is not an averaged value (such as *smt*) but a daily temperature derivative. For the same reasons, *ddg0 and ddg5* show significant differences between the two-indicator period lengths due to their direct relation to the number of days in the respective time span, making them less ideal indicators. Despite the high variances and period dependency, Körner and Paulsen (2004) have reported a correlation of the *ddg0* indicator with the treeline position when applied within one geographical region, e.g. the Alps. They found no correlation, however, when *ddg0* values were compared with worldwide treeline positions.

4.3. Air versus root-zone temperature based treeline indicators

For all treeline indicator values, significant differences depending on the underlying temperature types were found. Indicator values calculated from air temperature showed not only higher absolute values but also higher variations than the ones calculated from soil temperature. This can be explained by the known damping effect of soil temperatures. For simple treeline prediction, the differences in variance do not directly entail a qualitative rating of the temperature types. However, for spatial modeling, soil temperature based indicators may be favored due to the lower prediction uncertainty (e.g. a lower confidence interval) which would allow more accurate spatial treeline mapping. However, as soil temperatures are difficult to spatially interpolate along elevation gradients, this would require high density measurements or model calculations from air temperatures.

5. Conclusion

Our results have shown that daily mean soil temperatures at the treeline can be modeled accurately from daily mean air temperatures by using our soil-to-air transfer model ASTRAMO. Consequently, treeline indicators based on such modeled soil temperatures turned out to be equally accurate as the treeline indicators based on measured root-zone temperatures. From all the treeline indicators evaluated, soil seasonal mean temperature (*smt*) showed the lowest variation irrespective of the investigated indicator period lengths. It was therefore considered to best describe the position of the Alpine treeline. The *smt* indicator based on air temperatures, while showing a higher variation, was also deemed usable for prediction. To what degree these indicators can spatially delineate the treeline correctly in contrast to the closed forest below and the unforested area located above, will have to be evaluated. However, with the complex models involved, such applications will require a considerable investment of both calculation power and time.

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